Efficient and Endured Aerial Mobility on Mars Using Novel Morphing Micro Aerial Vehicle Designs. A. Ramezani, [1] E. Sihite[2], S. Devey[2] and M. Gharib[2] [1] Electrical and Computer Engineering Dept., Northeastern University, Boston, MA (a.ramezani@northeastern.edu), [2]Aerospace Engineering Dept., California Institute of Technology (ericsihite@gmail.com, sdevey@caltech.edu, mgharib@caltech.edu).

Introduction: NASA's Mars Perseverance rover carried the Ingenuity Mars Helicopter for the first demonstration of aerial mobility on another planet. Weighing only about 4 pounds (1.8 kilograms), Ingenuity's propulsion systems are based on a standard coaxial configuration consisting of four specially made carbon-fiber blades, arranged into two rotors that spin in opposite directions at around 2,400 rpm – many times faster than a drone on Earth, which is mainly due to Mars' thin atmosphere makes it difficult to achieve enough lift.

The application of rotary-wing systems, which operate based on producing powerful and continuous air jets, can be very costly from an energy consumption standpoint. While the magnitude of dissipative and drag forces acting on the Ingenuity robot passing through Mars atmosphere can be negligible, the large and fast-rotating blades used to maximize lift in a low-density atmosphere require powerful actuators because of their massive mass inertia. These energy-hungry actuators can significantly reduce the operation time of the Ingenuity robot. We have developed a flapping Micro Aerial Vehicle (MAV), shown in *Figure 1*, that can offer efficient aerial mobility for future Mars explorations. Here, we briefly describe the technology.

State of The Art: Many flapping robot designs have been introduced, including small and medium to larger robots, which all share a common design theme: no active wing planform articulations. In all of these systems, the wings are widely made of a single segment. They can translate relative to the body to a flapping motion. Hence, these systems are mono-modal because they only possess one kinematic mode. Wing kinematic adjustments occur in the form of quasi-static joint movements at the wing base (e.g., lagging or feathering) for flight control purposes.

Here, we consider wing planform dynamic conformations because of the underlying energy efficiency mechanisms involved in fast wing expansion and contractions [1]. Below we briefly describe the idea.

Efficiency Mechanism for Endured Flights in Mars Thin Atmosphere: One wingbeat cycle in our robot (shown in *Figure 1*) flight consists of two movements: a downstroke phase, which is initiated by both wings expanding and an upstroke phase, which brings the wings upward followed by collapsing the elbows. This motion pattern improves the efficiency of the animal through a two-fold mechanism.

First, during upstrokes, the negative lift force, which depends on the wing surface area is reduced compared to downstrokes yielding a larger net positive force through a single wingbeat. Second, a wing with reduced moment of inertia travels faster in space resulting in shorter upstrokes. This means that the duration within which the center of mass accelerates downwards due to the negative lift force is reduced. Despite being challenging, copying this dynamic morphing feat can significantly improve flight efficiency of future Mars flying robots.

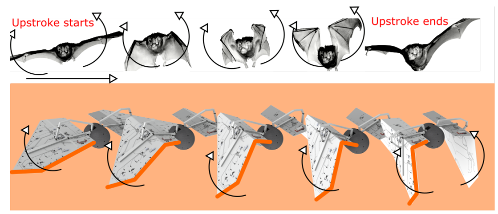

Figure 1: Mars Morphing Micro Aerial Vehicle

Challenges. Here, the main challenges, including hardware and control design, have been partially addressed. In tail-less flapping flight, the main issue is instability since the passively stabilizing components such as tail, rudder, etc., are missing. In our design, the stability properties are even weaker due to dynamic wing planform conformations (we have noticed large pitching instability modes). Therefore, active stabilization through closed-loop feedback must be considered. For active stabilization and control, other than predicting complex fluid-structure interactions, we require small actuators with large energy density for fast response and corrections from a hardware standpoint. Because these morphing drones possess many active coordinates, the state-of-the-art actuators, which are often very bulky, is impossible. Therefore, as part of the ongoing research, we are addressing some of the challenges.

Ongoing Research. Currently, we are studying indicial models of fluid-structure interactions. These models, whose state-space forms can be hard-coded in the system and without significant computation overhead, can accurately predict the resulting aerodynamic forces. While finding these models can be challenging by itself, the gains are enormous for real-time closed-loop feedback.

Concluding Remarks: Mars's unusual environment can pose major challenges for future aerial vehicles. Rotorcraft have shown proven capabilities on Earth; however, they can suffer from their high-rate energy consumptions. We have explored novel bioinspired propulsion designs based on dynamic wing planform conformations that have not been studied before. These designs can promise endured operation times in future Mars explorations.

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References:

[1] A. Ramezani, S.-J. Chung, and S. Hutchinson, "A biomimetic robotic platform to study flight specializations of bats," *Science* (Robotics-AAAS), volume 2, issue 3, pages: eaal2505, February 2017 (cover article; [also featured in *Nature* 542,140 (09 February 2017) doi:10.1038/542140a]).