

Ultrasound-Driven Electronically Programmable Microbubbles

CNF Project Number: 2416-16

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Primary CNF Tools Used: Heidelberg DWL2000, AJA Sputter Deposition, Oxford PECVD, Oxford 81/82 etcher, Zeiss SEM, Veeco AFM

Abstract:

We present an on-chip bubble customization platform that enables active bubble writing, erasing, and reconfiguration via electrolysis on electrode arrays. The bubbles, when actuated by an external ultrasound input, create a variety of programmed flows ranging from streaming due to volumetric oscillation of a single bubble, to diverse symmetry-broken directional flows when multiple bubbles interact. Interestingly, we generate a novel bubble shooting flow pattern whose flow direction depends on the incident ultrasound frequency. The active bubble reconfiguration ability unlocks a range of new acoustofluidic functions in a single device with unprecedented controllability.

Research Summary:

Ultrasound resonant microbubbles have emerged as a powerful driver for numerous technologies. At the microscale, microbubbles have been used to achieve propulsion, steering, and deformation of actuators, swimmers, and end-effectors (1–3). While current ultrasound-microbubble systems have demonstrated advanced functionality, scalability, and rapid response, their lifetime, programmability, and controllability remain limited. For example, under continuous oscillation, microbubbles are prone to rectified diffusion, leading to device failure in the long run (4, 5). Unwanted excitation coupling among bubbles also compromises frequency selectivity and independent control (6, 7). Many of these limitations arise because microbubbles utilized in most acoustofluidic systems are passively captured, which does not allow for altering their configurations and rejuvenating devices. One way forward is to change the passive capture paradigm and introduce active, real-time, and in situ microbubble generation and modulation in next-generation ultrasound-microbubble systems.

We unite electrolysis-driven bubble generation with ultrasound actuation to create an active microbubble customization platform. In our approach, a single electrode switches the microbubble states between bubble generation and bubble detachment by tuning the voltage of the localized electrolysis. At low voltages, electrolysis will lead to a low gas-generation rate and a slow increase in bubble volume over time. Upon turning off the electrolysis, the bubble will stop growing and be trapped on the electrode surface due to the surface tension and pinning force (Fig. 1, panel i). Once the bubble reaches the desired size, externally incident ultrasound waves will excite oscillations that induce flows (Fig. 1, panel ii). To clear a bubble, we would simply increase the electrode voltage to generate sufficient hydrogen to detach the bubble (Fig. 1, panel iii). Interestingly, if the bubbling was maintained and coupled to acoustic oscillations, we observed bubbles being actively ejected and transported in the x - y plane, which we termed “bubble shooting” (Fig. 1, panel iv).

This microbubble reprogramming approach embodies a universal framework that can be adapted to multiple electrodes in arrays. Toward this end, we fabricated electrode arrays where each electrode was individually wired and controlled. Because the bubble state on each electrode could be individually tuned, the generated bubbles could be used alone or in combination by controlling a series of time-staggered DC voltage pulses for each electrode along with the globally applied ultrasound amplitude and frequency. To highlight the platform’s potential capabilities, we demonstrated four acoustofluidic operations, including modulating bubble size, inducing bubble interactions, programming modular bubbles, and generating shooting bubbles (Fig. 2).

We show that the platform is capable of real-time bubble generation and modulation and provides multi-degree-of-freedom flow programming for microscale actuation

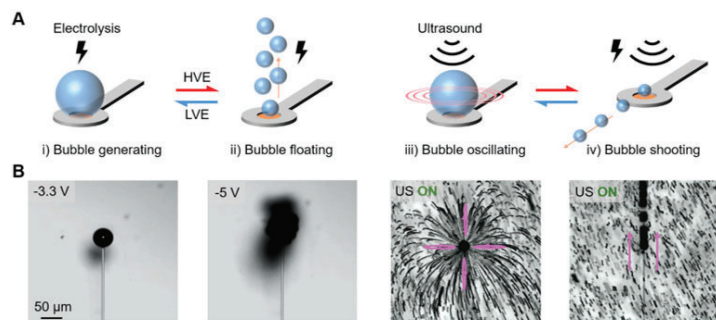


Figure 1: Ultrasound-driven electronically programmable microbubbles. (A) Schematic illustration of bubble state switching on a single electrode, including: i) bubble generating; ii) bubble floating; iii) bubble oscillating; iv) bubble shooting. HVE and LVE denote high-voltage and low-voltage electrolysis, respectively. US denotes ultrasound. (B) Representative images corresponding to the four bubble states in (A) with ultrasound at 74 kHz and 10 VPP. Flow fields were visualized using 5 μm -diameter tracer particles and superimposed frames, with magenta arrows indicating flow directions. Yellow arrows indicate bubble moving directions.

