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Foldable Wings Inspired by Earwig Hindwings

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1 Introduction

Gliding is an energy-efficient mode of aerial locomotion, and the utilization of gliding can enhance the energy efficiency of flying robots. To generate a substantial lift force during gliding, a considerable wing area is necessary. However, this results in an increase in the size and transportation cost of the flying robot. To address this issue, foldable and deployable artificial wings have been developed, mimicking the folding mechanisms of insect or bird wings [1–4].

Earwigs provide a promising inspiration for the development of artificial wings with a higher folding ratio than previous designs. Their hind wings can be folded to one-tenth of their expanded size. A geometric analysis of the folding structure of earwig hind wings has been conducted [5]. By mimicking this structure, it may be possible to develop artificial wings with a higher reduction ratio.However, there have been no studies that have produced artificial wings mimicking the earwig's hindwing folding structure and evaluated their gliding or flying capabilities. This may be due to the complex overlapping fold structure of the earwig's hind wings, which is difficult to reproduce with conventional pin joint hinges that are commonly used in artificial wings.

In this study, we designed and developed an artificial wing that mimics the folded structure of the earwig's hindwing. We conducted gliding experiments using the fabricated artificial wings to investigate their gliding ability. We use compliant hinges that utilize the material's flexibility in the folds. The foldable wing achieved a folding ratio of less than 10%, with a minimum of 7%. During gliding experiments, we compared the flying distances of the artificial wings in both deployed and folded states to that of a non-foldable flat wing. Some of the foldable artificial wings achieved the same flying distance as the non-foldable flat wing in the deployed state, demonstrating that the foldable artificial wings have flying capabilities.

2 Method

2.1 Artifisial foldable wing

Figure 1(A) shows the unfolded state of the fabricated artificial wing and Figure 1(B) shows the folded state of the wing. First, three Kapton sheets and two adhesive sheets were cut using a laser cutter with a drawing from a previous study [5]. This drawing includes compliant hinges at the folds, allowing the fold direction to be specified without the use of pin joint hinges. Next, the Kapton sheets and adhesive sheets were alternately layered and glued together and cut along the outline using a laser cutter. Lastly, a straight shape-memory alloy was attached, referencing the actual wing veins of the earwig's hind wings. The artificial wing can be folded in two steps from the deployed state, similar to earwigs. Attaching a shape memory alloy to the artificial wing body increases stiffness, allowing it to maintain its shape during the gliding experiments described below.

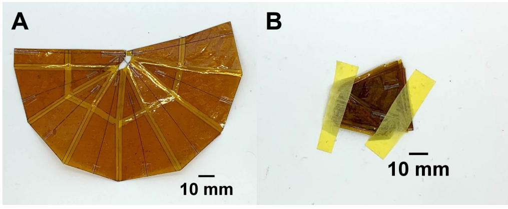

Figure 1: Fabricated 16-segment artificial wing.

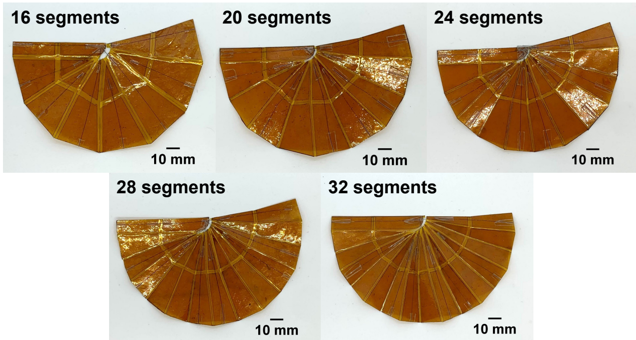

Figure 2: Fabricated five type artificial wings.

In this research, the area delimited by the folded part is called a segment. The artificial wing shown in Figure 1 has 16 segments, however, we fabricated a total of five types of artificial wings with 20, 24, 28, and 32 segments (Figure 2). We measured the area of these five types of artificial wings when deployed and folded in the image using ImageJ, and calculated the folding ratio.

