

Article

An Origami Flexiball-Inspired Metamaterial Actuator and Its In-Pipe Robot Prototype

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Abstract: Usually, polyhedra are viewed as the underlying constructive cells of packing or tiling in many disciplines, including crystallography, protein folding, viruses structure, building architecture, etc. Here, inspired by the flexible origami polyhedra (commonly called origami flexiballs), we initially probe into their intrinsic metamaterial properties and robotized methods from fabrication to actuation. Firstly, the topology, geometries and elastic energies of shape shifting are analyzed for the three kinds of origami flexiballs with extruded outward rhombic faces. Provably, they meet the definitions of reconfigurable and transformable metamaterials with switchable stiffness and multiple degrees of freedom. Secondly, a new type of soft actuator with rhombic deformations is successfully put forward, different from soft bionic deformations like elongating, contracting, bending, twisting, spiraling, etc. Further, we redesign and fabricate the three-dimensional (3D) printable structures of origami flexiballs considering their 3D printability and foldability, and magnetically actuated them through the attachment of magnetoactive elastomer. Lastly, a fully soft in-pipe robot prototype is presented using the origami flexiball as an applicable attempt. Experimental work clearly suggests that the presented origami flexiball robot has good adaptability to various pipe sizes, and also can be easily expanded to different scales, or reconfigured into more complex metastructures by assembly. In conclusion, this research provides a newly interesting and illuminating member for the emerging families of mechanical metamaterials, soft actuators and soft robots.

Keywords: origami; polyhedra; metamaterial; soft robot; soft actuator; 3D printing



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1. Introduction

Recently, increasingly innovative research cases [1,2] indicate that origami has far exceeded its traditional definition of manual cutting and folding arts. Its remarkable characteristics, including reversible foldability, adaptive multistability and tunable stiffness, have provided extensive innovative inspirations for scientists and engineers to develop nontraditional structures, mechanisms and materials, such as deployable structures [3,4], mechanical metamaterials [5–7], soft actuators or robots [8–10], biomedical devices or capsules [11,12], stretchable or flexible electronics [13–15] and other attractive possibilities [16,17].

Undoubtedly, origami has been recognized as a powerful and exciting inspiration source to chase the long-standing human dream: the whole physical system is fully programmable including its geometric deformation, material properties and even behavior under external stimulation. By deeply exploiting the novelty of origami, more and more concepts of traditional disciplines are revolutionarily refreshed. For example, a variety of origami-based mechanical metamaterials are demonstrated, such as tunable negative Poisson's ratio [18], autonomous deployability [19], anisotropic multistability [20], self-locking [21], etc. On another hand, many new types of soft actuators or soft robots with novel deformation modes have been developed, including (but not limited to) self or active folding [22], variable stiffness [23], twisting motion [24], curvilinear deployment [9]

and adaptive envelopes [25]. However, most research mainly focuses on a few crease patterns: Miura-ori pattern [25], waterbomb base [13,26], Yoshimura pattern [27] and Ron Resch pattern [28,29]. There are still many exquisite origami structures worthy of further exploration.

The initial motivation of this work is to reveal the intrinsic metamaterial properties of flexible origami polyhedra (commonly called origami flexiballs). Traditionally viewed as the underlying constructive cells of packing or tiling problems, polyhedra have fascinated scientists of many disciplines, including crystallography [30], protein folding [31], virus structure [32] and building architecture [33]. Here, we regard them as flexible and reconfigurable frameworks, and probe into their new properties from metamaterial perspectives.

Further inspired by the flexible origami polyhedra, we hope to break through the deformation patterns of current soft actuators. Usually, the research community of soft robotics pays more attention to soft bionic deformations like bending [34], stretching [35], twisting [36], spiraling [37], coiling [38], etc. In this work, however, we intend to construct a new type of soft actuator through magnetically stimulating the basic origami rhombic cell.

This paper is organized as follows. Firstly, the intrinsic metamaterial mechanisms of origami flexiballs are clarified through the analysis of their topology, geometries and elastic energies during shape shifting. Next the fabrication and actuation methods of the origami flexiball are introduced. Lastly, a fully soft in-pipe robot prototype is experimentally presented as an applicable attempt.

2. Intrinsic Metamaterial Mechanisms of Origami Flexiball

The source of our research inspiration is a popular and interesting origami flexiball with transformable rhombuses, in which modular sheet units are folded and snapped together into a flexible polyhedron with extruded outward faces, such as the rhombic triacontahedron shown in Figure 1.