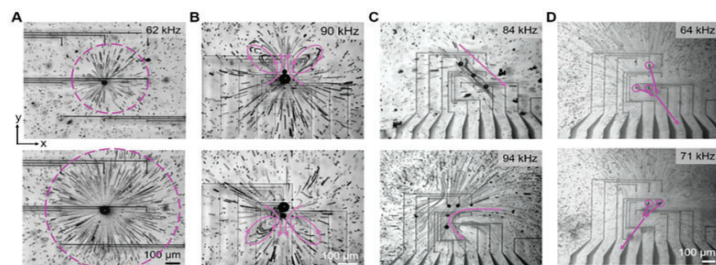


Figure 2: Active bubble configuration and flow programming. (A) Bubble-size modulation and flow scaling. (B) Controlled bubble-pair interaction and flow polarization. (C) Dynamic bubble patterning and flow programming. (D) Frequency-selective directional bubble shooting. Flow fields were visualized using 5 μm -diameter tracer particles and superimposed frames, with magenta arrows indicating flow directions.

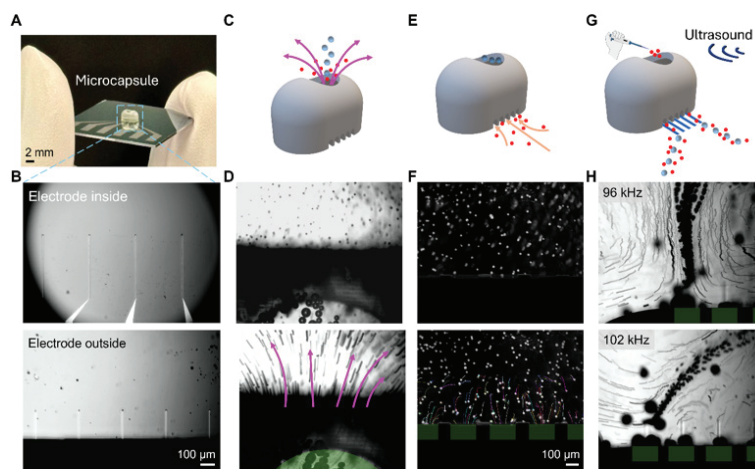


Figure 3: A multifunctional microcapsule enabled by programmable bubble shooting. (A) Optical image of a microcapsule printed by two-photon polymerization on a Si substrate with electrode arrays. It contains a circular top opening and five bottom semicircular openings, each aligned with a microelectrode. (B) Electrodes positioned inside (top panel) and outside (bottom panel) the capsule for different operating modes. (C) Schematic of preloaded cargo released from the top opening driven by bubbling from internal electrodes. (D) An image before bubbling and the superimposed image of particle release during bubbling at -5 V using five electrodes. (E) Schematic of particle collection through the bottom openings driven by bubbling from internal electrodes. (F) Images before bubbling and particle trajectories during bubbling at -8 V using five electrodes. (G) Schematic of selective directional release of preloaded contents through programmable bubble shooting by switching the ultrasound excitation frequencies. (H) Superimposed images showing directional bubble shooting at 96 and 102 kHz, respectively. The ultrasound excitation voltage was 5 VPP, and the electrolysis voltage was -4 V. Magenta arrows denote flow directions. Green rectangles denote the positions of openings.

and manipulation. In lab-on-chip systems, the platform may be assembled into higher-level workflows for particle/cell routing, sorting, and localized sample processing. For microscopic robotics, electronically selected bubble pairs could generate reconfigurable thrust and steering under external ultrasound excitation. To further advance the functional scope, by integrating the electrode array with a two-photon-polymerized microcapsule, controllable bubble generation and shooting enabled directional drug release and on-demand chemical reactions (Fig. 3).

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Two-photon Printing of Electrospray Emitters

CNF Project Number: 2953-21

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Primary CNF Tools Used: Nanoscribe GT2, DISCO Dicing Saw, AJA Sputters, Odd/Even Evaporators

Abstract:

This report summarizes the study "Two-photon printing of monolithic glass electrospray emitters with TPMS micro-architectures" [1]. We present a high-resolution additive manufacturing approach to fabricate monolithic fused-silica electrospray emitters using two-photon polymerization (TPP) printing followed by thermal conversion. Triply-periodic-minimal-surface (TPMS) micro-porous architectures were deterministically integrated into the emitter body to provide passive capillary propellant transport to the tip.

Research Summary:

Motivation: Electrospray propulsion offers high efficiency and precise thrust control for small spacecraft like CubeSats. However, traditional subtractive manufacturing methods (e.g., wet/dry etching, laser ablation, CNC milling) lack independent control over internal and external geometries. This restricts the design space and prohibits integration of engineered microporous networks for passive capillary propellant transport. Additive manufacturing (AM) has emerged as a promising alternative for electrospray emitter fabrication, offering key advantages over traditional subtractive techniques. In this work, we leveraged two-photon polymerization (TPP) printing to fabricate high-resolution electrospray emitters, with embedded triply-periodic-minimal-surface (TPMS) engineered micro-structures for passive fluid transport.

