Monolithic fabrication of an insect-scale self-lifting flapping-wing robot

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Robots on the order of insect-scale are difficult to manufacture using MEMS technologies for sub-millimetre structures or conventional methods for large devices beyond centimetres. This work presents an electromagnetically driven, monolithically fabricated, insect-scale self-lifting flapping-wing robot for the first time. This robot is created using a simple monolithic method, by which most of the components are integrated and fabricated from a single sheet. Finally, the monolithic insect-scale flapping-wing robot can generate sufficient lift to take off.

1. Introduction: The development of fabrication technologies has made it possible to create insect inspired flapping-wing micro aerial vehicles [1]. Flapping-wing robots fabricated by traditional manufacturing technologies or 3D printing have successfully demonstrated their capability of liftoff or even controlled flight [2–6]. However, structures fabricated by these technologies become inefficient and inapplicable for insect-scale robots when size decreases. MEMS technologies are appropriate for producing smaller machines; however, they are severely constrained by the materials available and the feature limitations [7]. Lille University and ONERA have developed a 22 mg flapping-wing nano air vehicle using MEMS technologies, but it has failed to produce sufficient lift for flight [8]. Beihang University has presented a 3 mg MEMS electrostatic flapping actuator which can only generate a lift force of 1 mg [9].

The smart composite microstructures (SCMs) process proposed by researchers from Harvard University and UC Berkley has vigorously promoted the development of micro robots [10]. By using this method, Harvard University has realised the first takeoff of an insect-sized flapping-wing robot [11]. UC Berkeley has developed an autonomous 2.4 g crawling hexapod robot with onboard power and control electronics [12]. Based on the SCM process, Harvard University has realised automatic 'pop-up' assembly of a 90 mg monolithic flapping-wing robotic insect by introducing pre-strained elastic layers, scaffold-assisted assembly and wave soldering [13]. However, more layers and more processes can affect the accuracy of the alignment and the assembly and increase the possibility of system failure. Most importantly, the 'pop-up' technology will inevitably introduce some additional layers and structures into the robots, increasing the weight of the robots. This is unfavourable for the flying robots which are sensitive to their own weight.

In this Letter, inspired by the SCM process, an electromagnetically driven insect-scale flapping-wing robot is designed and fabricated using a simple monolithic method. By using this method, most of the components (especially those with assembly relations) are integrated and fabricated from a single sheet. It is worth emphasising that the monolithic insect-scale flapping-wing robot has successfully taken off.

2. Design: Inspired by the insect flight mechanisms, previous work has demonstrated the first electromagnetically driven, self-lifting, sub-100-mg, insect-inspired flapping-wing robot [14]. However, such robot consists of a series of components, including an electromagnetic actuator, a four-bar transmission, several airframe components, a pair of wings and wing roots as shown in Fig. 1. All of them are separately manufactured and manually assembled by a complicated process. Such process may accidentally result in assembly errors, asymmetries and inconsistencies, which will in turn affect the performance of the final robot.

To face with these problems, the flapping-wing robot in this Letter is designed and fabricated by a monolithic method. As shown in Fig. 2, the transmission, the airframe components and the wing roots are integrated into one component. After sequential accurate folding, the monolithic component can finally form the

