Energy harvesting and wildlife monitoring

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Energy budget fundamentally limits science

Tree Swallow migration map

LEGEND
- Year Round
- Summer (breeding)
- Winter (non-breeding)
- Migration

Map by Cornell Lab of Ornithology
Range data by NatureServe
Options for tracking/data collection

Terrestrial Collars
(large land animals)

Marine Tags
(large fish/mammals)

VHF Beacons
(small birds/bats/insects)

Avian PTT
(Larger birds)

Acoustic-Implantable
(Small Fish)

- Telonics
- SPLASH10-F-296
- SPOT-275
- Holohil Systems Ltd.
- Hydroacoustics Technology Inc.
Does this make sense?

Energy storage  Active Element
Energy harvesting: The conversion of ambient energy sources to electrical power, typically associated with small power systems.
Outline

• Previous work in bio-based energy harvesting
• Development of piezoelectric energy harvester for birds
  – Power available from bird flight
  – Compatibility with bird motion
  – Flight testing
• Opportunities for marine animal based energy harvester
  – Current system energy requirements
  – Options for energy transduction
  – Estimates on required conversion efficiencies
  – Overview of current prototype
• Concluding remarks
Short review of bio-based energy harvesting

- Bio-based energy harvesting has been accomplished on a number of species
  - Humans:
    - Backpack straps (piezoelectric stack) [2]
    - Shoe-inserts (piezoelectric and PVDF) [3]
    - Knee swing (electromagnetic generator) [4]
  - Insects
    - Green june beetle (piezoelectric bender) [5]
    - Hawkmoth (piezoelectric resonators) [6]
  - Birds:
    - Various species (solar) [8]

Can we apply this to birds?
Alternate power sources

• Solar is a good power source, but..
  – Microwave telemetry, Inc.:
    • “As useful as the solar powered Argos/GPS PTTs were, they were not suitable for all species of birds….birds living in areas without abundant sunshine cannot rely on solar power.”

• Key difference:
  – Piezoelectric E.H.s draw energy from the animal

• Major research questions:
  – How much power is available from a flying bird?
  – Will piezoelectric E.H.s work on a flying bird?
  – Does it affect the bird’s flight?
Power available from a flying bird

- Power model for bird flight from Pennycuik [9]
- Know that birds can carry ~4% of their mass long term
- Additional power is required to fly with 4% payload?

MAXIMUM OUTPUT POWER (carrying 4% payload)

- Investigated hummingbirds to snow geese
- When transducer mass was included, power was on the order of 0.01-10 mW
Bird flight acceleration measurements

- Measured acceleration in flight on Swainson’s Thrush and Western Sandpiper
- Acceleration magnitude on the order of 1-2 g’s
- Flapping frequency ~12-14 Hz
- Consistent frequency in time [10][12][13]
Piezoelectric energy harvesting testing system

- Piezoelectric beam tuned to ~9 Hz
- Servo to wirelessly lock beam
- 100 Hz data recorder for
  - 3-channel PWM recording
  - Piezoelectric voltage
  - 3-axis accel
- Total mass 12g (2.2-3.3% of pigeon mass)
In-flight test photos

Installation of plastic chassis

System slid into chassis
Testing video results
Effects of system on flight accelerations

- Harvested 0.2-0.3 mW of power (RMS)
- Significant when compared to average power requirements of tags
State of the art: Marine bio-loggers

- Bio-loggers began as simple depth gauges
  - Maximum and time at depth [14, 15]
- Capabilities significantly enhanced from ARGOS satellite system
- Technology has progressed steadily. Now capable of [16]:
  - Position (GPS/ARGOS)
  - Heart rate
  - Acoustic Recording
  - Heading
  - Accelerometer
  - Swim speed
  - Environmental Measurements
    - Temperature
    - Salinity
    - Pressure
    - Light
  - Others
- Significant volume and mass of systems devoted to batteries
- Satellite communications are energy hogs!
Bio-logger energy consumption

- Use tags from *Wildlife Computers™* as energy budget basis.
- Energy consumption depends on how data is offloaded and number/type/fidelity of sensor measurements.
  - Lowest: Radio/acoustic beacon. Requires listening station and triangulation (not shown)
  - Medium: Data stored on tag. Requires retrieval.
  - High: Data stored on tag. Processed and transmitted via ARGOS.
- Tradeoff between capabilities and tag lifetime based on stored energy.
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Available energy sources

- Marine environment provides a number of potential sources
  - **Solar**: bio-fouling, reductions as depth
  - Fluid-kinetic: energy from flow around the animal
  - Hydrostatic Pressure: energy required to overcome buoyancy
  - Direct from animal: thermal, body articulation, etc.