Fabrication Process: An overview of the emitter fabrication process is presented in Figure 1. The emitter baseline geometry is modeled using standard computer-aided-design (CAD) software, in which the size and characteristic dimensions (tip radius, height, cone angle) were prescribed. Next, the template CAD model was processed using a geometric algorithm to embed TPMS lattice structure into the body of the emitter geometry,

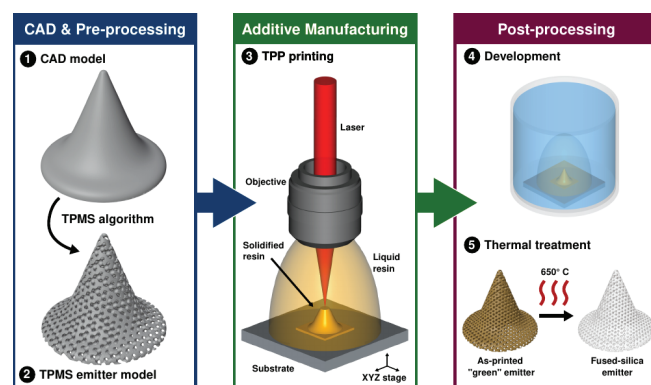


Figure 1: Overview of the emitter fabrication process.

producing a micro-porous internal structure as illustrated in step (2) of Figure 1. The TPMS emitter geometry was TPP-printed using the Nanoscribe Photonic Professional GT2, available in the CNF cleanroom. TPP printing operates by selectively exposing a photosensitive resin using a focused laser, creating solidified "voxels" which are formed into lines and layers to build the desired structure. The 10X objective was used to maximize the printing field and minimize print time. Slicing distance was reduced to 1 μm (5 μm default) to best resolve the intricate TPMS structure. The first 3 layers were printed at half scan speed to improve adhesion to the substrate, and the rest of the structure was printed at full scan speed to minimize print time. Total print time per emitter was approx. 8 minutes. After TPP printing, the emitters were developed in isopropyl alcohol (IPA) for 20 minutes and set aside to dry naturally. The emitters were TPP-printed using a nanoparticle-free silica resin (synthesized in-house) which chemically transforms into fused silica after mild thermal treatment at 650°C for 1 hour.

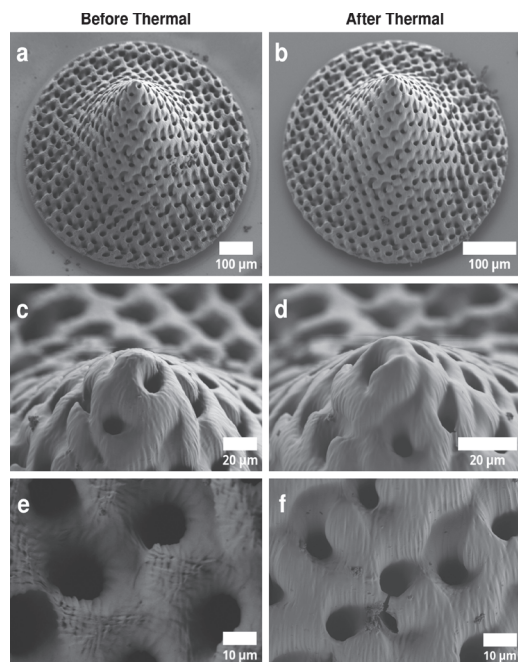


Figure 2: SEM images of a TPP-printed emitter before (left column) and after (right column) thermal processing. The emitter tip is shown in the middle row (c, d), and close-up images of the pores are presented in the bottom row (e, f).

Micro-structure Characterization: Figure 2 presents scanning electron microscopy (SEM) images of a TPP-printed microporous electro spray emitter before (left column) and after (right column) thermal processing. The top-most row (a, b) shows full-view images of the overall emitter geometry, and the zoomed-in views (c, e) and (d, f) focus on the detailed TPMS microstructure and surface texture. At the full-emitter scale (a, b) there are no observed changes/effects from thermal treatment on the emitter shape or TPMS microstructure. The overall emitter shape and TPMS structure look almost identical when comparing the pre-thermal and post-thermal images. However, the higher magnification images (c, d, e, f) reveal some changes in surface roughness and TPMS pore morphology resulting from thermal treatment. Before thermal treatment (d, f) the pores exhibit irregular, jagged boundaries, with visible printing (hatch) lines and artifacts, and a rough surface texture. After thermal treatment (d, f) the surface appears significantly smoother and densified, which suggests localized material reflow and relaxation that occurs during the thermal treatment.

Performance Testing: The emission characteristics of the TPP-printed electro spray emitters were evaluated using direct current-voltage (I-V) measurements. This diagnostic provides insight into key electro spray operating parameters, including onset voltage (to initiate emission) and emission linearity. Sequential I-V curves of a TPP-printed emitter are presented in Figure 3. The I-V curves show highly linear emission behavior

in both positive and negative firing modes across all four runs, with emission currents reaching approx. 800 nA at +3 kV and -500 nA at -3 kV. The measured onset voltage and current response remained consistent across sequential sweeps, indicating repeatable emission behavior over the duration of testing. Overall, the TPP-printed emitters show competitive performance metrics compared to conventionally-fabricated electro spray emitters.

