TOWARDS AERODYNAMIC CONTROL OF MINIATURE ROCKETS WITH MEMS CONTROL SURFACES
Ahad M. Rauf, Brian G. Kilberg, Craig B. Schindler, Sang A Park, and Kristofer S. J. Pister
Berkeley Sensor & Actuator Center
University of California, Berkeley, California, USA

ABSTRACT
We demonstrate a MEMS-actuated aerodynamic control surface integrated into an untethered 16.9 g, 20 cm rocket. The system’s flight performance was characterized inside a wind tunnel. The actuator system generates 3.6 μNm of torque about the rocket’s body axis in 13.3 m/s airflow with 5.1° angle of attack, inducing a maximum roll velocity of 100°/s. This is the first electrostatic inchworm motor-actuated MEMS control surface to perform aerodynamic maneuvers in a self-contained rocket body.

KEYWORDS
MEMS Airfoils, Miniature Rockets, Micro-Air Vehicles, Electrostatic Inchworm Motors

INTRODUCTION
Miniature autonomous rockets provide a natural solution to problems such as micro-air vehicle (MAV) swarm interception and rapid area surveillance, where conventional systems with larger sizes or ballistic trajectories tend to be either expensive or unportable [1], [2]. These rockets benefit from recent improvements in battery energy density and the decreasing size, power, and cost of digital computation and sensors, which could enable low-cost, highly maneuverable autonomous MAVs with size scales <15 cm.

The smallest guided rocket currently in production is the US Navy’s 64 cm long, 57 mm diameter Spike missile. Miniaturizing rocket guidance systems even further will require reducing the size of rocket propellant systems, control and communication electronics, and control surface mechanisms. Previous research has already miniaturized composite propellant rocket motors [3]–[4] and developed 2x3 mm² wireless system-on-chips that can be used as miniaturized avionics and telemetry platforms [5]. These technologies are developed enough that they could be feasibly integrated into a microrocket in their current state.

Recent research efforts have also focused on developing miniaturized control surfaces using microelectromechanical systems (MEMS) technologies such as microbubble actuator arrays, piezoelectric actuators, and electrostatic inchworm motors [6]–[9]. Kilberg et al. have previously demonstrated MEMS control surfaces based on electrostatic inchworm motors, which could be viable for controlling cigarette-sized microrockets due to their small sizes and efficient operation [8], [9]. This mechanism enables 100x smaller device scales compared to previous MEMS aerodynamic actuators [6] as well as 5x lower drive voltages and 2x larger actuator displacements compared to previous piezoelectric aerodynamic actuators [7].

This work presents further improvements towards miniaturizing this MEMS-actuated control surface design.

THEORY AND DESIGN
Aerodynamics and Airfoil Design
Most aircraft use control surfaces such as ailerons, elevons, and canards to control their trajectories. For small angles of attack (α < 15°), the lift force $F_l$ produced by these airfoils can be modeled using thin airfoil theory.

$$F_l = \frac{1}{2} \rho v^2 2\pi A$$  \hspace{1cm} (1)

where $\rho$ is the density of air, $v$ is the airflow velocity, and $A$ is the airfoil’s area. Our control surface uses electrostatic inchworm motors and rotary pin joints to rotate a 2x4x0.03 mm³ steel foil airfoil. Previous simulations showed that control surfaces generating ~10 mN of lift force suffice to control a millimeter-scale rocket [2]. With our airfoil’s dimensions, we can achieve this lift force at an airflow velocity of $v = 35$ m/s, and we’ve previously observed in simulation that our rocket can readily achieve this speed throughout most of its flight path [8].

The resulting aerodynamic lift force applies a torque on the rocket, providing us with a method of controlling roll and yaw.

$$\tau_{roll} = F_l (r + r_{Cop})$$  \hspace{1cm} (2)

$$\tau_{yaw} = F_l d_{Cop}$$  \hspace{1cm} (3)

where $r$ is the rocket’s body radius (7.5 mm), $r_{Cop}$ is the radial distance from the base of the fin to the fin’s center of pressure, and $d_{Cop}$ is the distance between the rocket’s center of gravity and the fin’s center of pressure (defined by the fin’s quarter-chord within thin airfoil theory). Equations 2 and 3 allow us to control roll and yaw with one aerodynamic airfoil, and adding multiple airfoils around the rocket’s circumference gives us full control over roll, pitch, and yaw.
MEMS Actuator Mechanism
The MEMS actuator, fabricated in a simple 2-mask silicon-on-insulator (SOI) process, comprises a pair of electrostatic inchworm motors and rotary pin joints. The inchworm motors pull on a lever arm attached to the airfoil slot, which rotates the airfoil (Figure 2). We applied the higher-density electrostatic inchworm motor design described in [10] to increase our force density by 65% compared to previous work done in [9], as measured by the ratio between the capacitive finger overlap area and the entire motor’s layout area. This redesign allowed us to shrink the MEMS device’s area by 21% from 9x7 mm$^2$ to 5x9 mm$^2$, realizing our design goal of a MEMS actuator that can fit on a 6 mm diameter rocket [8].

