RESNICK INSTITUTE
science + energy + sustainability

RESEARCH HIGHLIGHTS

From the Resnick Sustainability Institute Graduate Research Fellows at the California Institute of Technology

Shape-Adaptive Ultra-Lightweight Solar Concentrators

Xin Ning

In collaboration with John Steeves and Marie Laslandes under the guidance of Professor Sergio Pellegrino

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Global Significance

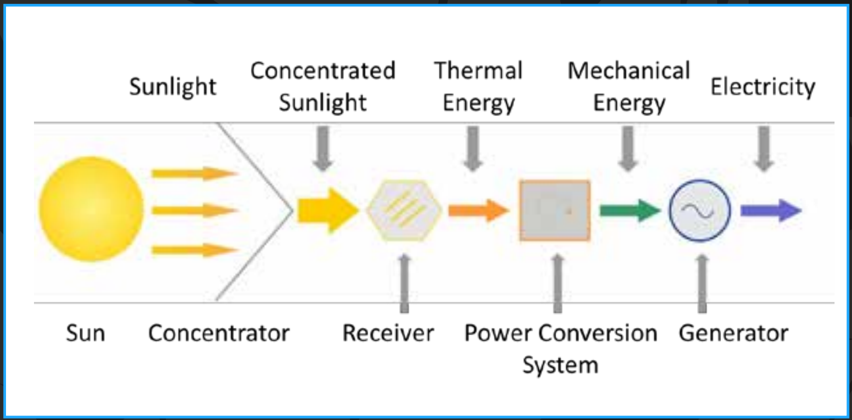
Solar energy offers a number of benefits such as reducing greenhouse gases and air pollutants, providing unlimited energy supply, gaining independence from fossil fuel sources, etc. Despite these benefits, solar energy currently supplies only a small fraction of global energy needs, mainly because its costs are much higher than conventional energy sources.

Concentrating solar power (CSP) uses mirrors to focus the sunlight down to 100-1000x the normal intensity, and uses that concentrated energy as heat to drive turbines and generate electricity. Solar concentrators are one of the key components of a CSP system. However, their optical accuracy is susceptible to environmental disturbances such as wind loading and temperature changes, preventing the system from operating at its peak efficiency.

In addition, the heavy structures of traditional solar concentrators dramatically increase the costs of manufacturing, installation and operation. The costs of solar concentrators can be up to 50% of the total costs of a CSP plant. Significant improvements in solar concentrators are necessary in order to make CSP affordable without subsidies.

To address these issues, we have developed a novel solar concentrator design made from thin, lightweight, and shape-adaptive materials. Our design can improve optical accuracy and reduce structural weight, and has potential to significantly reduce the costs of solar concentrators.

Parabolic dish concentrator. (Courtesy of PSA, Spain)



Schematic of a CSP system per www.csp-world.com

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Project Summary

We are developing a method to construct large aperture mirrors (~1m diameter) for CSP which are shape-adaptive and ultra-lightweight. The shape-adaptive capability makes it possible to adjust the surface of the mirrors in order to correct optical aberrations introduced by wind loading or thermal deformations during operation. This can improve the optical accuracy and hence the efficiency of energy conversion.

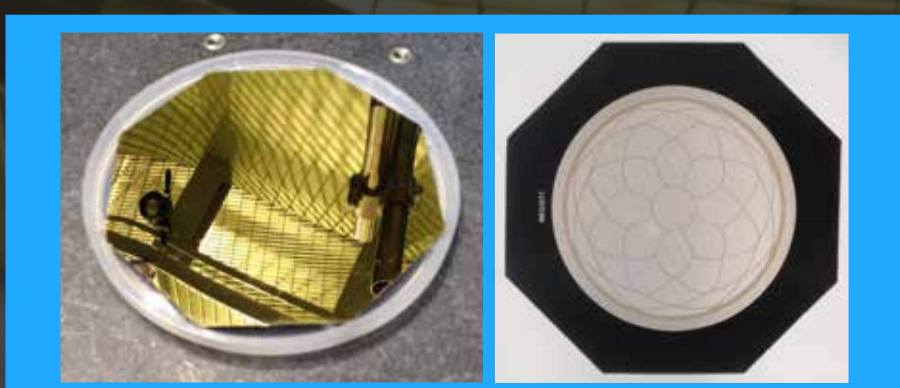
Highly accurate manufacturing processes are no longer required since the mirror can correct shape errors during operation. The relaxation of manufacturing requirements can lead to the reduction of manufacturing costs. The ultra-lightweight mirrors also offer the benefits of further reducing the costs of CSP systems. Firstly, the reduced mass of the mirrors allows for lightweight, small and less expensive sun tracking systems to be utilized in place of traditional bulky/expensive systems. Second, the weight of supporting structures and the costs of shipment and installation can also be reduced. All these benefits of shape-adaptive ultra-lightweight solar concentrators can potentially make CSP affordable without government subsidies.

The projects draws on many disciplines such as aerospace engineering, materials science, structural mechanics, composite manufacturing, optical system engineering, and structural optimization.

