Graphene-Based Bimorphs for Micron-Sized Autonomous Machines

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Primary CNF Tools Used: Oxford Flex ALD, Arradiance ALD, Oxford Cobra ICP etcher

Abstract:

We are developing origami into a tool for fabricating autonomous, cell-sized machines. In our approach, devices can interact with their environment, be manufactured en masse, and carry the full power of modern information technology. Our approach starts with origami in the extreme limit of folding 2D atomic membranes. We make actuators that bend to micron radii of curvature out of atomically thin materials, like graphene. By patterning rigid panels on top of these actuators, we can localize bending to produce folds, and scale down existing origami patterns to produce a wide range of machines. These machines change shape in fractions of a second in response to environmental changes, and perform useful functions on time and length scales comparable to microscale biological organisms. Beyond simple stimuli, we are currently developing voltage responsive actuators that can be powered by on-board photovoltaics. These new electronic actuation technologies are currently being combined with silicon-based electronics to create a powerful platform for robotics at the cellular scale.

Summary of Research:

Our group is shrinking down origami-robotics to become the fundamental platform for nanorobotics by folding atom's thick paper. In origami robotics, actuators, patterned on a sheet, are used to fold complex, reconfigurable 3D structures. This platform is prime for miniaturization because fabrication can be done in plane with tools like photolithography, designs are scale invariant, and flat panels linked by the folds provide a natural place to integrate electronics.

The most basic challenge to miniaturizing origami robots is in actuator design. A single actuator must be capable of bending to micron radii of curvature, produce force outputs large enough to lift embedded electronics, and maintain electrical conductivity across folds while bending. Through research conducted at the CNF, we have shown how actuation technologies based on atomic membranes, like graphene, can achieve these key functional requirements.

First, atomic origami devices can bend to micron radii of curvature using strains that are 100x smaller than the fracture strain for inorganic hard materials, thus maintaining electrical functionality across the actuator. Second, the devices are extremely stiff, capable of lifting the weight equivalent of a 500 nm thick silicon chip, enabling embedded electronics. Third, they can be fabricated and deployed en masse: 10 million devices fit on a 4-inch silicon wafer. Finally, devices can change shape from flat to folded in fractions of a second. Overall, the size, speed, stiffness and strength of these new actuators offer a new perspective on what is possible with nanoscale mechanical technology.

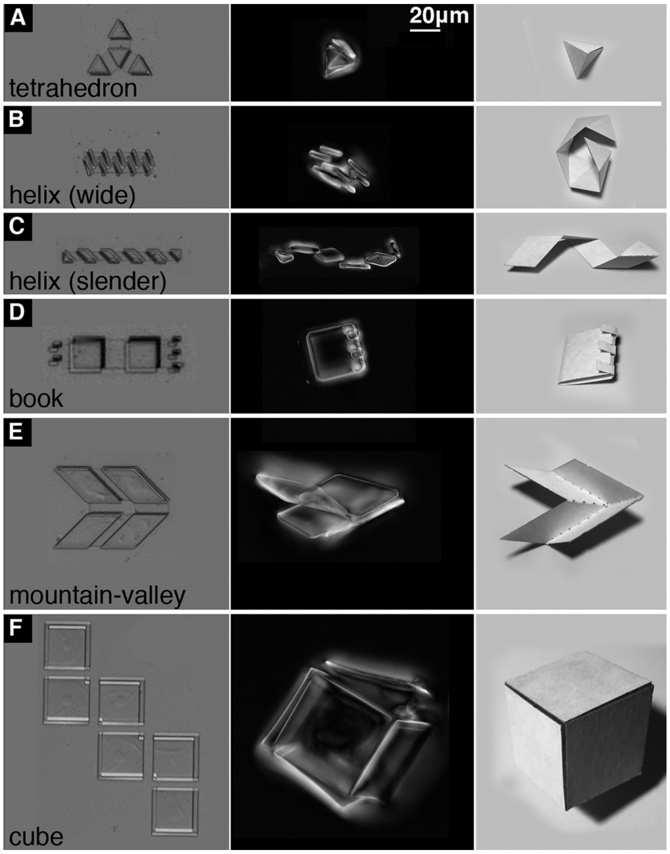
As our first prototypes, we designed and built actuators out of graphene and nanometer thick layers of glass.

