A FAST-MOVING ELECTROSTATIC CRAWLING INSECT

Mingjing Qi[1,2,†], Yangsheng Zhu[1,†], Zhiwei Liu[1], Xiaoyong Zhang[1,4], Xiaojun Yan[1,3,4,], and Liwei Lin[2]*
[1]School of Energy and Power Engineering, Beihang University, Beijing, China
[2]Mechanical Engineering Department, University of California at Berkeley, USA
[3]Collaborative Innovation Center of Advanced Aero-Engine, Beijing, China
[4]National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, China

ABSTRACT
We report an insect-size crawling robot with fast moving speed driven by electrostatically induced self-vibration for the first time. Under an applied DC voltage, the robot with a total mass of 47mg has achieved a forward crawling speed up to 30mm/s (1.5 body lengths per second). Using an integrated on-board capacitor, it can move freely without electrical powering wires for up to 10 seconds with a speed of 2mm/s. The simple structural design including power supply and vibration-based driving methodology could open up new directions for micro-robot research.

INTRODUCTION
Artificial crawling micro-robots, which can be used in limited spaces due to their small size, have the potential to play important roles in many occasions, such as search and rescue, infrastructure inspection and medical treatment, etc. For the past decades, research groups have investigated many kinds of crawling robots driven by DC motor to achieve good maneuverability with high efficiency. For example, the “RHex” has 6 motors located at each hip to crawl at the maximum speed of 0.55m/s at rugged and obstacle-ridden ground [1]. The “iSprawl” is a 155mm-length crawling robot driven by one single motor and can also achieve a stable locomotion [2].

When the sizes of these crawling robots decrease to centimeter-level or even millimeter-level, since the performances (efficiency, power output, etc.) of the DC motor reduce rapidly, micro-robots will call for actuators with different principles and structures, such as SMA actuators [3, 4], piezoelectric actuators [5, 6], magnetic actuator [7] and electrostatic actuators [8]. For example, the robot “RoACH” is actuated by SMA and fabricated with the process of smart composite microstructure, realizing autonomous crawling with weight of only 2.4g (including control electronics and battery) [4]. The “HAMR”, driven by six piezoelectric actuators for lift and swing separately, achieves a high speed locomotion up to 37cm/s with off-board power supply [5]. Electrostatic actuators have also been utilized in micro-robots through silicon comb-structures to result in a crawling speed of 3 mm over 8 minutes [8].

To realize walking gaits and lateral movements, these robots mentioned above have been demonstrated by using complicated AC power supply and control circuits, which are very hard to be integrated into that small scale of robots and will slow down their moving speed. In this work, by using only DC voltage supply to power a self-excited electrostatic actuator [9], we present a new type of electrostatic-driven crawling insect with simple structures, self-sustained walking gaits and fast crawling speed. A prototype device has been designed, fabricated and tested to verify the feasibility of this new driving concept.

DESIGN AND FABRICATION
Figure 1 shows the 3D schematic model and an optical photo of the new concept of artificial crawling insect. It consists of cantilever beams, two electrodes, supporting structures, six legs and one commercial capacitor from Yageo Company.

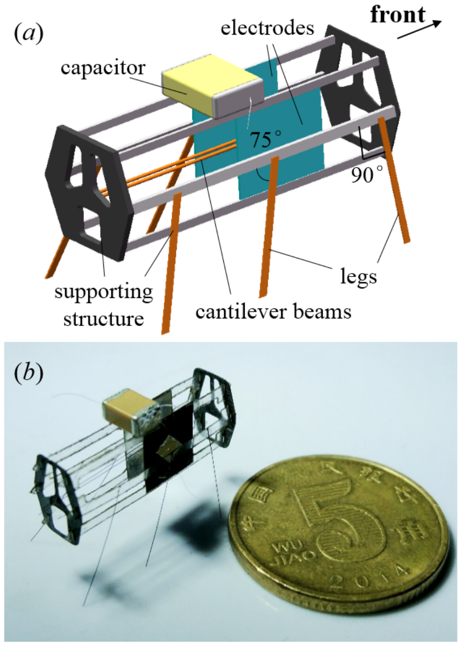


Figure 1: (a) 3D model and (b) an optical photo showing a fabricated electrostatic crawling insect.

