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RESEARCH ARTICLE

Inflatable Metamorphic Origami

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This study created a new type of inflatable metamorphic origami that has the advantage of being a highly simplified deployable system capable of realizing multiple sequential motion patterns with a monolithic actuation. The main body of the proposed metamorphic origami unit was designed as a soft inflatable metamorphic origami chamber with multiple sets of contiguous/collinear creases. In response to pneumatic pressure, the metamorphic motions are characterized by an initial unfolding around the first set of contiguous/collinear creases followed by another unfolding around the second set of contiguous/collinear creases. Furthermore, the effectiveness of the proposed approach was verified by constructing a radial deployable metamorphic origami for supporting the deployable planar solar array, a circumferential deployable metamorphic origami for supporting the deployable curved-surface antenna, a multi-fingered deployable metamorphic origami grasper for grasping large-sized objects, and a leaf-shaped deployable metamorphic origami grasper for capturing heavy objects. The proposed novel metamorphic origami is expected to serve as a foundation for designing lightweight, high-deploy/fold-ratio, low-energy-consumption space deployable systems.

Introduction

Deployable systems are thought to be an ideal solution for developing special intelligent systems that must change shape to a smaller size for easy storage and transportation while being deployed into a larger volume configuration to reach a large working space [1–4]. Deployable space systems [5–8], soft morphing robots [9–12], origami-inspired robots [13–17] and structures [18–22], and metamaterials [23–27] are some typical examples. The ability to deploy these systems makes them extremely flexible and adaptable to complex working environments.

Traditionally, deployable systems were always designed with fixed mobility [28–30]. Such fixed-mobility deployable systems are capable of realizing only a unique motion pattern, which can only conduct a single deploying or folding motion [31,32]. However, many systems may require additional manipulation motion tasks to be performed after the deployment motion. Therefore, traditionally, such deployable systems were mostly designed with an independent deployment motion and a manipulation motion, both of which were actuated by two separate actuation systems [33]. Such a design, however, had a greater energy consumption, higher complexity, and increased massiveness. In order to realize changeable mobility for a given mechanism, the metamorphic mechanism was first proposed by Dai and Jones [34], and many metamorphic systems have been developed in recent years [35,36]. However, a metamorphic system always needs an additional actuation system to adjust its mobility, such that the system is still very complicated [37]. In this context, a metamorphic system capable of generating multiple sequential motion patterns under a monolithic actuation source could be a suitable solution, although this research area remains relatively unexplored. A simple metamorphic origami unit in Fig. 1 is a typical example of such a system, its mobility multi-furcation property could inspire a set of novel deployable systems with multiple sequential motion patterns.

The inflatable metamorphic origami proposed in the present study is capable of generating sequential deploying and bending motions in response to pneumatic pressure. This special pattern of motion is characterized by a sequence of motions comprising an initial unfolding around the first set of contiguous/collinear creases followed by another unfolding around another set of contiguous/collinear creases as the pneumatic pressure increases. Next, to verify the effectiveness of the proposed novel metamorphic origami, the following were developed: a radial deployable metamorphic origami for supporting the deployable planar solar array, a circumferential deployable metamorphic origami for supporting the deployable curved-surface antenna, a multi-fingered deployable metamorphic origami grasper for grasping large-sized objects, and a leaf-shaped deployable metamorphic origami grasper for capturing heavy objects. All these deployable systems demonstrated that each metamorphic origami could, under a single actuation, realize multiple sequential motion patterns such as the deployment motion, bending motion for grasping objects, or multiple stable configurations for supporting loads.

