Origami self-sustained oscillators

Wenzhong Yan[1] and Ankur Mehta[2]

***Abstract*— Driven oscillation is a simple yet efficient strategy for periodic actuation and locomotion for robots, especially biomimetic soft robots. However, these oscillations require bulky rigid components or electronic control units restricting origami machines' full potential. Here we describe a class of origami oscillators that induces piston-like oscillation using a single constant electrical power source, without electronic controls. These oscillators are highly integrated, lightweight, low-cost, electronic-free, and nonmagnetic. The piston-like oscillation arises from a self-opening-enabled negative feedback loop resulting from the special configuration of a bistable mechanism and a conductive linear actuator. The generated oscillating motions enable extensive applications, which we demonstrate with (i) gliding of an origami swimmer on water, (ii) directional crawling of an origami walker on ground, (iii) LED light flashing, and (iv) stirring and mixing of fluid. The oscillation mechanism offers an approach of integrating simple control and logic functions directly into origami structures; this work paves the way for fully foldable autonomous origami robots with a high integration of actuation, control, and locomotion.**

I. INTRODUCTION

In nature, folding plays an important role in the creation of a wide spectrum of complex biological structures, such as proteins and insect wings. Inspired by nature, roboticists have started to explore folding as a design and fabrication strategy to build robots, called origami robots [1]. This folding strategy provides a simple yet elegant approach to construct a wide range of robot morphologies and functions, such as crawling[2], grasping[3], swimming[4], shape morphology[5], self-folding[6], locomotion[7], or combinations of these tasks[8], [9], [10]. However, origami robots may rely on bulky rigid components or electric control restricting the full potential of origami robots of being completely foldable, highly integrated, lightweight, and scalable. Specially, periodic actuation of origami devices require bulky rigid components (e.g., electromagnetic actuator) or electronic control. This work proposes a self-sustained oscillator, composed of two folded, self-opening switches, as shown in Fig. 1 A. This oscillator generates oscillating displacement output from a single constant voltage input; this output motion can, in turn, drive origami actuators and robots without the need of bulky rigid components or electronic controls.

II. RESULTS AND DISCUSSION

Previous methods to achieve periodic actuation of origami devices have relied on bulky rigid components, often requiring complex control systems and limiting use in applications where completely foldable origami robots are desirable or necessary. This paper presents an origami self-sustained oscillator resulting from two instabilities: the buckling instability of the bistable beam that control the ”closed” and ”opened” states of the biased contacts, and the system-level instability caused due to mechanical binding of the poles of the two self-opening switches, as shown in Fig. 1. This oscillator outputs periodic linear displacement and enables driving macroscale devices, merely supplying a