The cantilever beams are made of 56μm-diameter NiTi wires with an additional mass (a piece of carbon fiber plate) pasted on their free ends. The NiTi wires own the advantage of super elastic which means they can return to the origin position without plastic strain after large displacement during fabricating and operating processes. The cantilever beams are placed between the two electrodes made by carbon fiber plates (anisotropic, 60μm in thickness) covered with tin foils, giving the carbon fiber plates good stiffness for all the directions. The supporting structures are made of both carbon fiber plates and thin polymer films (plastic membranes) through the laser cutting process shown in figure 2a: two orthogonal layers of carbon fibers form the front and rear sides of the prototype, connected by six 0.1mm-thick supporting plastic beams. The 6 legs, divided into front, middle, and rear parts, are also made of NiTi wires in the prototype design, where the front legs are perpendicular to the supporting plastic beams as well as the ground, and other legs have an angle of 75 degrees as shown in figure 1a.

Figure 2b describes the details of assembly process to construct a 20mm-long, 47mg-weight prototype with a 143mg-weight commercial ceramic capacitor on board. In this assembly process, all of the formed parts are glued together through the designed mounting grooves and flanges, ensuring a good installed accuracy for the prototype components. The total weight of the whole system can be further decreased in the future by using structural capacitors, which are the combination of electrodes, supporting structures and power supply, along with the development of the manufacturing technologies.

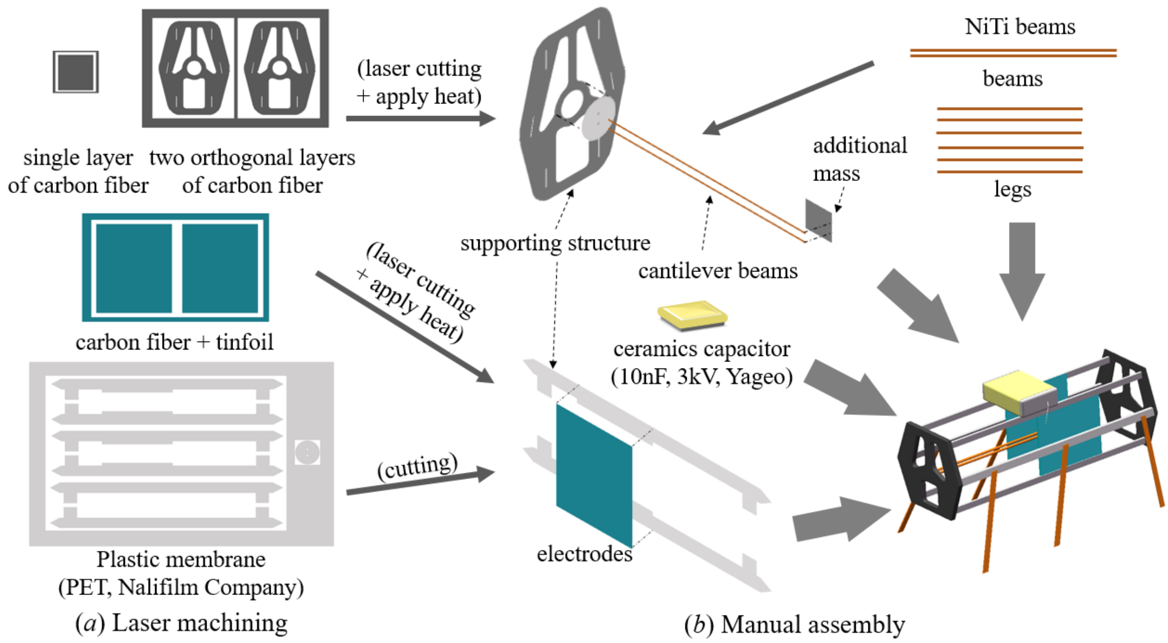


Figure 2: Fabrication and assembly processes of the electrostatic crawling insect. Lightweight thin polymer, carbon fiber, tinfoil and TiNi beams are chosen to have a total mass of 47 mg and the capacitor mass is 143 mg.

MECHANISM

The operating principle of the electrostatic crawling insect is based on the autonomous impact resonator reported by our previous works [10-12]. The cantilever-beams together with the additional mass can be excited to vibrate back and forth by high DC voltage to impact the electrodes in sequence (charging and discharging as well). The self-excited impact procedures can drive the electrodes as well as the supporting structures to shake due to the momentum conservation principle, and thus achieve self-sustained walking gaits which have been verified by the tests.

Inspired by the previous pipe crawling robots that utilize friction difference among legs to achieve forward movement [13], we design the structure where the rear and middle legs have the angle of 75 degrees to the supporting plastic beams as well as the ground while the front legs have the angle of 90 degrees to them. For the rear and middle legs, the friction induced by the forward movement at the beam inclining direction (f_2), is bigger than that induced by the backward movement at the opposite direction (f_1) as shown in figure 3. These two frictions are induced alternately during the crawling movement, and thus form a net forward driving force (f_2-f_1).