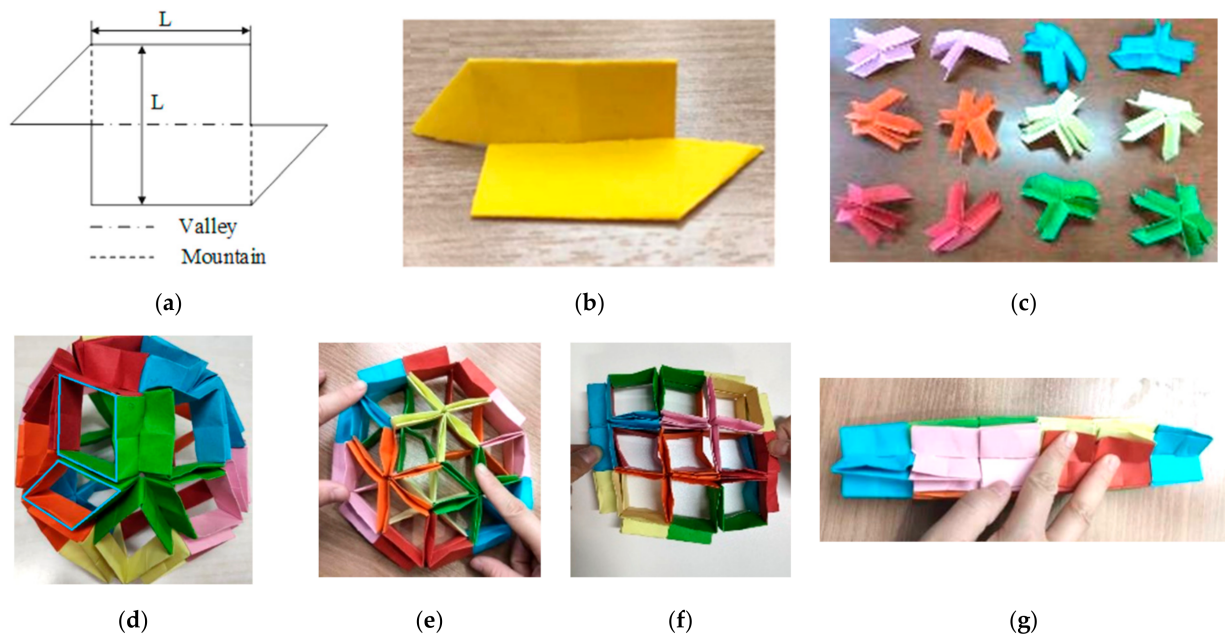


Figure 1. Origami flexiball: (a) flat folding pattern, (b) modular unit sheet, (c) snapping modular units, (d) flexible triacontahedron with extruded outward rhombic faces, (e–g) some kinds of switchable ultimate patterns.

While this origami model provides a geometric starting point for our research, our focus here is not on manual folding crafts, but on its flexible deformation originating from simple building block assembly. From this view, we intuitively anticipate that it should have some kind of relationship with the concept of metamaterials, which have remarkable

mechanical properties depending on repeating unit cells rather than the properties of bulk materials in nature.

2.1. Topology and Geometry of Origami Flexiball

As a geometric demonstration, there are only three isometrically symmetrical polyhedra with rhombic cells: rhombic hexahedron (RHD, i.e., cube), rhombic dodecahedron (RDD) and rhombic triacontahedron (RTD) [33]. Tables 1 and 2 together present the topology and geometries of these three types of origami flexiballs. Euler's theorem in topology implies that the Euler characteristic of the simple polyhedron is two, namely, the number of vertices V , the number of edges E and the number of faces F conform to

$$V + F - E = 2 \quad (1)$$

Table 1. Topology and geometries of origami flexiballs.

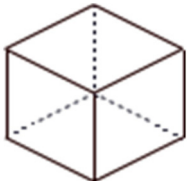
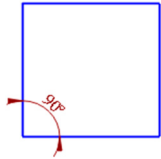

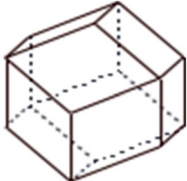
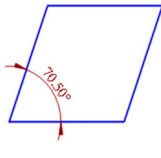

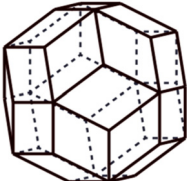
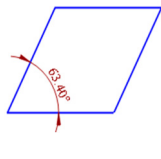

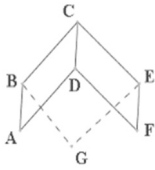
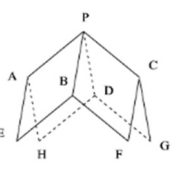
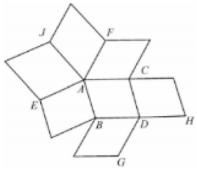



Polyhedra	Geometry	Vertex Type (See Table 2)	Face Type	Dihedral Angle	Origami Flexiball
Cube	 (V,F,E) = (8,6,12)	8{3}		90°	
Rhombic dodecahedron	 (V,F,E) = (14,12,24)	8{3} + 6{4}		120°	
Rhombic triacontahedron	 (V,F,E) = (32,30,60)	20{3} + 12{5}		144°	

Table 2. Vertex type and snapping module.