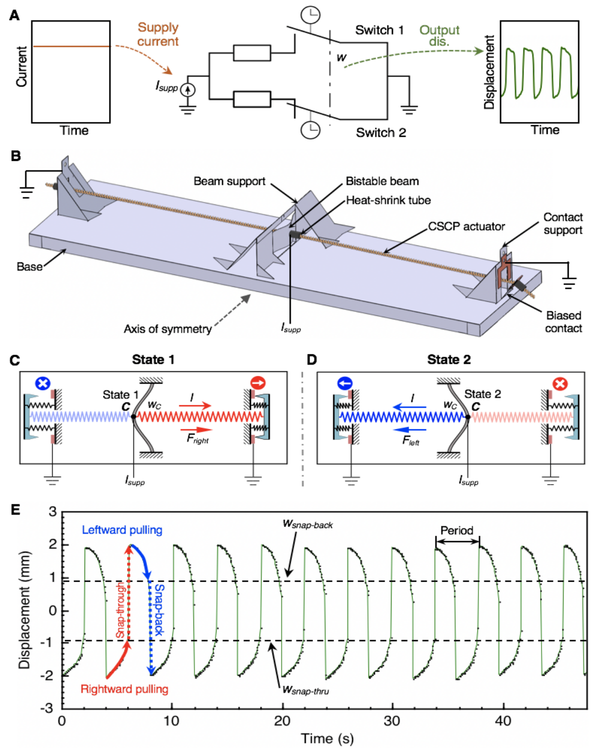

Fig. 1. Mechanism of a self-sustained oscillator. **(A)** Conceptually, an oscillator is composed of two self-opening switches in parallel with their poles linked. This special configuration leads to a systematic instability of any pole position: a constant electric current supply, I_{supp} drives an oscillatory displacement output w of the poles. **(B)** The actuator is created by combining two switches in a head-to-head configuration with a shared bistable beam; the actuated state of one switch is coupled to the unactuated state of the other **(C)** and vice versa **(D)**. Correspondingly, these two state are labeled as state 1 and state 2, respectively. **(E)** The two-switch actuator generates an oscillating output motion when a constant current power supply is applied. $w_{\text{snap-thru}}$ is the displacement required to transition the bistable beam from its state 1 to its state 2; and $w_{\text{snap-back}}$ is the displacement needed to transition from its state 2 to its state 1. The red and blue arrows overlaid onto the plot indicate the rightward pull and leftward pulling processes, respectively. The corresponding red and blue dashed arrows represent the snap-through and snap-back motions. Scale bar, 1 cm.

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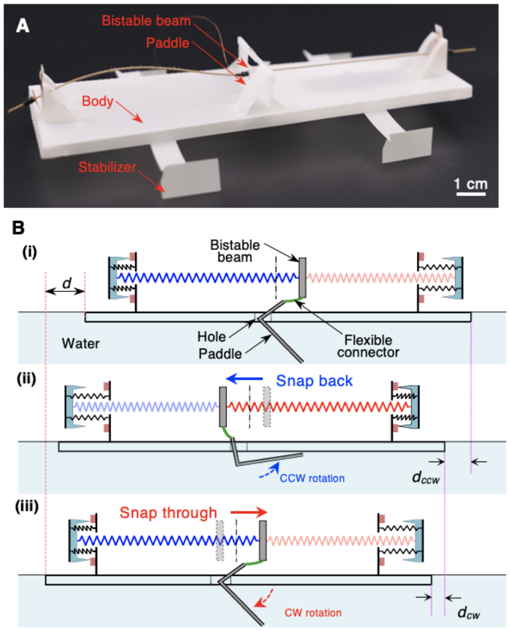

Fig. 2. Autonomous origami swimmer. **(A)** The swimmer consists of an oscillator, four stabilizers, and one L-shaped paddle. The stabilizers and paddle are folded structures and can be monolithically integrated into the oscillator design. **(B)** Simplified locomotion mechanism of the swimmer. (i) When the bistable beam snaps back (leftward in the figure), it drives the paddle counter-clockwise, propelling the swimmer leftward by a distance, d_{ccw}. (ii) When the bistable beam snaps through (rightward in the figure), the paddle thrusts the swimmer move further by another distance, d_{cw}. Thus, the swimmer can glide leftward by $d (= d_{ccw} + d_{cw})$ totally in one cycle.

single, constant voltage input. Thus, this device empowers oscillatory motions in completely foldable devices, illustrating the feasibility of embedding control into the electromechanical constructions (i.e., eliminating the need of bulky rigid control mainly through material properties). Moreover, this oscillation mechanism can be characterized as a generic physical strategy to convert a constant energy input into an oscillatory output; the input-induced responses function as a negative feedback to, in turn, modify the input introducing a systematic instability. This built-in instability enables a self-sustained periodic behaviors with only constant energy input.

We demonstrated the capability of the foldable actuator by (i) gliding of an origami swimmer on water (see Fig. 2 and 3), (ii) stirring and mixing of fluid (see Fig. 4), (iii) autonomous directional locomotion of an origami walker, and (iv) flashing a LED light (the other two applications will only be presented on the conference). When supplied with a constant voltage source, the oscillator could give rise to the aforementioned applications and others requiring periodic actuation. Moreover, when the power source is portable (e.g., battery), the actuator can enable these applications in remote environments without the need for supporting infrastructure. The actuator could, e.g., drive motion, or other functions in a truly "untethered" manner that do not rely on external electronic or electromagnetic components for control. This functionality may be particularly valuable in hazardous fields