- Replacing conventional glass material with lightweight carbon fiber composite has significantly reduced the structural weight.
- Our mirror is “smart”: it can change its shape to correct the optical aberrations.
- Custom actuator patterns produced to optimize the shape correction capabilities.

Potential Impact

- Compared to commonly used 4-millimeter second-surface silvered glass concentrators, our current mirror can reduce weight by 68%.
- Simulated results show that the amplitude of initial error can be easily reduced by 90%, using only 20 actuators.



A 150-mm-diameter prototype with a highly reflective layer on the front side (left)
Actuators pattern printed on the back side (right).

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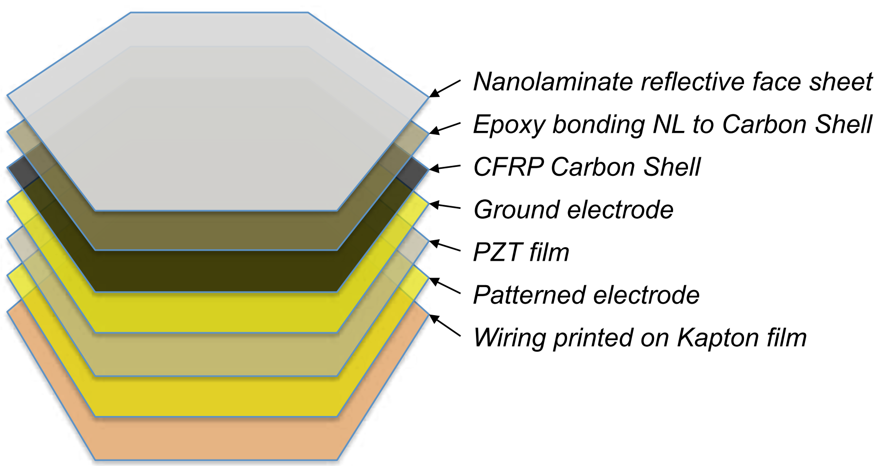
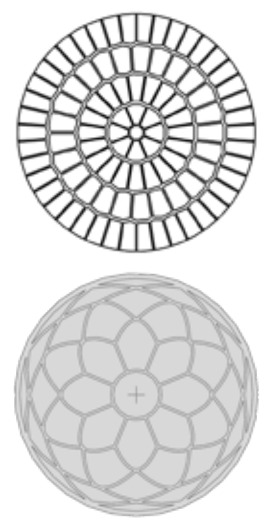
The Science

The objective of this project is to develop shape-adaptive ultra-lightweight solar concentrators. The shape-adaptive capability is obtained by bonding an active layer to the substrate of the mirror. When voltage is applied on the active layer, it can shrink or expand and change the shape of the substrate since it is bound to the substrate layer. Ultra-thin carbon fiber reinforced polymer (CFRP) was chosen as the substrate material because of its low weight and high stiffness. PZT was chosen as the active material due to its high actuation capability and commercial availability. Surface replication of a high-quality glass mandrel provides an initial reflective surface and a nanolaminate face-sheet provides the final highly reflective front-surface.



Exploded view of mirror



Top: Optimal Voronoi actuator pattern.
Bottom: “Notre Dame ” actuator pattern.

The pattern of actuators plays an important role in improving the shape-correction capability. We have developed two optimization approaches. The first approach treats the actuator pattern as a Voronoi tessellation and optimizes the tessellation through an evolutionary algorithm. The second approach uses an intuitive "Notre Dame" actuator pattern to correct the asigmatism error, which is one of the dominant optical aberrations for our thin mirrors.

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Key Results

We have developed manufacturing techniques for shape-adaptive ultra-lightweight solar concentrators. A small prototype was constructed having an areal density of only 3.3 kg/m^2, 68% lower than the commonly used 4-mm glass of traditional solar concentrators. Tests on the prototype show that the shape-adaptive mirror is able to significantly reduce initial shape error and improve the ability of light concentrating. We have also developed techniques for general optimization of shape-adaptive mirrors.

Future Steps

- The improved initial mirror shape, along with the shape-correction ability, can further increase the optical accuracy and improve the efficiency of energy conversion.
- Construct thinner mirrors. This can further reduce the structural weight of solar concentrators, as well as increase the actuation capability.
- Construct larger mirrors, moving towards 1m diameters.

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Publications

- **Active Layer Optimization of Shape-Adaptive Solor Concentrators** (poster). Ning, X., Laslandes, M., Steeves, J. and Pellegrino, S. KISS Workshop of Adaptive Multi-Functional Space Structres for Micro-Climate Control. (19-22 May 2014) Pasadena, CA.
- **Imperfection-insensitive Axially Loaded Cylindrical Shells.** Ning, X., and Pellegrino, S. 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. (8-11 April 2013) Boston, MA, AIAA-2013-1768.
- **Ultra-thin Highly Deformable Composite Mirrors.** Steeves, J. and Pellegrino, S. 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. (8-11 April 2013) Boston, MA, AIAA-2013-1523.