Shape-changing micromachines

Daniel López
Electrical Engineering and Computer Science
Materials Research Institute
Pennsylvania State University

dlopez@psu.edu
This webinar is hosted by:

The Nanotechnology Application and Career Knowledge (NACK) Resource Center is a National Science Foundation (NSF) Advanced Technology Education (ATE) Regional Center for Nanofabrication Manufacturing Education. NACK is a subsidiary of the Center for Nanotechnology Education and Utilization (CNEU) in the Penn State College of Engineering’s department of Engineering Science and Mechanics.
This webinar is being recorded and links will be available at:

https://www.cneu.psu.edu/tag/webinar/
http://www.nano4me.org/webinars

Please use the Q&A module for questions related to the webinar topic.

Technical questions (i.e. issues with the webinar controls, etc.) may be put in the chat window.
Hosts and Presenters:

Bob Ehrmann
Managing Director
NACK Center

Mike Lesiecki
Co-PI
Preparing Technicians for the Future of Work

Daniel Lopez
Liang Professor of Electrical Engineering and Computer Science
Penn State
Shape-changing micromachines

Daniel López
Electrical Engineering and Computer Science
Materials Research Institute
Pennsylvania State University

dlopez@psu.edu
Miniaturized machines

Nanomachines: Nanoscale systems
Anything that can gather information and manipulate environment at the micro and nano world.
Micro Electro Mechanical Systems technology

- Typical size: few µm to 100’s µm
- Well known materials and fabrication processes
  - Si is a well understood material
  - Easy to design, control and manipulate
  - Elasticity theory works well (Hooke’s law)
- Applications: basic science to high-end products
- Hard environments: X-rays, accelerations,…

Bell Labs
ANL
2D scanner
Microphone
Magnetometer
MEMS for communications

Handle large amount of information: Big Data
Micromachines today
MEMS technology today: actuation forces

Coulomb balance - 1785

Electrostatic forces vs. Mechanical deformation
MEMS technology today: 3D structures

Micro-machines can be used to assemble and build micro-machines.
Micromachines technology evolution

• Very large-scale integration of MEMS
• Intelligent micro-systems
Very large-scale integration

One transistor

Few transistors

Few million transistors

High-end microprocessor (AMD “Epyc”) contains 40 billion transistors in a chip about 3 cm on a side.

Building the mechanical equivalent of a Pentium chip: giving arms to a microprocessor
MEMS-based Spatial Light Modulators

Neural Engineering System Design (NESD)

- Device that can read $10^6$ neurons and write to $10^5$ neurons

Optimization with Noisy Intermediate-Scale Quantum devices (ONISQ)

- Trapping of neutral atom with parallel operation of gates and beam shaping at µsec speed

Adaptive Laser Headlights

- Active shaping of a vehicle’s high beam
From MEMS to NEMS

- NO Moore’s law for nano-systems
- NOT scale invariant (physics is scale dependent)
Micromachines technology evolution

Intelligent micro-systems

Questions?
Intelligent micro-systems

Physical Intelligence (PI)
Encoding intelligence (perception, action & adaptation/learning) inside the physical body of a physical agent (structure, machine, robot, etc.)

Physical intelligence versus neural Computational Intelligence
- Centimeter and larger scale: CI dominant
- Millimeter scale (limited on-board powering/actuation/computation): PI \approx CI
- Microscale (no on-board powering/actuation/computation): PI only

Metin Sitti - Max Planck Institute for Intelligent Systems

Theo Jansen
Tardigrades exhibit robust inter-limb coordination across walking speeds (bioRXiv – 3/20/21)- Daniel Cohen’s group
Intelligent micro-systems

Tardigrades exhibit robust inter-limb coordination across walking speeds (bioRXiv – 3/20/21)- Daniel Cohen’s group
How to create Physical Intelligence in Micro-systems?

- Physical self-adaptation to changing conditions
  - Reconfigurable morphology, stiffness, damping, color

- Self-sensing & self-reacting to external stimuli or forces
  - Light, temperature, flow,

- Encoding autonomous behavior by smart materials & interactions
  - Mechanical memory
  - Self-propulsion
  - Self-organization
A vision for intelligent microsystems

Flat optics
Kirigami nano-actuators
2D Electronics

New paradigm for designing intelligent microsystems
Metasurface-based flat optics

Conventional bulk optics

Metasurface-based flat optics

- Straight-Forward Fabrication
  - One mask level, cost effective
- Compact
  - Light weight
- Unprecedented Control of Dispersion
- Overcome Limitations of Conventional Optics
  - Aberrations, multifunctionality
- CMOS compatible

Primary wavefront

Secondary wavelets

$t >> \lambda$

$t < \lambda$

5 μm
Metasurfaces and MEMS

Incorporation of flat-optics onto MEMS scanners → Flat optical systems

F. Capasso (Harvard)
Origami - Kirigami structures

Inspired by the ancient Japanese art of paper folding and cutting, and recent developments in modeling that allow inverse design of complex shapes from a single sheet of paper, Origami and Kirigami had emerged as a powerful strategy to transform 2D layouts into scale invariant 3D complex architectures that are difficult to achieve by conventional fabrication processes and additive manufacturing.

