Soft robotics

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Light-driven actuator with high output power density inspired by insect wings

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An actuator that mimics the actions of muscles in wings of insects by a constant stream of light as its power source provides a high output power for powering rapid motions of robots.

One of the grand goals in the field of robotics is to develop systems that can perform tasks using power received from sunlight. The vision is to create a class of untethered, sunlight-powered robots capable of moving autonomously and performing a wide range of tasks. An effective approach involves integrating solar panels with robots[1]. This approach, however, is indirect, as it requires first the conversion of solar energy into electricity before powering the motion of the robot. The components needed for this conversion add weight to the robots and reduce their versatility. A direct approach involves using solar energy to directly power the robots without relying on solar panels or electronics.

To achieve this goal, engineers have been developing light-driven robots with the necessary functionality and performance[2]. However, one of the most important challenges is to construct a robot with sufficient output power relative to its weight (the power density). A higher power density as the output enables the robot to be more versatile in its movement and operations. As a reference, the power density of a variety of biological organisms ranges from a few to tens of watts per kilogram for motion. For the motion of running, lizards need an output power density of 4–12 W kg^{-1} (ref. 3); for swimming, fish need 5–30 W kg^{-1}; and for flying, insects need 18–26 W kg^{-1} and hummingbirds need 26–29 W kg^{-1} (ref. 4). However, it is challenging for synthetic light-driven robots to achieve similar levels of output power. Another challenge is to generate motion based on only a constant stream of light. Motion of systems typically involves oscillations, such as walking or flapping of wings. However, oscillations are complex dynamics that often involve repeating multiple synchronized processes, including repeating synchronized activation and inhibition steps[5]. Hence, it is fundamentally difficult to achieve oscillations by using only a constant stream of light, instead of using a specifically engineered alternating on-and-off stimulus. It is especially challenging to achieve the complex dynamics of oscillations and generate high levels of output power for sufficient motion of robots.

Now, reporting in *Nature Materials*, Ximin He and colleagues have drawn inspiration from flying insects to generate motion with high output power density using only a constant stream of light[6]. For flying, insects typically use a pair of muscles (Fig. 1a). During flight, these muscles alternate their states in an antagonistic, synchronized and periodic manner: when one set of muscles contracts, the other relaxes. Inspired by this design from nature, the authors developed a flapping actuator made from a thin rectangular slab of material (length: 2.5 cm and thickness: 0.61 mm) that consists of three layers: two light-responsive layers (liquid crystalline elastomers embedded with photo-absorbers) that sandwich a non-responsive layer (elastomer) in the middle (Fig. 1b). When light is applied to the flapping actuator, the light-responsive layer that is exposed to the light contracts and bends the actuator. After moving out of the light exposure, it relaxes while the opposite light-responsive layer becomes exposed to the light and bends in the opposite direction. Therefore, the use of two light-responsive layers on opposite sides replicates the antagonistic action of the pair of muscles found in insects. Importantly, the coupled contraction of one layer and relaxation of the other layer enhances both the bending amplitude and frequency of the flapping actuator, thus increasing its power output. After examining and optimizing the many factors of the flapping actuator, the authors obtain a remarkable output power density of 33 W kg^{-1}. This output power density is comparable to that needed by many biological organisms to move – including to fly – and much higher than previous designs. The elegant design of only two light-responsive layers on opposite sides interestingly allows a constant stream of light to generate the complex dynamics of sustained oscillations while maximizing the harvesting of light energy.

In addition to achieving high output power, the flapping actuator proves to be an effective engine for powering robots. When attached to a boat floating on water, the flapping actuator propels the boat forward at a substantial speed of 1.6 mm s^{-1} (Fig. 1c,d). When attached to a robot on a wire, the robot can be controlled to move either forward or backward with speeds ranging from 0.8 to 2.5 mm s^{-1}. The flapping actuator provides a lifting force of 147 μN, thus achieving a force-to-weight ratio of 0.32. Besides serving as an engine, the flapping actuator exhibits unexpected versatility. The flapping actuator can be fabricated to harvest energy from a broad spectrum of light, from blue to near-infrared, while maintaining a consistent oscillating frequency. In addition, it can sense its own movement (proprioception) or convert its kinetic energy into electrical energy by incorporating piezoresistive or piezoelectric layers into the flapping actuator.