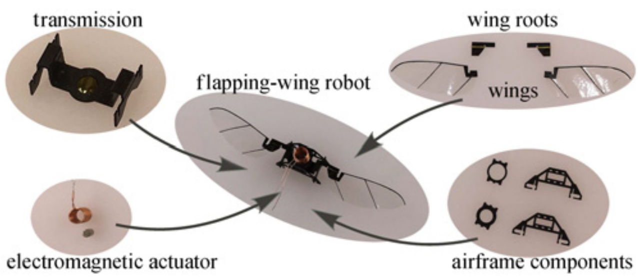

Fig. 1 *Photo of the flapping-wing robot and its components*

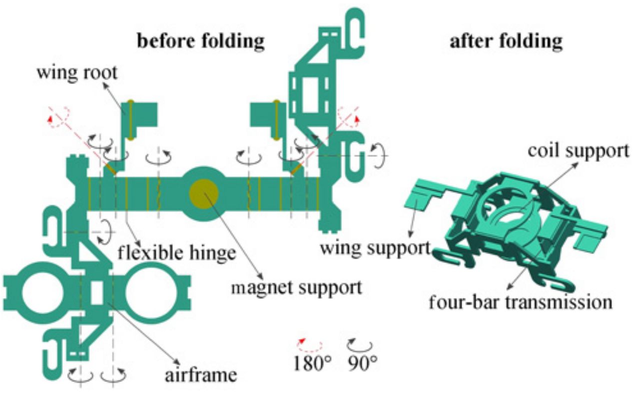

Fig. 2 *Monolithic integrated manufacturing strategy of the transmission, the airframe and the wing roots*

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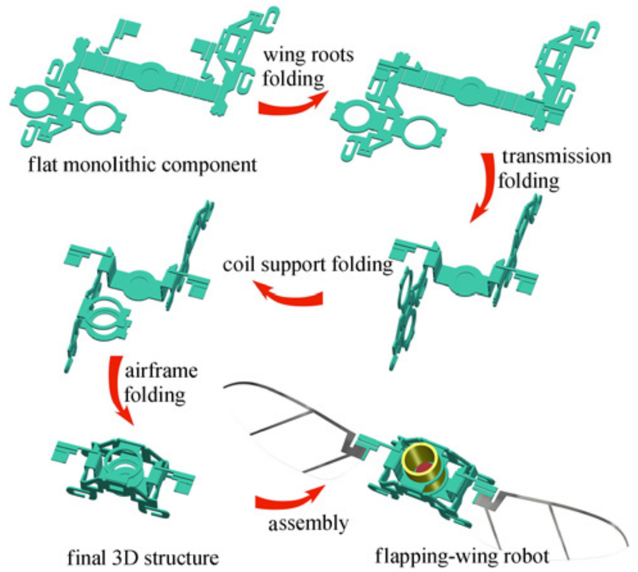

Fig. 3 *Folding order of the monolithic component*

desired three-dimensional structure of the flapping-wing robot. The folding order is shown in Fig. 3. It is worth noting that the wing roots are folded through a 180° rotation while the others are folded through a 90° rotation.

3. Fabrication: The fabrication of the monolithic component consists of three different structures: flexible hinges, 90° rotation creases and 180° rotation creases. They are all fabricated from two layers of 80 µm thick carbon fibre and a layer of 7.5 µm thick polyimide, however, with different pre-machined structures as shown in Fig. 4. We use a 355 nm ultraviolet laser to fabricate individual material layers, creating features as small as 15 µm. The whole fabrication process of the monolithic component is shown in Fig. 5. The pre-machined layers are laminated together by pin alignment and bonded with each other through a vacuum bag process. Once released, the flat monolithic component can be folded and locked to form the required three-dimensional structure as shown in Fig. 6.

The wings are made from 60 µm thick carbon fibre and 1.5 µm thick polyester with a process similar to the previous work in [15]. The final flapping-wing robot can be obtained after a simple assembly process. Table 1 lists the weight of the components and the whole robot.