Solar power beneath the ocean surface [19]
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<table>
<thead>
<tr>
<th>Species</th>
<th>Average Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern elephant seal</td>
<td>0.9 - 1.6</td>
</tr>
<tr>
<td>Yellowfin tuna</td>
<td>0.46-0.9</td>
</tr>
<tr>
<td>Sperm whale</td>
<td>0.8</td>
</tr>
<tr>
<td>Orca (shallow/respirating)</td>
<td>1.6</td>
</tr>
<tr>
<td>Orca (deep/hunting)</td>
<td></td>
</tr>
<tr>
<td>Leatherback seaturtle</td>
<td>0.9</td>
</tr>
</tbody>
</table>

\[ P = \frac{1}{2} \rho V^3 A \]
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  - Solar – bio-fouling, reductions as depth
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  - **Hydrostatic Pressure**: energy required to overcome buoyancy
  - Direct from animal: thermal, body articulation, etc.

<table>
<thead>
<tr>
<th>Species</th>
<th>Dive Frequency (dives/day)</th>
<th>Mean Dive Duration (min)</th>
<th>Mean Dive Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern elephant seal</td>
<td>60</td>
<td>22</td>
<td>428</td>
</tr>
<tr>
<td>Yellowfin tuna</td>
<td>20.2</td>
<td>2-10</td>
<td>50-300</td>
</tr>
<tr>
<td>Sperm whale</td>
<td>29</td>
<td>36.2</td>
<td>800</td>
</tr>
<tr>
<td>Orca (shallow/respirating)</td>
<td>600-756</td>
<td>0.38-0.55</td>
<td>2.75</td>
</tr>
<tr>
<td>Orca (deep/hunting)</td>
<td>66-102</td>
<td>4.25-4.75</td>
<td>29</td>
</tr>
<tr>
<td>Leatherback seaturtle</td>
<td>84-120</td>
<td>10</td>
<td>61.6</td>
</tr>
</tbody>
</table>

\[ E = \rho ghV \]
Energy estimates for pressure/dive

- Estimate uses average number of dives per day
- Assumptions:
  - Volume of 250 cm$^3$ (~1 cup) of displacement
  - One harvesting cycle per dive (could get two)
  - 200 J/day energy target
- Very low required efficiencies

<table>
<thead>
<tr>
<th>Species</th>
<th>Depth (m)</th>
<th>Pressure at depth (atm)</th>
<th>Energy (J)</th>
<th>Energy/day (kJ/day)</th>
<th>Req. Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern elephant seal</td>
<td>428</td>
<td>43</td>
<td>1080</td>
<td>65</td>
<td>0.31</td>
</tr>
<tr>
<td>Yellowfin tuna</td>
<td>175</td>
<td>17</td>
<td>440</td>
<td>8.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Sperm whale</td>
<td>800</td>
<td>80</td>
<td>2020</td>
<td>59</td>
<td>0.34</td>
</tr>
<tr>
<td>Orca</td>
<td>2.75/29</td>
<td>0.3/3</td>
<td>7/73</td>
<td>11</td>
<td>1.8</td>
</tr>
<tr>
<td>Leatherback seaturtle</td>
<td>29</td>
<td>6.2</td>
<td>160</td>
<td>16</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Energy estimates for fluid-kinetic source

- **Assumptions**
  - Average swimming speed at 50% of the time per day (likely under estimate)
  - Control surface for fluid flow (2 and 5 cm²). Size of US penny and quarter
  - Use a 200 J/day energy target for generation (>150J/day ceiling)
  - Assume a required efficiencies are small (even with the conservatism)