Vertex Degree	3	4	5
Schematic			
Snapping module			

Further, the RDD has two types of vertices: eight vertices with three edges, and six vertices with four edges. The RTD has another two types of vertices: twenty vertices with three edges, and twelve vertices with five edges. The acute angles of their congruent rhombic faces are, respectively, 90° , 70.5° and 63.4° . The theoretically dihedral angles (the angles between adjacent faces) of these three rhombic polyhedra are, respectively, 90° , 120° and 144° .

In geometry, these rhombic polyhedra have many types of symmetries, because they are convex, face-transitive (isohedral) and isotoxal (edge-transitive). In addition, the rhombic dodecahedron is a parallelohedron with four sets of parallel edges.

With the assumption that the faces are rigid and connected at the edges by revolute joints, convex polyhedra are always rigid. However, once we regard them as frameworks without rigid faces, they will have certain motion degrees of freedom (DOFs) and sometimes possess peculiar kinematic properties [39].

2.2. Energy Landscape of Origami Flexiball

Obviously, the great motion mobility or shape shifting of the origami flexiball can make them absorb elastic energies of multiple magnitudes. However, due to the low rigidity of paper sheets, it is very difficult to accurately build a general framework for the elastic energy calculation of origami structures. Here, we suppose that the paper faces remain rigid during deformations, that is, they do not store any energy. Then, we only estimate the fold elastic energy U_{crease} of one crease by parameterizing its torsional stiffness k , the rest crease angle φ_0 and the opening angle φ . The widely accepted formula [5,20,40] is written as

$$U_{\text{crease}} = \frac{1}{2}k(\varphi - \varphi_0)^2 \quad (2)$$

Further, the total elastic energy U_{total} of the whole origami flexiball can be approximated by

$$U_{\text{total}} = \sum_{i=1}^E U_{\text{crease}-i} \quad (3)$$

Meanwhile, during the origami flexiball deformation by manually applying a force, its volume also changes remarkably. If ignoring the origami sheets' own volumes, the total volume V_{total} of the origami flexiball only includes two parts: the internal polyhedron cavity V_{cavity} , and all volumes of the extruded rhombic cavity $V_{\text{cell}-j}$, that is, they will fulfill the following equation:

$$V_{\text{total}} = V_{\text{cavity}} + \sum_{j=1}^F V_{\text{cell}-j} \quad (4)$$

Table 3 lists the possible maximum volumes and the corresponding elastic energies of the three types of origami flexiballs with the same edge length L , and the rest crease angle 60° .

Table 3. Volumes and elastic energies of origami flexiballs.

Origami Flexiball	Polyhedron Volume	Rhombus Volume	Total Volume	Elastic Energy
Rhombic hexahedron	L^3	$0.5 L^3$	$4 L^3$	$0.18 k$
Rhombic dodecahedron	$\frac{16}{9}\sqrt{3}L^3 \approx 3.08 L^3$	$0.47 L^3$	$8.72 L^3$	$5.84 k$
Rhombic triacontahedron	$4\sqrt{5+2\sqrt{5}}L^3 \approx 12.31 L^3$	$0.45 L^3$	$25.66 L^3$	$37.39 k$

Further, we depicted the volumes versus the elastic energies of four switchable ultimate patterns of the three types of origami flexiballs, as shown in Figures 2–4. In the figures, we marked the crease opening angles and the numbers of different patterns by

$\{(\text{angles degree, edges number})\}$. Although this evaluation approach is somewhat rough, the energy landscapes of shape-shifting origami flexiballs are still clearly described. Firstly, we can see that the changes of elastic energies vary with the directions of elastic deformation. Secondly, during the transformations of different ultimate patterns, large volume reductions are also produced. Taking an RTD as an example, the maximum volume reduction happens between the fully expanded Pattern #1 and the fully compressed Pattern #4, and the maximum volume ratio is approximately 14-fold. Thirdly, it is important to note that for the same origami flexiball, the relationship between the volumes of different ultimate patterns and their elastic energies is highly nonlinear. Further, Pattern #1 of the RHD and Pattern #3 of the RDD have the same volume value, but the elastic energy of the former is more than 20 times that of the latter. Pattern #1 of the RDD and Pattern #3 of the RTD are very close in volume, but the elastic energy of the latter is more than 15 times that of the former. This fully demonstrates that the elastic energy of an origami flexiball not only depends on the numbers of unit cells and their topological connections, but also depends on the motions of crease opening angles.