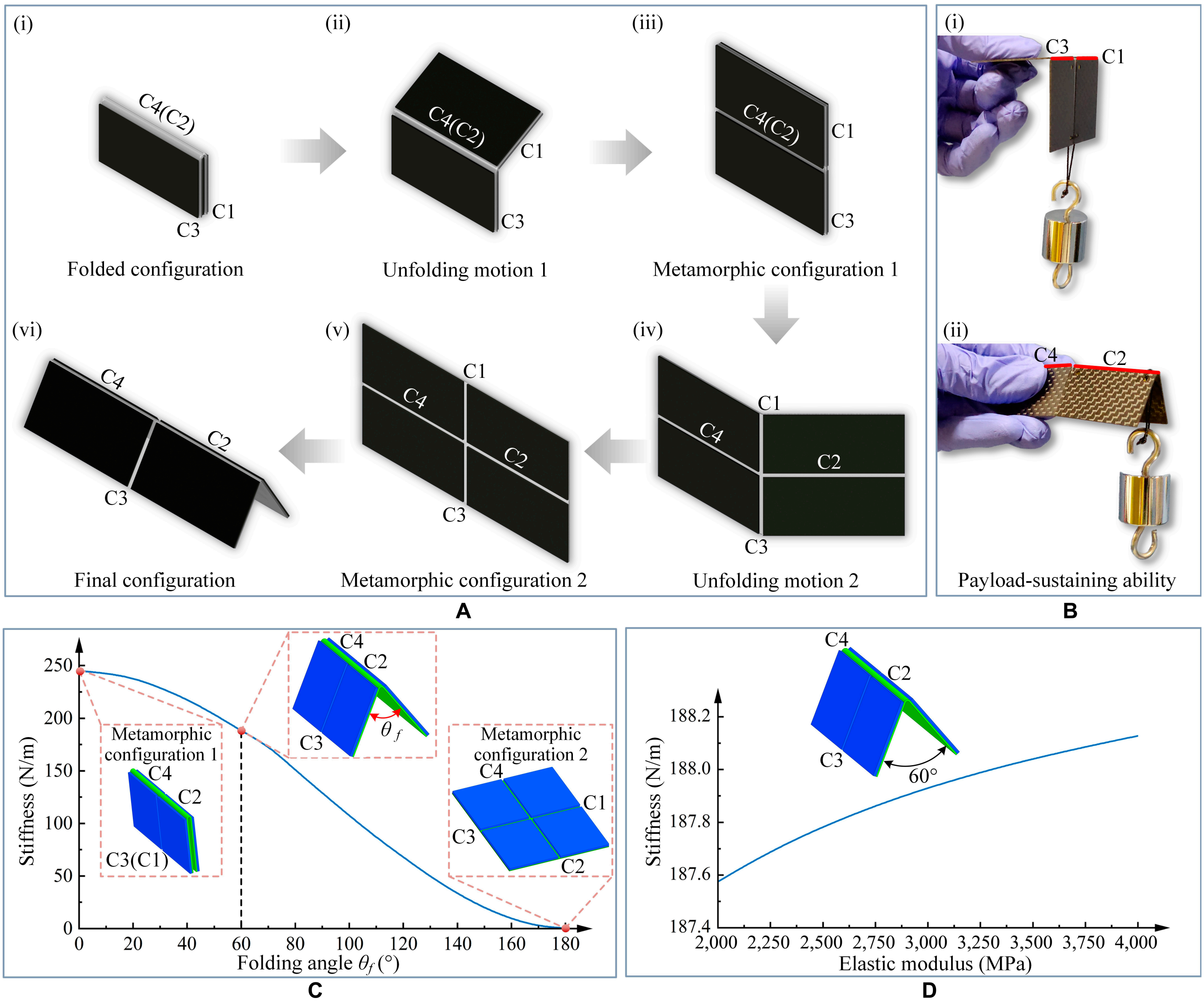

Fig. 1. The metamorphic origami unit. (A) The metamorphic unfolding process. (B) The payload-sustaining ability. (C) The stiffness behavior of the metamorphic origami unit at different folding angles. (D) The stiffness behavior of the metamorphic origami unit at different elastic modulus values.

Results

Origami with mobility multi-furcation

Figure 1 shows a metamorphic origami unit with mobility multi-furcation. The origami unit comprised 4 facets and 4 creases. In the folded configuration [(i) in Fig. 1A], the unit could be unfolded around the contiguous creases C2 and C4; in this configuration, creases C1 and C3 are neither contiguous nor collinear. When the unit begins to unfold [(ii) in Fig. 1A], it would, at a certain point, reach a unique intermediate configuration in which creases C1 and C3 are collinear [(iii) in Fig. 1A]. This configuration is the first metamorphic configuration of the origami unit. In this metamorphic configuration, the origami has a mobility bifurcation, such that the origami could continue to unfold around the contiguous creases C2 and C4 or unfold around the new collinear creases C1 and C3. If the origami was unfolded around the collinear creases C1 and C3, then the creases C2 and C4 would no longer be contiguous, thereby preventing the origami unit from being rotated around creases C2 and C4 again [(iv) in Fig. 1A]. The origami is incapable of sustaining load as it is possible to rotate it around creases C1 and C3 [(i) in Fig. 1B]. The unit then continues to unfold to another special intermediate configuration in which creases C2 and C4 are also collinear. This configuration is the second metamorphic configuration of the origami [(v) in Fig. 1A]. In the metamorphic configuration 2, the origami also has a mobility bifurcation. When the origami is rotated around the collinear creases C2 and C4, it moves into another motion pattern until the creases C1 and C3 are no longer collinear [(vi) in Fig. 1A]. After that, the origami would not rotate around creases C1 and C3 again, i.e., the rotation around creases C1 and C3 would be locked. In other words, origami has load-bearing ability in this configuration [(ii) in Fig. 1B and Movie S1]. The metamorphic origami unit with 4 facets and 4 creases was evaluated quantitatively using the ABAQUS software. The simulation process is illustrated in Note S2. Figure 1C illustrates the stiffness of the metamorphic origami unit when the origami unit was folded around the collinear creases C2 and C4 from the metamorphic configuration. The stiffness was observed to increase as the folding angle was decreased. This property