<table>
<thead>
<tr>
<th>Species</th>
<th>Speed (m/s)</th>
<th>A = 2 cm² (ϕ= 1.6 cm)</th>
<th>A = 5 cm² (ϕ= 2.5 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern elephant seal</td>
<td>1.25</td>
<td>200 (2.3)</td>
<td>500 (0.9)</td>
</tr>
<tr>
<td>Yellowfin tuna</td>
<td>0.68</td>
<td>30 (14.3)</td>
<td>80 (5.7)</td>
</tr>
<tr>
<td>Sperm whale</td>
<td>0.8</td>
<td>50 (8.8)</td>
<td>130 (3.5)</td>
</tr>
<tr>
<td>Orca</td>
<td>1.6</td>
<td>420 (1.1)</td>
<td>1000 (0.4)</td>
</tr>
<tr>
<td>Leatherback seaturtle</td>
<td>0.9</td>
<td>80 (6.2)</td>
<td>190 (2.5)</td>
</tr>
</tbody>
</table>
Pressure system initial prototype

- System operates by allowing high pressure seawater to flow into an empty chamber
- Micro-turbines convert flow to electrical energy
- Initial Turbine Efficiency Testing
  - ~1.5-1.8% efficient across input pressures tested
  - Slight modifications have shown large increases in efficiency
  - Should easily be able to meet 200 J/day target

- Initial system testing
  - 90 psi (~60 m depth)
  - 1.6 J (2 x per dive)
  - 192 J/day for elephant seals
  - Currently testing for exact dives profiles
Conclusion

- There is a current need for energy harvesting for wildlife telemetry systems
  - Long, remote deployment. Science capabilities currently limited by energy stored on batteries
  - Majority (mass and volume) of systems are devoted to batteries
  - Increases in daily energy allowance would enable higher fidelity data and transmission via satellite.
  - This excites biologists

- A number of energy sources are available across species

- With conservative assumptions,
  - Fluid-kinetic transduction systems require 0.5-6% efficiency
  - Hydrostatic pressure cycle generators require 0.3-2.2% efficiency

- This appears to well within the reach of standard energy harvesting technologies.
Acknowledgements

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• Lab members

Dr. Eric Morgan (post-doc)  Greg Hahn (M.S. candidate)  Cody Reed (undergraduate)
One last note... if I have time

- VHF Locating Drone
- Senior Capstone Team
- 3 Mechanical Engineers
- 6 Electrical Engineers
- Expected multi-year project
Questions/Refs

- Always interested in collaborative projects!
  - Michael.Shafer@nau.edu
  - Phone: 928.523.8696
  - www.cefns.nau.edu/Groups/dasl/

[17] Photo credit: Daniel Costa. UC Santa Cruz.
PACIFIC OCEAN AT SAN DIEGO, CALIFORNIA

DOWNWELLING IRRADIANCE

TEMPERATURE: 15-18°C

PANEL ORIENTATION: HORIZONTAL, UPWARD FACING

INSOLATION ON HORIZONTAL WATER SURFACE: 80 mW/cm²

TIME: NOON ON AUGUST 20, 1978

SECCHI VISIBILITY: 16.5 ft

Voltage (V)

Surface

1 ft depth

5 ft depth

10 ft depth

Power (W)

Voltage (V)
Dive profile of sperm whale
Spacecraft analogy

- **Voyager**
  - Designed for deep space
  - No local energy sources
  - Uses RTG (nuclear power source)
  - Long term battery

- **Hubble**
  - In Earth orbit
  - Abundant solar power
  - Almost all spacecraft with orbits closer than asteroid belt use solar power
Unlocking of piezoelectric harvester

- Acceleration but no voltage
- Acceleration and voltage
- Harvester unlocked

Graph showing the locking signal with marked regions indicating acceleration with and without voltage.
Piezoelectric energy harvester overview

\[ \sigma_x = E_x \varepsilon_x - eE^f_y \]

- Stress
- Strain
- Electric field

**Piezoelectric Layers**

- Host Structure
- Substrate Layer

**Variables**
- \( w_h(t) \)
- \( w(x, t) \)
- \( t_s \)
- \( t_p \)
- \( m_{\text{tip}} \)
- \( L \)
Significant harvestable power from birds

Harvestable power as a function of bird mass and transducer specific power
Significant harvestable power from birds

Harvestable power as a function of bird mass and transducer specific power

Species Histogram [11]