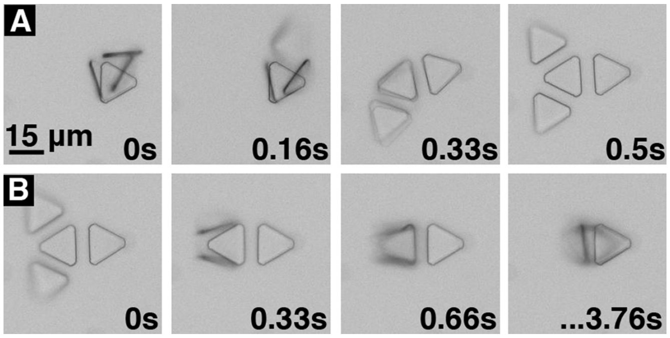
These glass layers were deposited at CNF using the Oxford Flex atomic layer deposition tool. By patterning

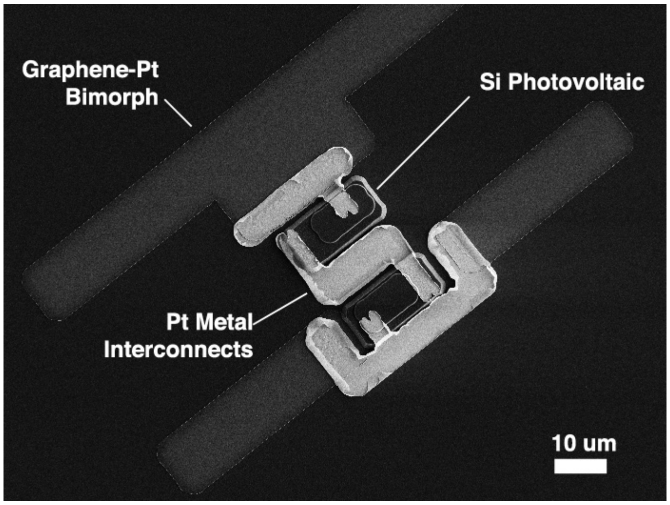
2-µm-thick rigid panels on top of bimorphs, we were able to localize bending to the unpatterned regions to produce folds. Although only nanometers thick, the graphene glass bimorphs were able to lift these panels, the weight equivalent of a 500-nm-thick silicon chip. Using panels and bimorphs, we showed how to scale down existing origami patterns to produce a wide range of machines. We demonstrated that these machines were capable of changing shape in fractions of a second when crossing a tunable pH threshold.

Combined, the work developed a platform for building machines that sense their environments, respond, and perform useful functions on time and length scales comparable with microscale biological organisms.

Currently we are taking key steps in moving towards true robotic systems at the cellular scale by integrating nanoscale origami actuators with electronics. We are now capable of designing and building high efficiency actuators for self-folding machines that are powered by voltage. This advance relies on new metal atomic layer deposition capabilities through the CNF's Arradiance atomic layer deposition tool. These devices can be powered and controlled using standard CMOS electronic components like photovoltaics and transistors. As a first step, we are building basic prototypes that use on-board photovoltaics to power origami actuators. The resulting device can then change shape from flat to folded when external power is supplied through light fields. By combining this actuation technology with origami motifs, we are working to create a walking, autonomous robot no bigger than a few red blood cells in size.







References:

[1] Miskin, et al., Graphene-based bimorphs for micron-sized, autonomous origami machines, PNAS, 2018.

Figure 1, top right: *Graphene origami can be used to fabricate numerous 3D structures at the micrometer scale. Shown here are tetrahedron (A), helices of controllable pitch (B and C), high-angle folds and clasps (D), basic origami motifs with bidirectional folding (E), and boxes (F). In Left, we show the device flattened and still attached to the release layer during fabrication. After the release layer is etched, the bimorphs self-assemble to their targeted 3D geometries (Center).* ***Figure 2, middle right:*** *Graphene origami devices are capable of rapid actuation due to the extreme slenderness of the working materials. Here a graphene origami tetrahedron changes shape from flat to folded and back in response to variations in local electrolyte content. The folding processes is fast, taking place in less than second.* ***Figure 3, bottom right:*** *A first prototype integrating a silicon based photovoltaic with atomic origami actuators. These origami actuators are capable of transforming from flat to folded by applying a voltage of only a few hundred millivolts and nanowatts of power. The photovoltaics supply rough 3x more voltage than is needed and roughly three orders of magnitude more power. The resulting machine will be capable of walking to explore its environment, fully untethered, using the actuators for locomotion and the photovoltaics for power.*