Micro/Nano Mechanical Systems Lab – Class#5

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Outline

- Review – Energy Harvesters
- Intro - MicroRobots
Power Sources for Electronics & Sensors in IoT?

THE INTERNET OF THINGS
AN EXPLOSION OF CONNECTED POSSIBILITY

1. Sensors
2. Power

"IoT will consist of almost 50 billion objects by 2020". — Dave Evans, Cisco
# Energy from Mechanical Sources

There are many available mechanical energy sources in the real world, ranging from human motion, water falls, ocean waves, bridge/building/train motion, wind, cars, sound/acoustics … There have been several research reports on mechanical energy harvesters.

<table>
<thead>
<tr>
<th>Source</th>
<th>Frequency</th>
<th>Generated Power</th>
<th>Reference/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge/building</td>
<td>1-40 Hz</td>
<td>Acceleration from 0.01 to 3.8g; Power Density 0.01 to 9539 μW/cm³</td>
<td>7. Abu Riduan, M. et al. J. Semicond. 2012, 33, 074001. 8. Khan, F. et al. Shock and Vibration, 2016, 1340402.</td>
</tr>
</tbody>
</table>
There are significant mechanical energy sources available for harvesting in human activities using different sizes for optimal energy collections, such as: finger motions (chip-size), footsteps (palm-size) and body motions (large size) using potential various energy conversion mechanisms, including piezoelectric, triboelectric, electrets …

<table>
<thead>
<tr>
<th>Human Motion</th>
<th>Generated Mechanical Power</th>
<th>Ideal Converted Electrical Power</th>
<th>Ideal Converted Electrical Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood Flow</td>
<td>chip 0.93 W</td>
<td>0.16 W</td>
<td>0.16 J</td>
</tr>
<tr>
<td>Expiration</td>
<td>chip 1 W</td>
<td>0.17 W</td>
<td>1.02 J</td>
</tr>
<tr>
<td>Breathing</td>
<td>large 0.83 W</td>
<td>0.14 W</td>
<td>0.84 J</td>
</tr>
<tr>
<td>Upper Limb Motion</td>
<td>Palm/large 60 W</td>
<td>10-30 W</td>
<td>10.2 J</td>
</tr>
<tr>
<td>Finger Motion</td>
<td>chip 6.9-19 mW</td>
<td>1.2-3.3 mW</td>
<td>226-406 μJ</td>
</tr>
<tr>
<td>Walking Motion</td>
<td>palm/large 67 W</td>
<td>11-39 W</td>
<td>18.6 J</td>
</tr>
</tbody>
</table>
MEMS Integrated Harvesters

1. Integrated CMOS process
2. High volume low cost fabrication
3. Materials & process development
4. Design & application demos
“Beyond Microelectronics”
Current state-of-art microelectronics are powered by external power sources. On-chip power sources such as MEMS energy harvesters can extend the chips to another dimension beyond the current capabilities. CMOS is the most widely utilized process to be utilized here.
Multilayered piezoelectric flexible energy harvester using interleaved electrodes

a. Multiple layers of 20 µm piezoelectric polymer (e.g., P(VDF-TrFE)) sandwiched with metal electrodes
b. Development of novel piezoelectric polymer with additives to form polar phase with enhanced piezoelectricity
c. Enhanced output power by electrically parallel-connection and impedance matched design
d. Low-temperature, low-cost and scalable process for IOT applications
Part I:
Flexible Piezoelectric Transducer
Piezoelectricity

Piezoelectric Effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress.
Piezoelectric Materials

Single Crystal materials: Zinc Oxide (ZnO), Quartz, Barium Titanate (BaTiO₃), etc.
Polycrystal materials: There is no piezoelectricity before poling. Piezoceramics (PZT), Piezopolymers (PVDF), etc.

Electrical Poling: Applying high electrical field to dipoles

Before poling  In poling  After poling
Example: ZnO Nanowires

Transport is governed by a metal-semiconductor Schottky barrier for the PZ ZnO NW.
Electromechanically coupled discharging process of aligned piezoelectric ZnO NWs observed in contact mode.
Piezoelectricity of Monolayer MoS$_2$

Second-Harmonic Generation (SHG)

Lab Experiment Schedule
Etcheverry Hall 1113

01/30 Tuesday 1pm: Harrison Khoo, Ian Connett · Martin Xu
01/30 Tuesday 2pm: Dan Xu, Vedang Patankar
01/30 Tuesday 4pm: Margann Rui, Tiffany, Vatsal
01/31 Wednesday 3pm: Amruth, Marina Rizk, Lujain Alobaide, Nate
02/01 Thursday 1pm: Neil, Junpyo Kwon
Part II: Flexible Electrostatic Transducer
Electrets

An electret is a piece of dielectric material exhibiting a quasi-permanent electric charge

Even hundreds of years

J. A. Malecki, *PRB* 1999, 59, 9954
Corona Discharge

Electret material: Teflon (PTFE)

Dielectric strength 20-200 MV/m
Relative permittivity 1.90-2.2
Volume resistivity $10^{16}-10^{19}$
Melting Point 327~342 °C
Charge density $-5.0 \times 10^{-4}$ C/m²

G. M. Sessler, Electrets (2nd ed), Berlin: Springer-Verlag, 1987
Surface Potential Detection

PTFE

0.1-1 mC/m²

PE

PET

PP

0.1-1 mC/m²
Example: Paper-Based

Example: Cloth-Based Shirt

S. Li, Q. et al, ACS Applied Materials & Interfaces 2015, 7, 14912.
Challenges
**I: Energy Conversion Efficiency**

**Input mechanical energy:**

\[ W_F = \int_0^{A/2} F ds = 1.07 \times 10^{-3} J \]

**Output electricity:**

\[ W_e = \int_0^{T/2} I^2 R dt = 3.46 \times 10^{-6} J \]

**Efficiency:**

\[ \eta = \frac{W_e}{W_F} \times 100\% = 0.32\% \]
II: Output Power

Larger Power, More Applications!