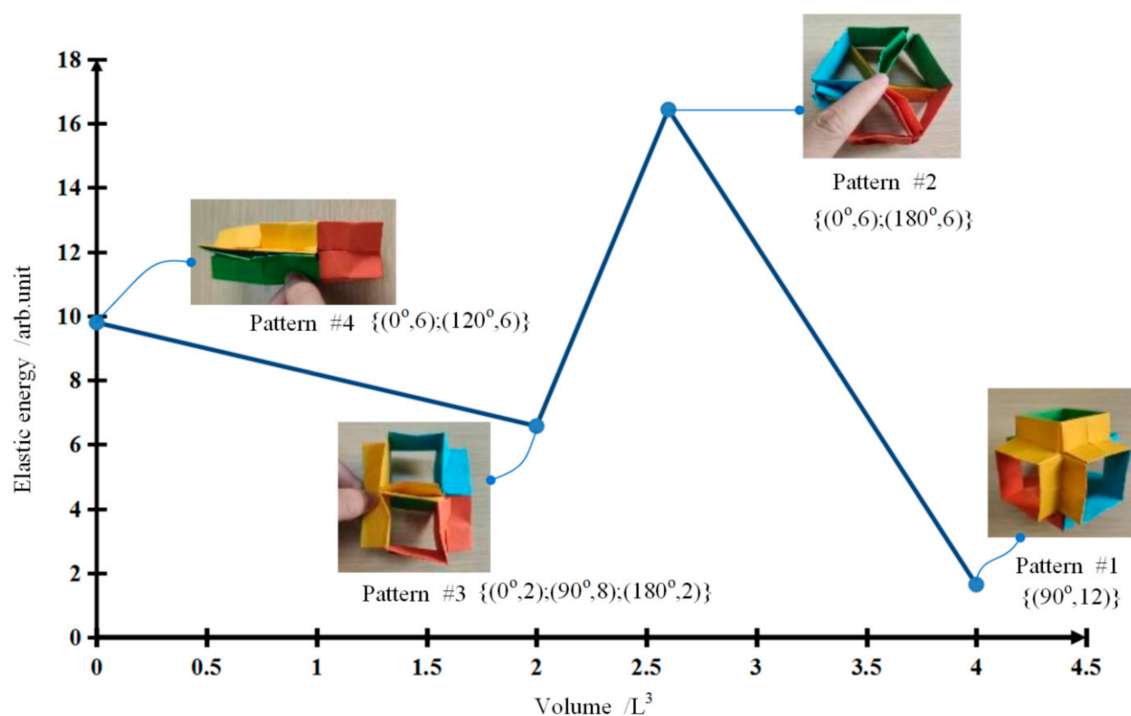


Figure 2. Shape shifting, energy landscape and cavity volume of rhombic hexahedron origami.

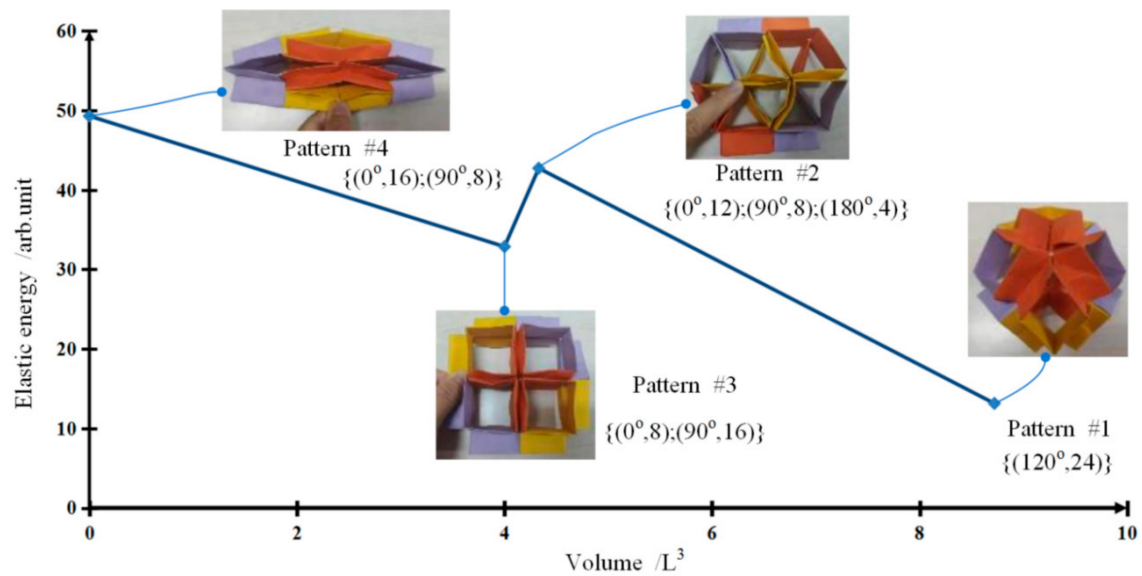


Figure 3. Shape shifting, energy landscape and cavity volume of rhombic dodecahedron origami.