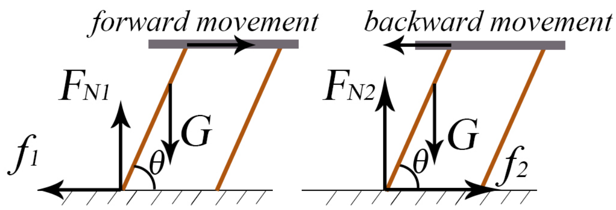


Figure 3: Force analysis on the legs under different movement.

Figure 4a illustrates the moving mechanism of the electrostatic crawling insect with self-excited walking gaits. When cantilever-beams vibrate toward the positive electrode (figure 4a, pic. 2), the whole structure rotates around the right rear leg in clockwise direction due to the principle of momentum conservation. When the beams vibrate back toward the negative electrode (figure 4a, pic. 3), the whole structure rotates around the left rear leg in counterclockwise direction. Since the existing of friction difference (f_2-f_1) on the moving legs during the rotating sequence, a continuous forward driving force is generated to result in forward crawling movement. Figure 4b records the sequence of movements by a high-speed camera.

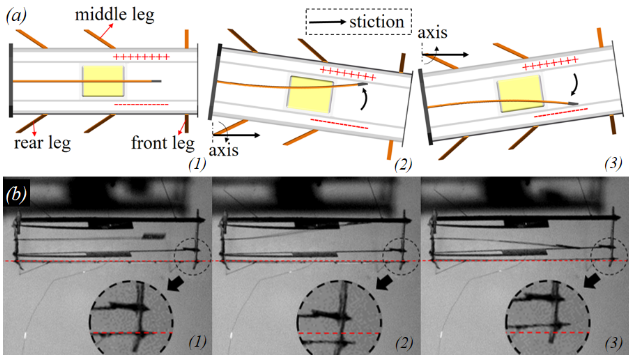


Figure 4: Moving mechanism of the self-excited crawling insect. (a) Schematic diagram to illustrate the forward movements by friction of the legs and conservation of momentum; (b) Optical photos captured by the high-speed camera. The enlarge views highlight the rotation of the whole structure during its crawling (the red dotted line is the reference line).

EXPERIMENT

We have established a test system to record the motion parameters of the prototype as shown in Figure 5, including a DC power supply, a high speed camera, and a smooth plastic plane. The DC power supply is connected to the electrodes of the artificial insect with aluminum-silicon bonding wires, which are soft and light enough and will not effect the crawling movement. The white smooth plastic plane has the functions of electrostatic insulation as well as reflecting more light to the high speed camera for the purpose of capturing pictures more easily and clearly. Figure 6 demonstrates the crawling movement of the artificial insect powered by a high DC voltage of 2500V via electrical wires with a moving speed up to 30mm/s, which is 1.5 body lengths per second.

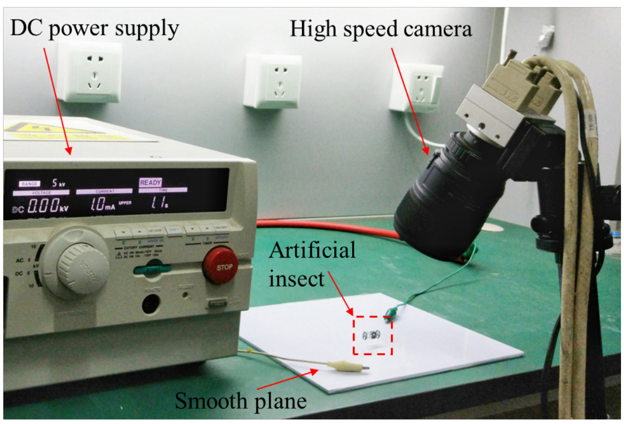


Figure 5: Test system for the artificial crawling insect.

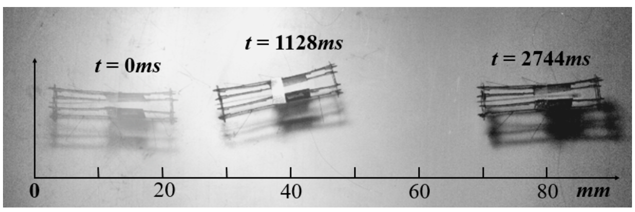


Figure 6: Forward movement of the crawling insect powered by DC power source via the electrical wires.