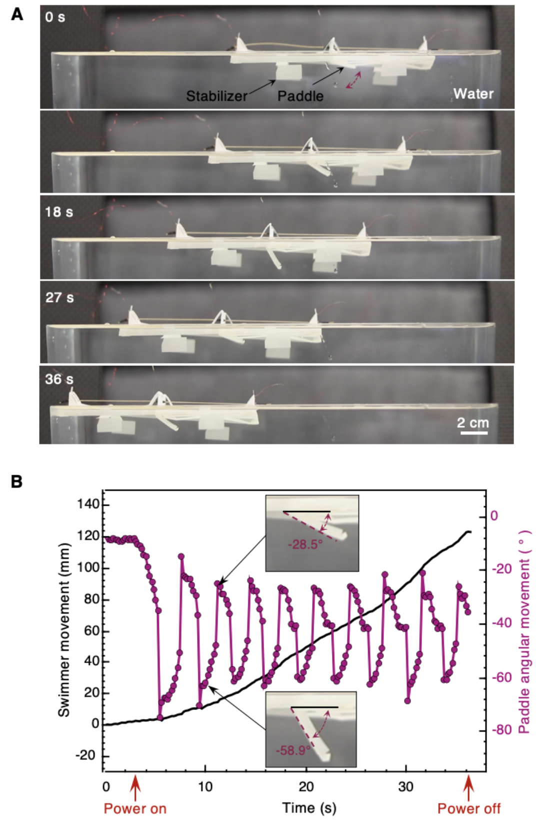

Fig. 3. Autonomous gliding of the swimmer on water. **(A)** Power was supplied after about 3-seconds; the resulting oscillation of the bistable beam drives the rotational motion of the paddle to propel the swimmer leftward over the water surface. *(B)* Time-resolved plots of the (angular) displacement of the swimmer and paddle. The average speed is about 3.66 mm/s.

(e.g., high radiative or high magnetic) though further advance in foldable autonomous control is necessary. A autonomous directional locomotion robot based on the foldable actuator could presumably travel into hazardous environment, take measurements or samples, and then return the collected data.

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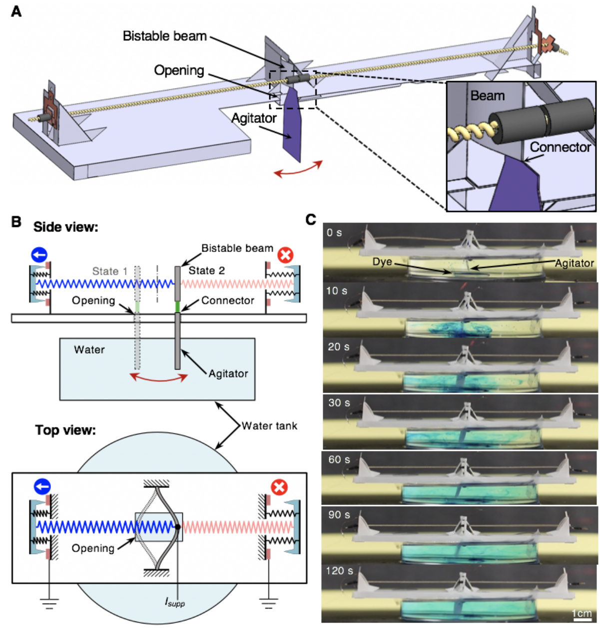

Fig. 4. Stirring and mixing of fluid. **(A)** The 3D rendering of the mixer. On the basis of the oscillator, an origami agitator (in purple) is attached on the bottom edge of the bistable beam through an origami hinge. **(B)** The mechanism of the stirring. The mixer is fixed on the top of a water tank. The agitator is driven by the bistable beam to disturb the fluid (top: side view; bottom, top view). **(C)** The blue dye is injected into water and rests for about 120 s before the stirring. Once a constant current power is supplied, the oscillation of the bistable beam drives the mixer stirring the water to achieve fluid mixing in 120 s.