Therefore, the flapping actuator has a high output power density that is comparable to natural systems, together with multifunctionality and diverse applications. This technology thus paves the way for developing a wide range of untethered soft robots without the need for electronics. While untethered electronic-based robots are burdened with either batteries or an energy-harvesting module, the soft flapping actuator is simple, compact and lightweight (47 mg). Owing to these characteristics, it can be attached simply to any robots for powering their motion. Future developments may include demonstrating higher levels of control (for example, more degrees of freedom) of the motion of the robots via using the light-driven flapping actuator. Other developments may involve integrating the flapping actuator with the many advanced properties of other soft materials, such as functional polymers. For example, incorporating other types of stimuli-responsive polymer into the flapping actuator could enable the robot to harvest energy from various natural stimuli and/or enable

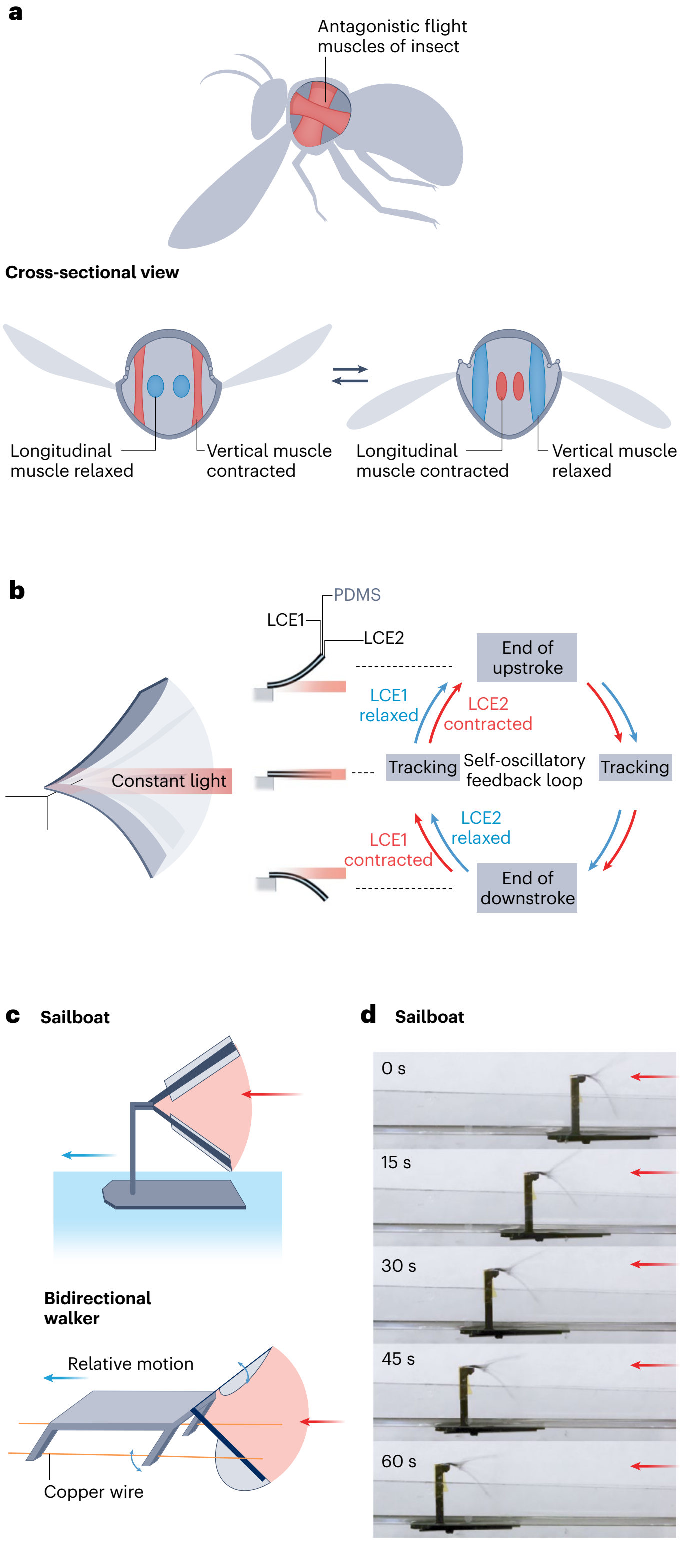

Fig. 1 | Nature-inspired design and applications of a flapping actuator with high output power density. a, The wings of insects are controlled by a pair of muscles that actuates in an antagonistic manner. During motion, one set of muscles contracts while the other relaxes. **b**, Structure of the synthetic flapping actuator based on the design of insect wings. The actuator consists of three layers: a top light-responsive layer (liquid crystalline elastomer, LCE1), a middle non-responsive layer (polydimethylsiloxane, PDMS) and a bottom light-responsive layer (a different liquid crystalline elastomer, LCE2). Application of light onto the actuator triggers a self-oscillatory feedback loop for achieving the flapping actuations. **c**, Flapping actuator attached onto a boat (top) and a walker on a wire (bottom) for powering the robots. **d**, A sailboat with the flapping actuator moves at a substantial speed of 1.6 mm s^{-1}. Figure adapted from ref. 6, Springer Nature Ltd.

multimodal control. In general, soft materials have been shown to exhibit numerous interesting stimuli-responsive functions, including complex shape changes, colour changes, self-assembly, self-healing, logical operations and memory. By integrating the flapping actuator with these advanced properties of soft materials, soft robots can be designed to perform a wide range of complex operations using sunlight as their source of power.

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Competing interests

The authors declare no competing interests.