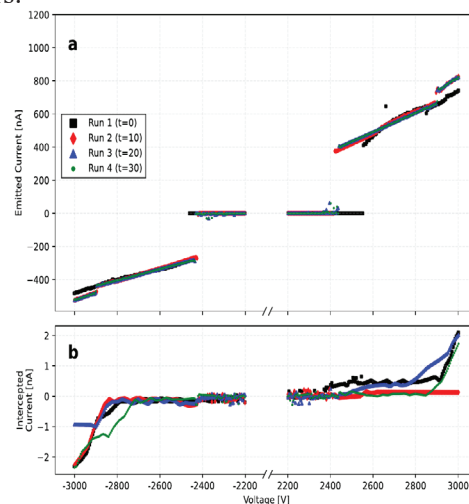


Figure 3: Emission characteristics of a TPMS porous glass electro spray emitter operating with EMI-BF₄ propellant. (a) I-V curves recorded over four consecutive runs at intervals of 10 minutes in both positive and negative polarities. (b) Corresponding intercepted current traces for each run.

Conclusions and Future Steps:

In this work demonstrated the first TPP-printed, monolithic fused-silica electro spray emitters featuring embedded TPMS internal micro-architectures. Combining microscale print resolution, deterministic micro-fluidic porous structure, and inorganic glass conversion enables a previously inaccessible design space for electro spray thrusters. These devices achieve performance metrics comparable to traditional state-of-the-art ionic liquid electro spray systems while providing superior geometric flexibility.

Future research will focus on scaling the TPP process to produce dense multi-emitter arrays capable of providing mission-relevant thrust levels. Achieving this will require optimizing print parameters, such as increasing layer slicing distance, to reduce overall array print times. Additionally, we plan to refine TPMS geometries, pore sizes, and surface morphology to optimize capillary transport, propellant distribution, and emission stability.

References:

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Magnetic Handshakes for Programmable Microscale Self-Assembly

CNF Project Number: 2964-21

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Primary CNF Tools Used: Oxford 81/82 etcher, YES EcoClean Asher, ASML DUV stepper, Gamma Automatic Coat-Develop Tool, JEOL 9500 EBL, JEOL 6300 EBL, SC 4500 odd-hour evaporator, AJA Sputter Deposition, Heidelberg DWL2000, PT770 etcher (left side), Unaxis 770 Deep Silicon Etcher, Oxford FlexAL, Oxford PECVD, Plasma-Therm Takachi HDP-CVD, Zeiss SEM, Veeco AFM

Abstract:

We develop a microscale self-assembly platform in which lithographically patterned nanomagnets encode local bonding rules into individual building blocks. The approximately 20 μm silicon-oxide particles contain arrays of single-domain cobalt nanomagnets whose orientation and position form digital magnetic “barcodes.” A global rotating field drives transport and repeated encounters, while the embedded barcodes determine which contacts become stable. Orthogonal multibit barcodes provide selective recognition among as many as 20 particle species, with ten intended partner pairs assembling together in a single bath. At the collective level, changing the external global field can reshape the energy landscape and reconfigure the target structure. Together, local magnetic encoding and global field control provide a fabrication-compatible route to selective and reconfigurable microscale assembly.

Research Summary:

Programmable self-assembly requires building blocks that can identify intended partners and alter their interaction rules in response to an external command. DNA-mediated interactions provide powerful molecular and colloidal specificity, but larger microscale components diffuse slowly and often require stronger, longer-range driving. Magnetic handshake materials offer a complementary strategy in which spatial patterns of magnetic dipoles encode binding information directly into each component (1–2). The global field supplies transport and control, while the patterned nanomagnets determine the local interaction between contacting particles.

Our building blocks are fabricated in parallel on four-inch silicon wafers. A sacrificial aluminum layer

supports multilayer silicon-oxide particle bodies containing optical identity markers and patterned cobalt nanomagnets. Electron-beam lithography defines single-domain magnets with controlled aspect ratios. Shape anisotropy sets both the remanent moment direction and coercive field. By combining two coercivity classes with two orthogonal orientations, four magnet groups can be addressed sequentially using global x- and y-directed field pulses. The resulting magnetization pattern forms a multibit barcode along selected particle edges. After fabrication, dilute tetramethylammonium hydroxide removes the aluminum layer and releases the particles to an air–water interface, where an in-plane rotating magnetic field mixes the population and promotes repeated encounters.

Selective Assembly through Orthogonal Magnetic Barcodes

We encode partner identity using eight-bit magnetic barcodes. Complementary edge patterns produce a strongly attractive interaction, whereas mismatched patterns are designed to be weakly interacting or neutral. The number of mutually orthogonal barcode pairs increases approximately linearly with barcode length, allowing an eight-bit design to support 16 selective pairs. We selected ten of these pairs for experiment, using 20 optically labeled particle species, 20 copies of each species, and 400 particles in a single bath. The designed interaction matrix isolates each intended pair from the off-target combinations. After magnetic mixing, intended dimers dominate the observed products: most pairs reach near-perfect partner-selection accuracy, although assembly yield varies among barcode sequences. The measured results show that local magnetic patterns can encode component identity and selective recognition without individually addressing the particles.