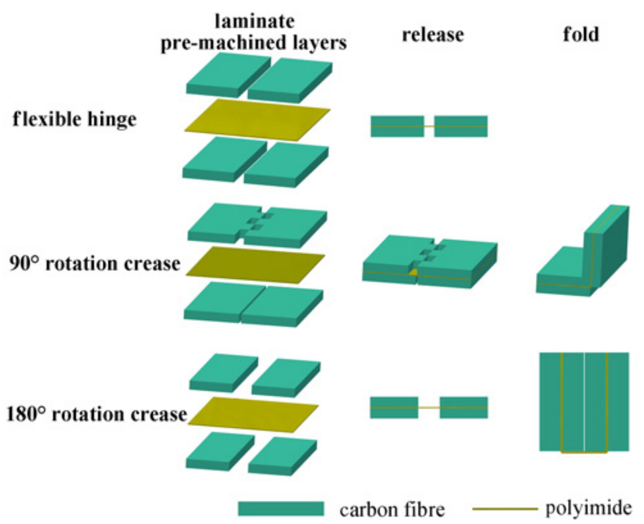

Fig. 4 *Fabrication of the flexible hinges, 90° rotation creases and 180° rotation creases*

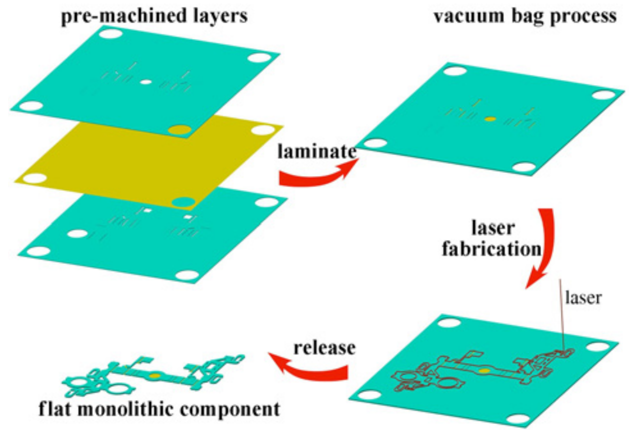

Fig. 5 *Whole process of the monolithic component*

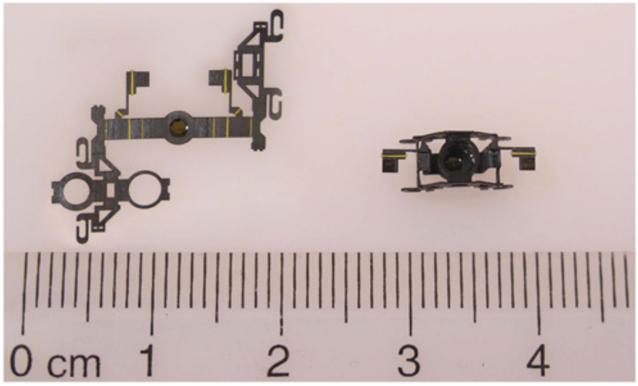

Fig. 6 *Photo of the monolithic component before and after folding*

Table 1 Mass of the components

Component	Mass, mg
electromagnetic actuator	58
monolithic component	15
double wings	1
wiring, epoxy	6
total body	80

4. Experiments: To determine whether the flapping-wing robot can generate enough lift to overcome its own weight, it is constrained by a pair of parallel vertical guide rails. When applied a sinusoidal voltage (80 Hz frequency and 1.1 V amplitude), the flapping-wing robot lifts off along the guide rails vertically (see Fig. 7).

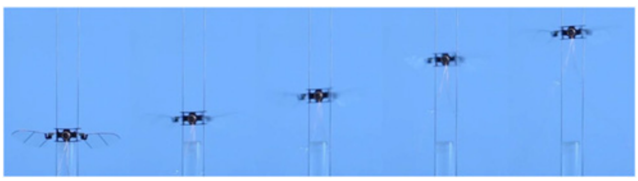

Fig. 7 *Liftoff of the insect-scale flapping-wing robot*

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A control experiment is also included to exclude the influence of the guide rails' vibrations on the performance of the robot. It presents the same results as those shown in [14].

5. Conclusion: This Letter has presented an electromagnetically driven insect-scale flapping-wing robot fabricated by a simple monolithic method. This method can avoid the assembly between components, thereby reducing the errors of the manual processes. By using this method, an 80 mg monolithic flapping-wing robot is created and is capable of liftoff. Such monolithic method has the potential to possess a wider application in the field of micro-robots.

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