A mechanically driven form of Kirigami as a route to 3D mesostructures in micro/nanomembranes

Yihui Zhang1,2, Zheng Yan1,2, Kewang Ncn, Dongqiang Xie1, Yuhao Liu4, Haiwen Luan1, Haoran Fu4, Xiahu Wang3, Qinglin Yang4, Jichen Wang5, Wen Ren1, Hongshi Li6, Pei Liu6, Lilun Yang5, Hejia Li7, Jumong Wang1, Kuxin Gao5, Hongying Luo4, Liang Wang3, Yonggang Huang4, and John A. Rogers1,2,4,7

Programming shape using kirigami tessellations

Gary F. T. Choi1, Levi H. Dudte1 and L. Mahadevan1,2,4,7

John Rogers (NU)  
L. Mahadevan (Harvard)  
K. Bertoldi, D. Nelson
Origami - Kirigami structures

Japanese art of paper folding (Origami) and cutting (Kirigami)

↓

Powerful strategy to transform 2D layouts

↓

Scale Invariant 3D complex architectures

The most innovative applications of Origami/Kirigami engineering is the combination of structural and morphing capabilities that alters a device shape or enhances a material property.
Kirigami-based metasurfaces

Incorporation of metasurfaces onto MEMS scanners

New methodology to fabricate complex 3D nanostructures: Reconfigurable Metasurfaces

New fabrication of complex and tunable 3D nanostructures
- Monolithic integration
- Van der Waals techniques
  - hybrid integration of materials
  - piezoelectric, 2D, metals, metasurfaces

Xu Zhang (CMU)
Haogang Cai (NYU)
Intelligent microscale systems: what’s next?

- Integrating sensing/learning functions
- Passive or active shape & dynamics
- Energetics of communications at small scale
  - High and expensive
  - how much communication you need
  - is local communication enough
- Swarms of autonomous micromachines
  - Coordination
  - Emergent behavior

Manu Prakash (Stanford)
How does biological matter and body computation work?

Radhika Nagpal (Harvard)
The Next Big Thing (?)

Materials and structures for space exploration and settlement

The Next Big Thing (?)

Materials and structures for space exploration and settlement

The most innovative applications of Origami/Kirigami engineering is the combination of structural and morphing capabilities that enhances or alters a material characteristic.

Materials challenges for the Starshot lightsail


The Starshot Breakthrough Initiative established in 2016 sets an audacious goal of sending a spacecraft beyond our Solar System to a neighboring star within the next half-century. Its vision for an ultralight spacecraft that can be accelerated by laser radiation pressure from an Earth-based source to ~20% of the speed of light demands the use of materials with extreme properties. Here we examine stringent criteria for the lightsail design and discuss fundamental materials challenges. We predict that major research advances in photonic design and materials science will enable us to define the pathways needed to realize laser-driven lightsails.

In order to reach relativistic speeds, the Starshot lightsail should have an area of ~10 m² and be kept to a mass of under ~1 gram, which translates into an equivalent thickness of approximately 100 atomic layers. The design of the lightsail will therefore need to push the boundaries of materials science, photonic design and structural engineering to enable high performance with minimal mass.

H. Atwater (Caltech)
Conclusions

• Very large-scale integration of MEMS
  • Intelligent micro-systems
# Acknowledgements

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>David Czaplewski, Changyao Chen</td>
<td>Argonne National Laboratory</td>
</tr>
<tr>
<td>Xu Zhang</td>
<td>Carnegie Mellon University</td>
</tr>
<tr>
<td>Haogang Cai</td>
<td>New York University</td>
</tr>
<tr>
<td>Federico Capasso, Shuyan Zhang</td>
<td>Harvard University</td>
</tr>
<tr>
<td>Mark Dykman, Steve Shaw</td>
<td>Michigan State University</td>
</tr>
<tr>
<td>Damian Zanette</td>
<td>Centro Atómico Bariloche</td>
</tr>
<tr>
<td>Thomas Kenny</td>
<td>Stanford University</td>
</tr>
<tr>
<td>David Nelson</td>
<td>Harvard University</td>
</tr>
<tr>
<td>Mark Bowick</td>
<td>UC Santa Barbara</td>
</tr>
</tbody>
</table>