Benefiting from principle of self-excited vibration, we can use a battery or capacitor to power this artificial insect directly and achieve an untethered movement without using extra AC driving circuits and power wires. As conventional battery can rarely withstand high voltages up to 3000V, we choose a commercial ceramic capacitor in our experiments to replace the large DC power source. Figure 7 records the crawling movement powered by an on-board capacitor without wires. The chip capacitor, with capacitance of 10nf and breakdown voltage of 3000 volts, is placed on the top of electrodes. After the capacitor is fully charged, it can power the artificial insect to crawl at 2mm/s for over 10 seconds.

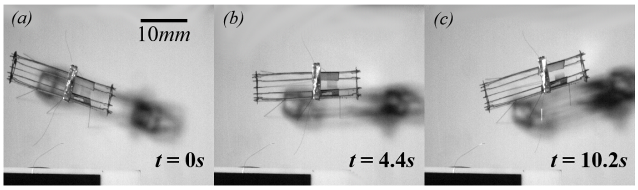
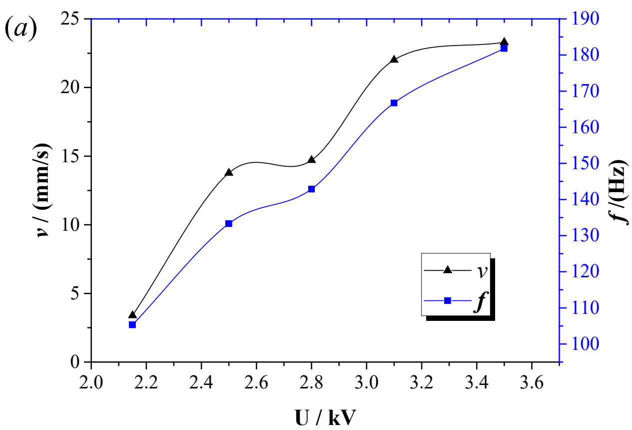


Figure 7: Untethered forward movement of the crawling insect powered by the on-board ceramic capacitor.

Figure 8a shows the curves of crawling speed (v) and operating frequency (f) with respect to applied DC voltage (U), obtained from another prototype. It can be observed that higher applied DC voltage can enhance the operating frequency and crawling speed, as it can offer more energy to the beams when impacting the electrodes. Figure 8b indicates that increasing weight of additional mass (M, at the free end of the beam) will decease operating frequency but still can increase the crawling speed. This is because that heavier mass of carbon fiber will have a more powerful impact energy during the operation, making the whole insect body to shake more fiercely and go farther for every walking cycle. As a result, the artificial insect can move faster with heavier mass even though the operating frequency is reduced. What's more, the stiffness of the legs and the friction coefficient of the ground also have great influences on the crawling speed. The prototypes, with legs made by solidified carbon fibers (more rigid than NiTi wires) or walking on a rough surface like foam board, will move extremely slowly.



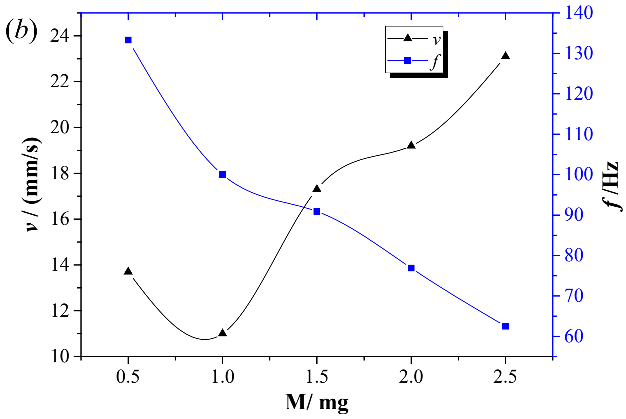


Figure 8: Experimental results of operating frequency (blue rectangle symbols) and crawling speed (black triangle symbols) versus (a) the applied DC voltage; and (b) the weight of the additional mass at the free end of the cantilever-beams under the applied voltage of 2.5kV.

CONCLUSIONS

This paper presents an artificial crawling insect which can achieve fast movement driven by self-excited electrostatic actuator under DC power supply. After integrated with an on-board capacitor, the artificial insect can move freely untethered by electrical powering wires. Our next work aims at further improving the moving stability as well as achieving the moving path control.

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CONTACT

* Xiaojun Yan, tel and fax: +86-10-82316356; yanxiaojun@buaa.edu.cn

†These authors contributed equally to this work.