Improving the Charge Density of the Electret and the Device Structure!

III: Package (against water)

Electret Film against Harsh Environment is a challenge!
Summary

Three Typical Application Fields
Assistance of Internet of Things

- Wearable Electronics
- Self-powered Sensors
- Energy Harvesting

Intro to MicroRobots
Lawsuit Reveals CIA Has Been Using Insect Drones To Spread Disease Since 1970’s

JANUARY 4, 2018 AT 9:16 AM
Factions Of Freedom

via Locks News Network
# Flying Insects

## Artificial Flying Insects

<table>
<thead>
<tr>
<th>Category</th>
<th>Nano Hummingbird</th>
<th>Robotic Insect*</th>
<th>Microrobot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>15cm</td>
<td>3cm</td>
<td>1.5cm</td>
</tr>
<tr>
<td>Status</td>
<td>Autonomous flight</td>
<td>Tethered flight</td>
<td>Flapping motion</td>
</tr>
<tr>
<td>Actuator</td>
<td>DC motor</td>
<td>PZT</td>
<td>Electrostatic</td>
</tr>
</tbody>
</table>

# Actuators

- **Actuators for Artificial Flying Insects**

<table>
<thead>
<tr>
<th>Actuator</th>
<th>DC motor</th>
<th>PZT</th>
<th>Electrostatic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantage</strong></td>
<td>High drive efficiency</td>
<td>Linear motion</td>
<td>High drive efficiency</td>
</tr>
<tr>
<td></td>
<td>DC power electronics</td>
<td>High power density</td>
<td>Miniaturization (easy)</td>
</tr>
<tr>
<td><strong>Disadvantage</strong></td>
<td>Rotary motion</td>
<td>AC power electronics</td>
<td>Pull-in effect</td>
</tr>
<tr>
<td></td>
<td>Miniaturization (hard)</td>
<td>Low efficiency</td>
<td>Low lift force</td>
</tr>
<tr>
<td><strong>Vibration</strong></td>
<td>Forced Vibration</td>
<td>(Flapping Frequency = Input Signal)</td>
<td></td>
</tr>
</tbody>
</table>

Inspiration from Nature

◆ Insects Muscle’s Vibration

- Flapping signal ≠ Neural signal
- Self-excited vibration

## Electrostatic Actuation

### Research Concept and Approach

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Electrostatic actuator</th>
<th>Our actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear motion</td>
<td>Maintain the advantages by using electrostatic actuation.</td>
</tr>
<tr>
<td></td>
<td>High drive efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ease of miniaturization</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>Electrostatic actuator</th>
<th>Our actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pull-in effect</td>
<td>Overcome the disadvantages by using self-excited vibration.</td>
</tr>
<tr>
<td></td>
<td>AC power electronics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low lift force</td>
<td></td>
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</table>
Self-excitation

◆ Self-excited Vibration of Beam

Experimental setup
- Insulated base
- Metal beam
- DC power source

Vibration course
- Electrostatic induction
- No Pull-in effect
- Charging and discharging

Operating Principle

◆ Vibration Course of the Beam (top view)

Structure parameters
- Materials: gold bonding wire
- Length: 10.5mm
- Diameter: 25.4μm
- DC voltage: 1100V

Vibration parameters
- Amplitude: 4.5mm
- Frequency: 80Hz

Actuator Design

◆ Configuration

- Flapping wing assembly: Four parallel beams and two wings
- Parallel metal beams: Enhance the driving force
- Two wings: Extracted from honey bees
- Fulcrum bars with oval holes: Allow the beams to rotate
Flipping & Rotation

◆ Rotational Fulcrum Bars

- Electrostatic induction
- Incline to electrodes
- Contact and charged
- Reverse direction
- Flap and rotation
Experimental Tests

◆ Experimental Setup

(a) 
High speed camera
Transmission bars
Actuator
Manual displacement platform
Electronic balance

(b) Left view
Monitor

d₀
Lift Force

◆ Experimental Setup

- High speed camera
- DC power source
- Electronic balance
- Left view
- Manual displacement platform
Comparisons with Insects

- **Flapping Motion**

  - Our actuator
  - Real insect
Video Demo

◆ Flapping Motion
Experimental Results

- Operation Frequency Characterizations

- Decrease with gap distance $d_0$
Effects of Electrode Gap Distance

- Flapping Angle Characterizations

- Increase with $d_0$ under high voltage
- Decrease with $d_0$ under low voltage
Lift Force vs Gap Distance

Lift Force Characterizations

- Increase with $d_0$ under high voltage
- Decrease with $d_0$ under low voltage
Vertical Takeoff

- **Vertical Lift-Off Setup**
  - U-shape rail: Allow the assembly to move upward
  - Extended electrodes: Provide continuous driving force
  - Upward speed: 2.2mm/s
  - Frequency: 70Hz
Video Demo

- Visual Demonstration of Lift Force
Structure Optimization

◆ Design to Enhance Wing Rotation

One oval hole  Two holes setup
Video Demo

◆ Enhanced Rotational Motion
Conclusion

- The actuator can be excited into resonance with frequency of 50-70Hz by simply DC power source.
- The actuator can drive two insect wings into reciprocation with flapping amplitude up to 48.5°.
- The flapping wing assembly can generate effective lift force (up to 3.1mg) high enough to result in self-lifting.
- Our next work aims at further enhancing the lift force and reducing the total weight, for the purpose of realizing the takeoff of the whole actuator.