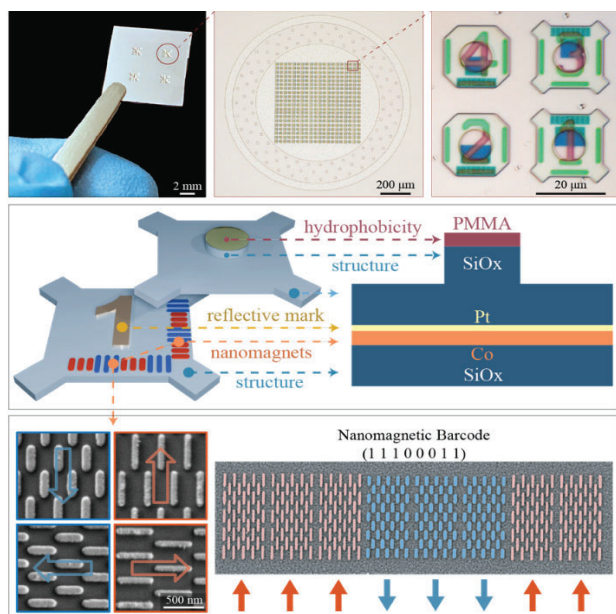


Figure 1: Wafer-scale fabrication of magnetic handshake particles and nanomagnetic barcodes.

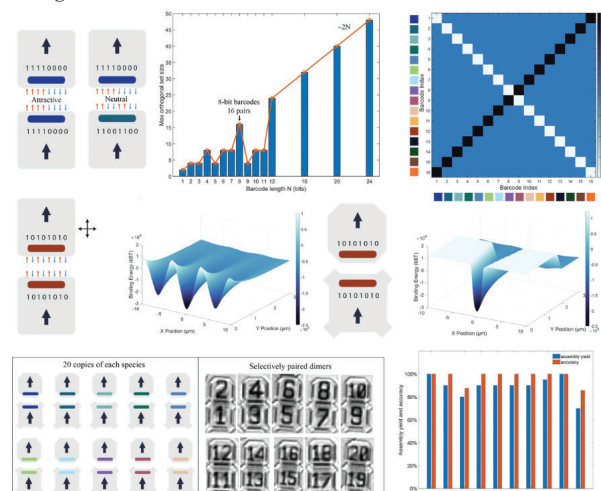


Figure 2: Selective recognition and assembly using orthogonal magnetic barcodes

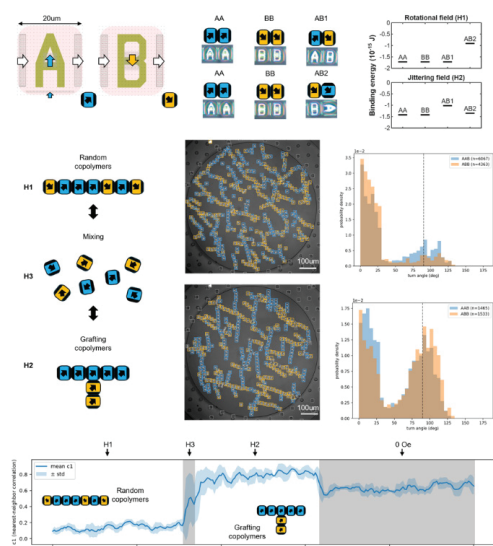


Figure 3: Field-directed rearrangement of chains composed of two types of particles.

Field-Driven Reconfigurably through Energy Landscape

The applied global magnetic field reconfigures the collective energy landscape by changing the relative stability of particle–particle bonding configurations. Under an in-plane rotating field, particles preferentially assemble into predominantly linear, random copolymer-like chains. A brief high-amplitude mixing pulse disrupts these existing bonds, allowing the particles to escape local energy minima and rearrange. Subsequent application of a jittering field stabilizes both linear and approximately 90° bonding configurations, producing branched, graft copolymer-like structures. Turning-angle distributions and nearest-neighbor correlations quantify this transition, demonstrating controllable field-driven reconfiguration between distinct target morphologies without changing the constituent particles.

Conclusions and Future Steps:

Together, the local barcode and the global field provide two complementary levels of control. The barcode specifies which components recognize one another, while the applied field controls the collective energy landscape and accessible target structures. This separation allows many particle species to be actuated together while retaining locally differentiated behavior.