Previous work has attempted to prevent out-of-plane forces from dislocating the silicon mechanisms by gluing a small silicon piece over the rotary pin joints [9]. One problem we found with this process was that commercial silver epoxy or superglue would often wick a significant distance from its initial application position, immobilizing silicon mechanisms. To solve this issue, we added extra slots to either side of the MEMS device, where we slotted in a bracket that lay over the lever arm and pin joint structures (Figure 3). The bracket is secured via epoxy only at the sides to prevent wicking from affecting any mobile MEMS components. We fabricated the brackets using the same 2-mask SOI process, and we observed no degradation in device performance after placing the bracket.

INTEGRATED ROCKET DESIGN
MEMS Actuator Mechanism
To mount the assembled control surfaces onto the rocket, we developed a custom flexible printed circuit board with room for 4 control surfaces (Figure 3). The MEMS device substrate is electrically connected via silver epoxy to a large ground plane, and the other control signals are routed from the PCB to the control surface via standard wire bonding techniques. The assembled flexible PCB is then wrapped around a custom 3D-printed fuselage and friction fit into the rocket body (Figure 1).

Electronics and Controls
The inchworm motors require 45 V–110 V to operate, which poses a power supply challenge at small scales. To solve this, we developed an 80 V high voltage buffer board based on Linear Technology’s LT3482 DC/DC boost converter. The board’s 13 mm diameter footprint enables it to be mounted normal to the rocket’s body axis, presenting a 4x area decrease and a 5 cm rocket length reduction compared to previous iterations [9] (Figure 4).

The rocket’s onboard control and wireless communication are handled by the Micro Inertial Measurement System (MIMSY), a 16x16 mm$^2$ node with an Arm Cortex-M3 microprocessor, 802.15.4 wireless transceiver, and a 9-axis IMU [12]. Input power was supplied via a 40 mAh single-cell lithium polymer battery, which can power the IMU and a constantly running TX radio broadcast for roughly an hour after the rocket lands.
AERODYNAMIC PERFORMANCE

The system was tested inside a wind tunnel with 13.3 m/s airflow. Because the rocket’s moment of inertia about its roll axis is much smaller than about its pitch or yaw axes, for ease of measurement we focused on measuring the roll generated from the airfoil’s aerodynamic lift. The full testing setup is shown in Figure 6. The rocket’s vertical suspension by tensioned string in the wind tunnel allowed us to model the system as a torsional pendulum.

\[ \sum \tau = I \ddot{\theta} = \tau_{roll} - K_{tension} \theta \]  
where the moment of inertia along the roll axis, \( K_{tension} \) is the suspension string’s torsional coefficient, \( G \) is the string’s shear modulus, \( G_L \) is the string’s second moment of area (\( G_L = \pi r^4/2 \) for a circular cross-section), and \( L \) is the string’s length. We used 0.005" diameter Berkley XLPS2-15 fishing line for our suspension string. To characterize the fishing line’s shear modulus, we measured its period of oscillation as a torsional pendulum given a test load of known moment of inertia. We fitted this data to Equation 5 to show that \( G = 6.9 \text{ GPa} \) for our fishing line with a \( r^2 \) value of 0.96, indicating high convergence to the theory.

To measure the control surface’s output torque \( \tau_{roll} \), we measured the rocket’s equilibrium position about its roll axis at different wind speeds and angles of attack (Figure 5). We tested fins at three different angles of attack: the 5.1° fin is electronically actuated, while the 10.5° and 19.6° fins are glued into place as control experiments. To account for any asymmetry in the rocket’s construction, we measured the difference between the rocket’s roll with and without the battery connected (or, in the case of the statically positioned fins, by replacing the MEMS actuator with a finless one). We also measured the torsional coefficient and airflow speed for each setup.

Table 1 factors in all these measurements to calculate the output torque on the rocket body. Experimental airflow output torque is shown to match reasonably well with the theory (Equation 2) for angles of attack under 10°, and the deviation between 10-20° angle of attack also matches the expected limit of thin airfoil theory from nonidealities. These results present a promising case for our ability to use linear control models to accurately control the rocket during flight.