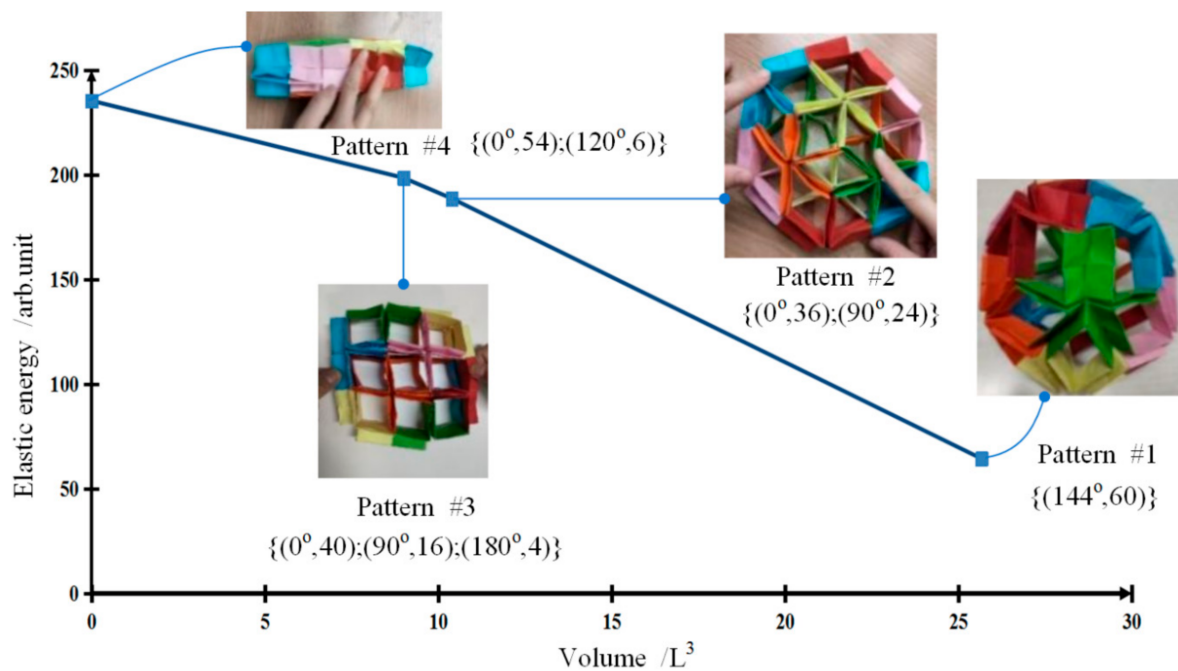


Figure 4. Shape shifting, energy landscape and cavity volume of rhombic triacontahedron origami.

2.3. Intrinsic Metamaterial Properties of Origami Flexiball

Obviously, according to the above analysis, if viewing the highly flexible and deformable rhombic module as an underlying unit cell, the presented RHD/RDD/RTD origami flexiballs exactly satisfy the definition of an origami-inspired transformable metamaterial with multiple degrees of freedom, which was put forward by Johannes et al. [41]. Further, both the RHD and RDD are parallelohedrons, which can tessellate in a certain space by translational copies of themselves. In light of this, they can be viewed as second-order underlying cells to be assembled into more complex reconfigurable structures like the three-dimensional (3D) printable origami assemblages [42].

Undoubtedly, here we introduce a new type of origami flexiball metamaterial, which has two remarkable properties, as follows: switchable rigidity and shape shifting with multiple degrees of freedom; hierarchical reconfigurability of rhombic cells, polyhedra and more complex assemblages. To make this point more understandable, let us look back the original intent of the term metamaterial, coined by Walser [43]: macroscopic materials having a human-made, 3D, periodic cellular architecture and exhibiting remarkable properties not available in nature. Academically, more and more novel metamaterials or metastructures have been put forward that blur the boundaries between material, structure, mechanism and even multifunctional materials [44]. For instance, Correll and Voyles [45] presented a new type of robotic material or computational metamaterial that tightly integrated sensing, actuation, computation, communication and power routing in a periodic fashion. As another example, Ion et al. [46] demonstrated the concept of metamaterial mechanisms by constructing 3D cell grid structures to transform input forces and movement into the desired outputs of force and movement. As mentioned in Section 1, these are all efforts to advance human long-standing dreams.

3. Magnetically Driven In-Pipe Robot Inspired by Origami Flexiball

3.1. Digital Fabrication of Origami Flexiball Metamaterial

Although the intrinsic metamaterial mechanisms of origami flexiballs have been demonstrated through the abovementioned analysis, this new type of origami metamaterial still encounters a practical application obstacle: manufacturability. Folding and assembling modular, unit-based thin sheets with negligible or zero thickness require a complex and tedious sequences of dexterous hand manipulations, and current manufacturing technologies cannot imitate this process automatically. In the past few years, harnessing the power of 3D printing technology to manufacture various soft robots has become an important trend [47]. Therefore, considering that 3D printing technology has strong adaptability to direct fabrications of complex geometries, we attempted to explore the digital fabrication approach of this origami flexiball metamaterial using the popular fused deposition modeling (FDM) method. Before 3D printing, the modular thin sheet structure needs to be redesigned to have a good trade-off between its 3D printability and foldability with high elasticity and damage tolerance. After many experiments, we designed the printable thin sheet units as shown in Figure 5.