References:

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Solid-State Ionic Actuator-Driven Wings for Sub-Millimeter Robotic Fliers

CNF Project Number: 3157-24

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Primary CNF Tools Used: AJA Sputter Deposition, Oxford FlexAL atomic layer deposition, Oxford 82 reactive-ion etcher, ABM contact aligner, critical-point dryer, and Zeiss SEM

Abstract:

This report describes a sub-millimeter flapping wing powered by solid-state ionic microscopic actuators (SIMAs). Nanometer-scale drive hinges, a lightweight panel, and a passive pitch joint are combined in one lithographically fabricated structure. The wing operates in air from low-voltage input. A microscopic wing with an approximately 250 μm span generated an 80° stroke near 530 Hz and retained motion for about 10^8 cycles. Its output power density was estimated at 1200 W/kg. Aerodynamic and energy estimates indicate that these wings could support a sub-mm flapping robot with small controller and photovoltaics. The work establishes an integrated wing module for future solar-powered microscopic fliers.

Research Summary:

Building a flying robot smaller than one millimeter requires a wing that combines large angular motion, high repetition rate, long life, and microwatt-scale energy use. The structure must also be made by planar nanofabrication and accept signals from a very small control circuit. Existing insect-scale aircraft demonstrate controlled flapping flight, but their actuators and transmissions remain too large for a sub-millimeter platform (1, 2). This project addresses that gap by integrating the actuator, wing panel, electrical leads, and compliant joints into one microfabricated assembly.

The active hinge contains three parallel SIMA strips made from an ultrathin platinum/tantalum-oxide/platinum laminate. The compact actuator serves directly as the active hinge, eliminating a separate transmission. For aircraft integration, the important features are solid-state operation in ambient air, low moving mass, and compatibility with approximately 3-5 V electronics. The actuators supply the main back-and-forth stroke, while

a separate flexible passive hinge allows the wing to change pitch during each cycle.

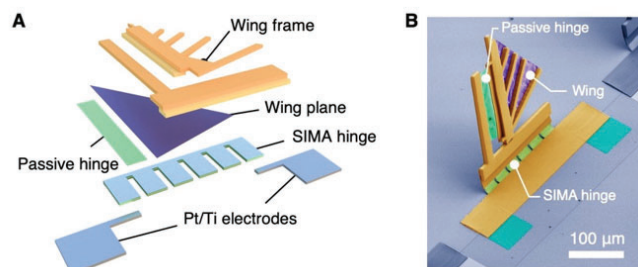


Figure 1: (A) Exploded schematic of a sub-mm flapping wing. (B) False-color SEM image of a sub-mm wing.

The completed wing spans about 250 μm and has a chord near 150 μm (Fig. 1). A titanium film forms the wing surface, while patterned nLOF and SU-8 reinforce the panel with little added mass. A thin tantalum-oxide flexure along the leading edge acts as the passive pitch hinge. The design separates powered stroke from pitch rotation, producing two coupled motions. Fabrication uses CNF processes including sputter deposition, atomic layer deposition, photolithography, plasma etching, and sacrificial release. All layers are patterned on a substrate before release, providing precise alignment of the actuator, panel, frame, and electrical connections.

Alternating voltage moves the released wing between forward and backward positions. At its designed operating point in air, the wing flapped near 530 Hz and swept approximately 80° between the two extremes (Fig. 2). This combination of broad stroke and small span suits the rapid kinematics required at sub-millimeter scale. A second wing from the same fabrication batch continued with substantial amplitude for roughly 100 million cycles, or about one day. From the measured motion and actuator mass, the specific mechanical

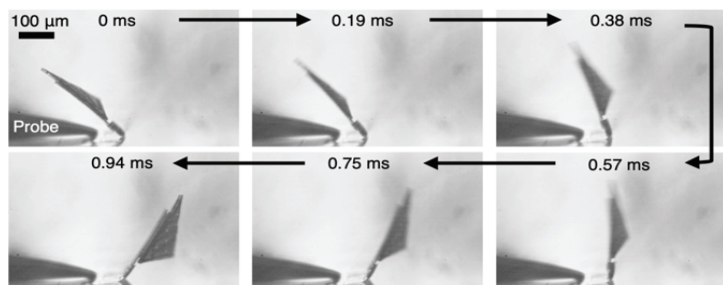


Figure 2: Wing operation in air, showing the stroke extremes, approximately 80° motion near 530 Hz.

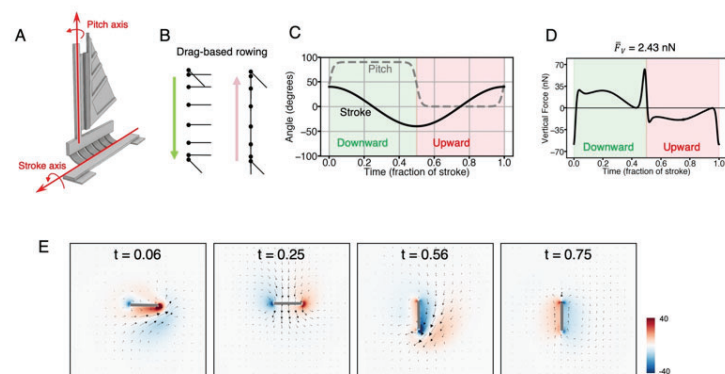


Figure 3: (A) Schematic illustrations of stroke and pitch motions. (B) Wing kinematics for wing chords. The green and pink arrows represent the stroke directions, the black solid circles represent the leading edges and the stick represents the wing chord. (C) Euler angles of pitch and stroke as a function of time over one complete cycle for the three Kinematics. (D) Simulated instantaneous vertical force as a function of time. (E) Vorticity fields (color map) for Kinematics 3, with arrows indicating the flow direction and magnitude (represented by arrow size). The vorticity fields are shown with a color scale ranging from -40 to 40 with blue indicating the clockwise direction and red indicating the counterclockwise direction.