2.2 Gliding test

We also investigated the flight performance by gliding experiments using the launching device (Figure 3). In the glide experiments, the artificial wing was attached to the flight body. A spring was used as the actuator of the launching device. The launching device can change the angle of launch and angle of attack respectively. In this experiment, the angle of launch and angle of attack was set to 0°, 10°,

Figure 3: The launching device for the experiment.

and 20°, respectively, and a total of nine different conditions were used in the experiments. The artificial wings were tested in the deployed and folded states. A flat artificial wing without a folded structure using the same materials as the folded wing (three Kapton sheets, two sheet adhesives, and shape memory alloy) was also made for comparison and experimented with under the same conditions. The number of trials was three under each condition. We measured the flying distance.

3 Result

Figure 4 shows the folding ratio for each number of segments. The shaded area is the range of the folding ratio of the earwig's wings (1/10 to 1/18). The figure shows that the folding ratio decreases as the number of segments increases, indicating that the folding performance is improving. The folding ratio of the artificial wing with more than 20 segments is equivalent to that of earwigs.

Figure 5 shows the flying distances of the 32-segment folded artificial wing in the deployed and folded states, and of the non-foldable flat artificial wing without the folded structure. The α and β denote the launch angle and the angle of attack, respectively. The average distance in three trials is shown for each condition in the figure. Comparing the deployed and folded states of the folding artificial wing, the mean flying distance was greater in the deployed state under certain conditions. This confirms that the folding artificial wing has flight performance in the deployed state. The flying distance of the deployed artificial wing was not significantly lower than that of the non-foldable flat artificial wing and was approximately 97.2% of that of the non-foldable flat wing under the conditions of launch angle 10° and angle of attack 0°. Additionally, the flying distance of the deployed artificial wing was greater than that of the flat artificial wing under certain conditions.

4 Discussion and Conclusion

In this study, five types of artificial wings with different folding ratios were fabricated to mimic the folding structure of the earwig hindwing. We measured the folding ratio and confirmed the flying ability of the wings by gliding experiments. Artificial wings with a folding ratio of less than 10% could be fabricated, which is equivalent to the folding ratio of the actual earwig wings. Furthermore, we confirmed the

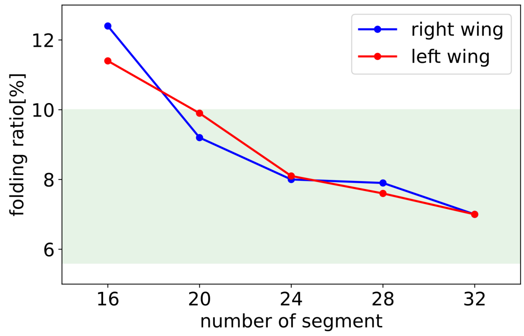

Figure 4: Folding ratio of the wings in each segment number.

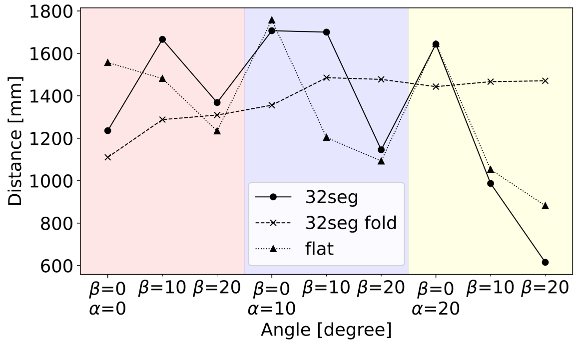

Figure 5: Flying distance of 32-segment artificial wings.

flight performance of the artificial wing by gliding the folded wing in the deployed state. The experimental results showed that the deployed artificial wing had a flight performance of approximately 97.2% of that of a non-foldable flat artificial wing. The reduction in stiffness of the artificial wing fabricated in this study due to the incorporation of the folding structure could be suppressed.

As future work, the development of an actuator for deployment/folding and the implementation of the wing in a flapping device are required. If an actuator that performs deployment and folding can be mounted, the wings can be kept folded until just before launch and then deployed after launch, reducing the drag force generated by the wings before launch, which could increase the flying distance. In addition, although gliding experiments were conducted this time, actual earwigs fly by flapping their wings, and the wing may be more suitable for flapping flight than gliding. Further applications may become possible by verifying flight using these foldable wings by flapping.

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