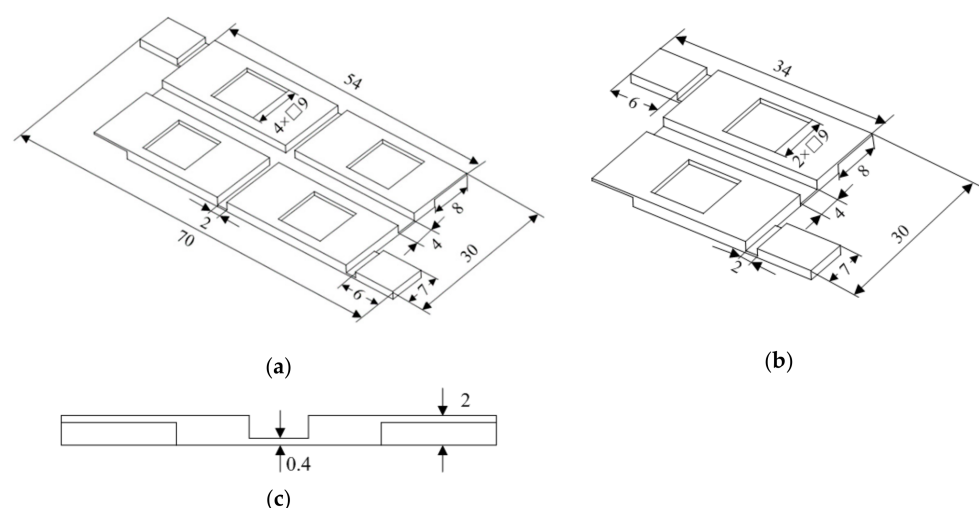


Figure 5. Redesign of thin sheet units: (a) schematic of the thin sheet unit with one hinge, (b) schematic of the thin sheet unit with two hinges, (c) connecting schematic.

Considering the actual capability of our own 3D printer, we employed flexible 1.75 mm polylactic acid (PLA) filaments and a 0.3 mm diameter extruder nozzle. The infill density of the grid pattern was set as 50%. The printing speed was at 50 mm/s and the layer

height was 0.2 mm. As illustrated in Figure 6, we then snapped the printed thin sheet units into the finalized origami flexiball using strong glue. Figure 7 demonstrates the multiple shape-shifting patterns of the finalized origami flexiball.

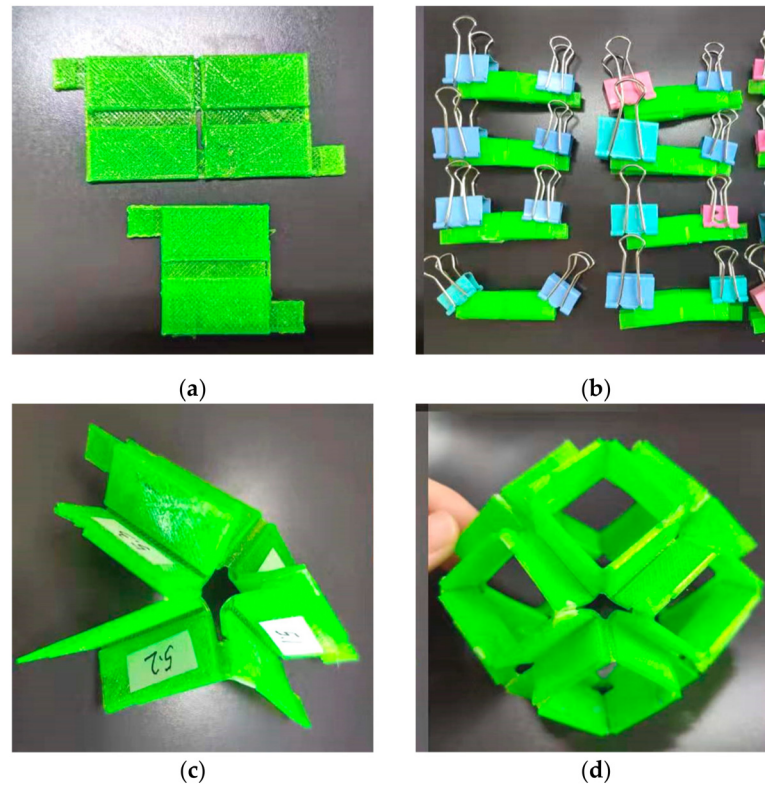


Figure 6. Fabrication of origami flexiball: (a) 3D printed thin sheet units; (b) bonding thin sheet units together; (c) a bonded module; (d) the finalized origami flexiball.