output was estimated at approximately 1200 W/kg, comparable to insect flight muscle and larger robotic flapping actuators (3).

Computational fluid-dynamic calculations evaluated vertical force using the measured geometry and motion: a 250 μm span, 530 Hz wingbeat, and 80° peak-to-peak stroke (Fig. 3). At the resulting low Reynolds number, a drag-based rowing pattern is favorable. The wing plane presents a broad face during the force-producing motion and turns to a narrow profile during recovery (4). With rapid passive pitching, the predicted average force reached about 2.43 nN per wing. Four wings would provide approximately 9.72 nN, greater than the estimated 6.7 nN combined weight of the wings, a 50 μm -scale controller, and thin silicon photovoltaics.

The electrical budget is also close to self-sufficiency. A 30,000 μm^2 photovoltaic area with 20% efficiency is estimated to produce about 6 μW under one-sun illumination. Four wings would consume approximately 5.4 μW , and control electronics are projected to require about 0.2 μW . A complete untethered aircraft has not yet been demonstrated, but the experiments place stroke, durability, force, control, and solar power within one design envelope.

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Micro-Optomechanical Acoustic Velocity Sensor

CNF Project Number: 3224-24

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Primary CNF Tools Used: Nanoscribe Photonic Professional GT2 Two-photon Lithography System

Abstract:

This project aims to develop an ultrasensitive, low-noise micro-optomechanical acoustic velocity sensor for detecting acoustic particle velocity in confined spaces. Existing acoustic systems predominantly measure scalar sound pressure and therefore provide limited directional information. Acoustic particle-velocity sensing enables vector detection, but achieving a high signal-to-noise ratio in a miniaturized device remains challenging. To address this challenge, our sensor integrates a spider-web-inspired, velocity-sensitive 2D microstructure with a fiber-based Fabry–Pérot interferometric readout. The device incorporates three key innovations: a bio-inspired structure with high responsivity to acoustic particle velocity, damping-enhanced suppression of thermomechanical noise, and compact fiber-optic transduction for ultrasensitive displacement readout. The device achieves a peak sensitivity of 0.5 V/Pa at 2.4 kHz and an average minimum detectable equivalent pressure of 7×10^{-5} Pa/ $\sqrt{\text{Hz}}$ over the frequency range from 100 Hz to 20 kHz. Building on these results, our current work at the Cornell NanoScale Facility explores mosquito-inspired three-dimensional microscale structures fabricated using two-photon lithography to further enhance damping and reduce thermomechanical noise.

Research Summary:

Existing acoustic sensors primarily detect sound pressure, a scalar quantity that lacks inherent directional information. Acoustic particle-velocity sensing can directly provide vector information [1,2]; however, achieving miniaturized devices with high sensitivity and low noise floors remains challenging. To address this gap, we developed an ultrasensitive, low-noise micro-optomechanical acoustic vector sensor for detecting weak particle velocity in confined spaces [3].

The micro-optomechanical sensor combines three key features: a spider-web-inspired sensing structure that

provides high mechanical responsivity to acoustic particle velocity, deliberately enhanced viscous damping that reduces thermomechanical noise [4], and a fiber-based interferometer that enables ultrasensitive displacement readout. The sensor operates by positioning a velocity-sensitive microstructure near the end of an optical fiber to form a Fabry–Pérot cavity. Reflections from the movable microstructure and the fiber end interfere within the cavity. Acoustic particle motion interacts viscously with the microstructure and induces mechanical displacement, which changes the cavity length and modulates the reflected optical intensity. The modulated optical signal is then detected by a photodetector, providing a compact and ultrasensitive means of converting weak acoustic motion into an electrical signal through optical transduction.

Figure 1 presents the fabricated sensing structures, the microfabrication process, and the assembled sensor. The silicon nitride sensing structures shown in Figure 1A were fabricated through five main steps, as illustrated in Figure 1B: thin-film deposition, photolithographic patterning, etching, structural release, and drying. These processes produced suspended velocity-sensitive microstructures. The silicon nitride thin film was deposited at the Cornell NanoScale Facility using low-pressure chemical vapor deposition. Figure 1C shows the assembled sensor.