<table>
<thead>
<tr>
<th>Angle of Attack (°)</th>
<th>( \tau_{roll,ideal} ) (µNm)</th>
<th>( \tau_{roll,measured} ) (µNm)</th>
<th>( \sigma ) (µNm) (N=3 trials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1°</td>
<td>4.2</td>
<td>3.6</td>
<td>0.035</td>
</tr>
<tr>
<td>10.5°</td>
<td>8.6</td>
<td>7.8</td>
<td>0.23</td>
</tr>
<tr>
<td>19.6°</td>
<td>15.8</td>
<td>7.8</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 1: Output torque from the fin’s lift force, measured across 3 trials for each angle of attack. All measurements were normalized to match a 2x4 mm² airfoil’s area and a wind speed of 13.3 m/s. The rockets tested were either electronically actuated or statically positioned.

We simulated the rocket’s launch performance with an Estes A3-4T engine using the software OpenRocket [13]. The rocket should have a maximum range of 360 m, a top speed of 79 m/s, and the ability to execute 10g maneuvers.

FUTURE VISION

The eventual design of a cigarette-sized rocket would comprise the Single-Chip Micro Mote (SCμM) [5] for communication and computation, an IMU for navigation, MEMS control surfaces for control, a miniaturized camera for sensing, and a rocket motor like in [4] for propulsion. The high voltage circuitry will be replaced by millimeter-scale high-voltage DC/DC converter integrated circuits [14]. Power will be supplied via two 1.5 V coin cell batteries like the SR521SW. Rocket control complexity will scale from roll stabilization using one control surface.
to full roll, pitch, and yaw control using 2-4 control surfaces spaced evenly around the rocket’s circumference. The rocket would be 10 cm long, 6 mm in diameter, and would have 400 m range, a top speed of 25 m/s, and the ability to execute 10g maneuvers [8]. The lack of performance degradation even at lower flight speeds highlights the maneuverability improvements of rocket miniaturization. This scaling is summarized in Table 2.

CONCLUSION

We demonstrated the integration of MEMS aerodynamic control surfaces into a fully integrated miniature rocket. Improvements in assembly techniques and MEMS design substantially improved yield, helping to create MEMS aerodynamic actuators ready for use in real-world systems. These results present a promising case for the ability of MEMS aerodynamic control surfaces to sufficiently control miniature rockets during actual launches, and our higher force density actuators indicate future potential for continued size reduction.

ACKNOWLEDGMENTS

The authors would like to thank the entire Pister group and Swarm Lab. This research was financially supported by the Berkeley Sensor & Actuator Center. MEMS devices were fabricated in the Marvell Nanofabrication Laboratory at UC Berkeley.

REFERENCES


CONTACT
A. M. Rauf, ahadrauf@berkeley.edu

Table 2: Current and projected rocket volumetric dimensions and mass with future scaling of rocket components. The control surfaces presented in this paper are well suited for miniature rockets as is, and incorporating the referenced circuitry and rocket engine designs could further reduce rocket size. The total row includes the above factors plus the rocket’s nose cone, electrical wiring, and fuselage.

<table>
<thead>
<tr>
<th>Component</th>
<th>Current Dimensions (mm³)</th>
<th>Current Mass (g)</th>
<th>Projected Dimensions (mm³)</th>
<th>Projected Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Surface</td>
<td>5 x 4 x 9</td>
<td>0.058</td>
<td>5 x 4 x 9</td>
<td>0.058</td>
</tr>
<tr>
<td>Battery</td>
<td>10 x 4 x 20</td>
<td>1.53</td>
<td>5.8 x 5.8 x 4.3</td>
<td>0.46</td>
</tr>
<tr>
<td>Power Circuitry</td>
<td>13 x 13 x 5</td>
<td>1.27</td>
<td>3 x 3 x 0.3 [14]</td>
<td>0.071 [14]</td>
</tr>
<tr>
<td>Control Electronics</td>
<td>16 x 4 x 16</td>
<td>1.24</td>
<td>2 x 3 x 0.3 [5]</td>
<td>0.047 [5]</td>
</tr>
<tr>
<td>Rocket Engine</td>
<td>13 x 13 x 45</td>
<td>8.5</td>
<td>6.4 x 6.4 x 60 [4]</td>
<td>1.4 [4]</td>
</tr>
<tr>
<td>Total</td>
<td>15 x 15 x 201</td>
<td>19.6</td>
<td>6.4 x 6.4 x 104</td>
<td>5.7</td>
</tr>
</tbody>
</table>