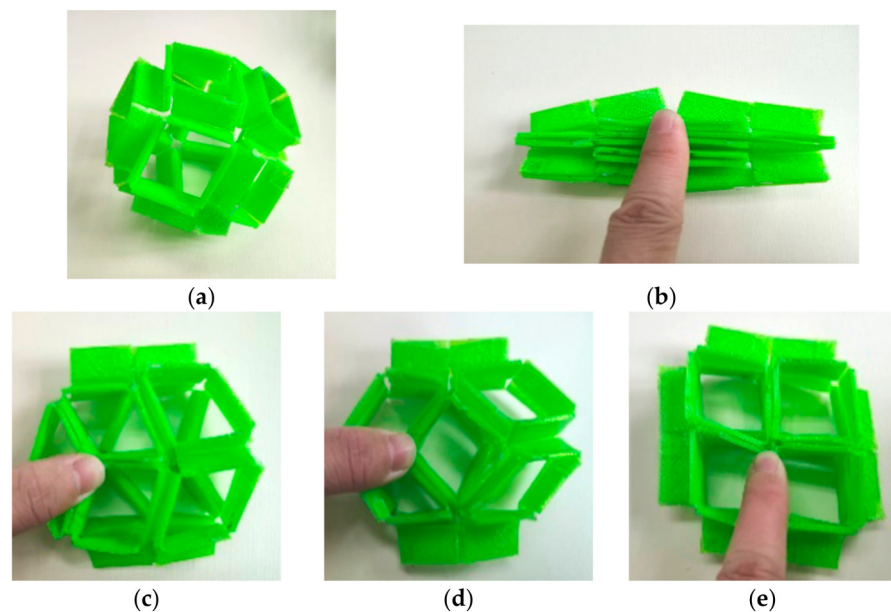


Figure 7. Shape-shifting patterns of 3D printed origami flexiball metamaterial: (a) freely expanded pattern; (b) fully compressed pattern; (c) fully compressed pattern at symmetric points; (d) fully compressed pattern at symmetric faces; (e) fully compressed pattern at symmetric edges.

3.2. Actuation of Origami Flexiball Metamaterial Actuator

Thus far, we have shown that the shape and volume of the origami flexiball can be altered by manually dexterous operations. It still cannot be actuated through various external stimuli, such as light, heat and magnetic and electric fields. Perhaps the most easy way to make it active is to use pneumatics to drive the motions of crease opening angles. However, this actuation method needs many flexible tethers to transfer the gas. In addition, we also forsake centering on the locally actuating concepts of hinge type or bending type active folds [48], and turn to a new actuation strategy.

Noting that the most basic deformation of the origami flexiball metamaterial is the rhombic cells opening and shutting, in this work, we present a magnetically driven soft actuator with rhombic motion, as shown in Figure 8. First, we used silicone as the medium to incorporate 5-micron magnetic powder particles of 30 wt.%, and achieved magneto-active elastomer (MAE) after drying and curing [49]. Then, we bonded the MAEs on the rhombic faces. In the experiments, the external magnetic field was a NdFeB permanent magnet with a magnetic field intensity of 2 T. Clearly, it can be seen that the rhombic unit cell with MAEs is quickly actuated to open or shut with the adjusting of the magnetic induction distance. The advantages of this actuation not only depend on the ease of quickly and accurately controlling the magnetic field direction and magnitude, but also on its ability to penetrate most materials without tethers. To our best knowledge, a soft actuator with rhombic deformations was created for the first time, which is distinctly different from the most current deformations of soft actuators, such as bending, twisting, stretching, compressing, buckling, wrinkling, etc.

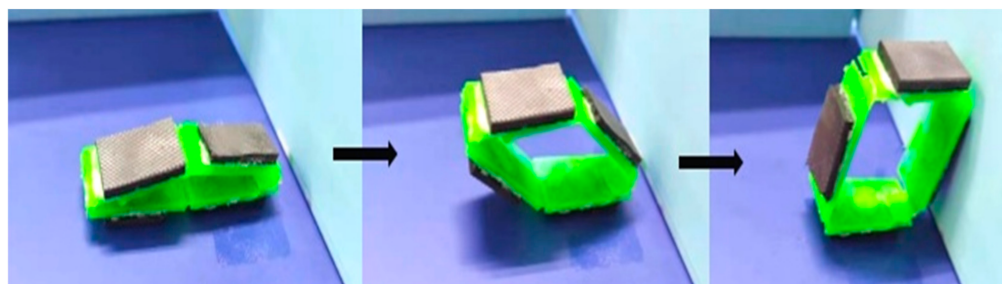


Figure 8. Magnetically driven rhombic deformations of soft actuator.

Next, we deployed MAEs onto the whole origami flexiball, as shown in Figure 9, according to the magnetic field simulation and actuation experiments. Similarly, under the stimulation of a NdFeB permanent magnet with a magnetic field intensity of 3 T, when the operating distance ranges from 140 mm to 10 mm, the origami flexiball can freely switch between the fully expanded pattern and the fully compressed pattern. This is very exciting and inspires us to wonder that how it can change into a kind of robot, after all, we have come a long way from the origami art, to metamaterial properties, and to this new type of soft actuator.



Figure 9. Magnetically driven shape shifting of the origami flexiball.