Figure 2 shows the measured acoustic performance. The optically measured sensitivity closely agrees with the independently measured mechanical sensitivity obtained using a laser Doppler vibrometer. The sensor reached a peak velocity sensitivity of approximately 208 V/(m/s), corresponding to an equivalent pressure sensitivity of approximately 0.5 V/Pa near the mechanical resonance at 2.4 kHz. Owing to the enhanced viscous damping of the mesh structure [4], the sensor achieved an average minimum detectable pressure of approximately 7×10^{-5} Pa/ $\sqrt{\text{Hz}}$ over the frequency range from 100 Hz to 20 kHz.

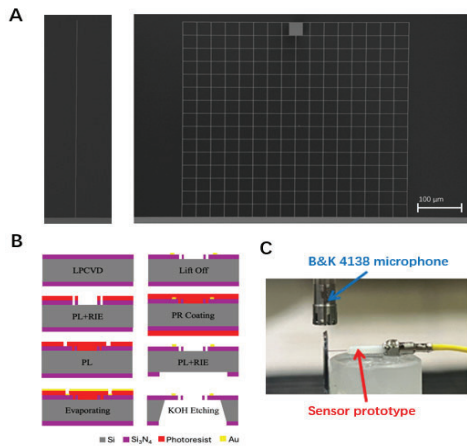


Figure 1: Sensor fabrication and assembly. (A) SEM images of the velocity-sensitive microstructures. The 1D cantilever has dimensions of $500\text{ }\mu\text{m} \times 2\text{ }\mu\text{m} \times 780\text{ nm}$, while the 2D mesh has overall dimensions of $500\text{ }\mu\text{m} \times 500\text{ }\mu\text{m} \times 780\text{ nm}$ and consists of $2\text{-}\mu\text{m}$ -wide beams separated by $30\text{-}\mu\text{m}$ gaps. (B) Microfabrication process. (C) Sensor prototype. A B&K 4138 microphone is placed nearby as an acoustic reference.

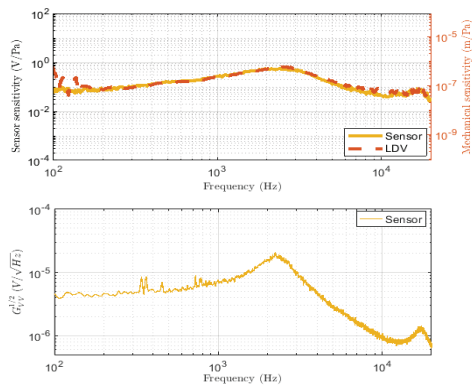


Figure 2: Sensor performance. (A) Sound-induced velocity response, showing close agreement between the sensor and a laser Doppler vibrometer (LDV). (B) Sensor noise floor, dominated by the thermomechanical motion of the 2D micromesh.

To further increase damping and thereby lower the noise floor, our current work at the Cornell NanoScale Facility uses the Nanoscribe Photonic Professional GT2 two-photon lithography system to fabricate three-dimensional microscale sensing structures. The structures are printed in IP-S photoresist using a $25\times$ objective, enabling the fabrication of relatively large three-dimensional beam networks while maintaining microscale feature resolution. Figure 4 presents an example of a fabricated three-dimensional lattice. Compared with conventional microfabrication methods, two-photon lithography offers greater geometric freedom for enhancing viscous damping while preserving sufficient mechanical responsivity. These initial trials are being used to optimize the device geometry and printing parameters for future optical integration and acoustic characterization.

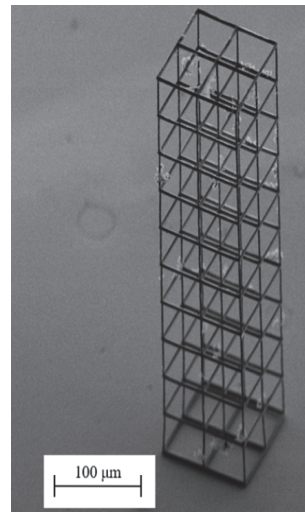


Figure 3: SEM image of a 3D lattice structure fabricated using a two-photon lithography system Nanoscribe GT2. The lattice has overall dimensions of $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$. Adjacent beams are spaced $50\text{ }\mu\text{m}$ apart, and each beam has a square cross-section of $2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$. The highly damped 3D lattice is designed to improve the noise performance of the velocity sensor.

Conclusions and Future Steps:

The current sensor has demonstrated highly sensitive, low-noise vector detection of acoustic particle velocity. Supported by the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health (NIH/NIDCD), our future work will focus on fabricating a higher-performance particle-velocity sensor with enhanced sensitivity, reduced noise, and a sufficiently compact form factor for operation in the confined ear canal. The velocity sensor will then be integrated with a miniaturized pressure sensor to create a dual-sensing ear-canal probe capable of simultaneously measuring acoustic particle velocity and sound pressure. By providing complementary vector and scalar measurements, the probe is intended to improve the accuracy and reliability of otoacoustic-emission measurements, enable better characterization of sound propagation within the ear canal, and ultimately support earlier and more precise detection of inner-ear dysfunction and hearing loss.

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