3.3. An In-Pipe Robot Prototype

For a very long time, many types of in-pipe robots have been developed by different enabling technologies to adapt to certain complicated pipe structures [50]. The importance of the regular inspection and maintenance of pipelines in various industries and hydraulic or pneumatic equipment cannot be overemphasized. Working in constrained pipeline environments (e.g., variable pipe diameter, partial clogging, fragile pipe wall and low stiffness) is always a great challenge for this research community [51]. So, can the origami flexiball with MAEs move in an in-pipe scene like a robot? Next, our experiments try to give an answer.

Firstly, we put the origami flexiball with MAEs into a polycarbonate pipe with a diameter of 71 mm, as shown in Figure 10a. Obviously, if there is no external magnetic field, the origami flexiball actuator would relax naturally. When the NdFeB permanent magnet approaches the pipe from below, the origami flexiball actuator would compress in a radial direction and elongate in an axial direction. Additionally, when the permanent magnet leaves from the top with a relatively lower speed than approaching, the origami flexiball actuator would spring back, and, meanwhile, the origami flexiball actuator would move forward about 23 mm. Being very similar to earthworm crawling [52], this locomotion is caused by two concurrent factors, the first of which is the wave effects along the origami flexiball actuator originating from the velocity difference of elongation and contraction deformations during the reciprocating stroke. Additionally, the second factor is that the kinetic frictions between the origami flexiball and pipe walls vary with the changes of contact areas during the alternating deformations. When the static frictional force blocks the elongation from front to back, the overall actuator will move forward. As assembly errors in 3D printed thin sheet units are inevitable, it is easy to determine the front end of the moving origami flexiball after driving experiments. Maintaining the above alternating changes of external magnetic fields will achieve continuous locomotion. Further, we simulated an in-pipe cleaning task, and the origami flexiball robot successfully pushed out the foam-like rubbish, as shown in Figure 10b.

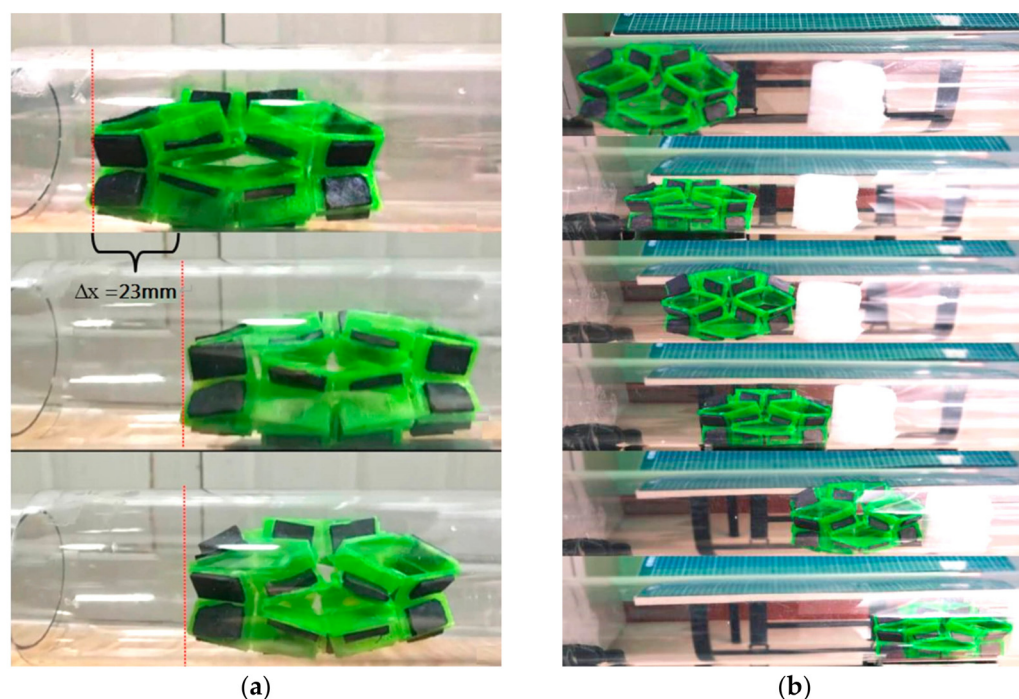


Figure 10. In-pipe locomotion of the origami flexiball robot: (a) undulatory motion, (b) cleaning experiment.

Additionally, the ability of self-adaptive variable diameter has also been viewed as an important indicator to measure the performance of in-pipe robots. Therefore, we

experimentally inspected the origami flexiball robot's adaptability to pipes of variable diameters. As illustrated in Figure 11, the connected polycarbonate pipes include three different pieces with inner diameters of 57 mm, 67 mm and 71 mm. Our presented origami flexiball robot smoothly crawled through the pipes in sequence, and the locomotion speed was up to 6 mm/s. At the joints between different diameter pipes, no jam, stagnation or other problems were observed. This fully demonstrated that the controllable adaptive deformation of the origami flexiball robot has high compliance for various pipe sizes by adjusting the stimulation of the external magnetic field.

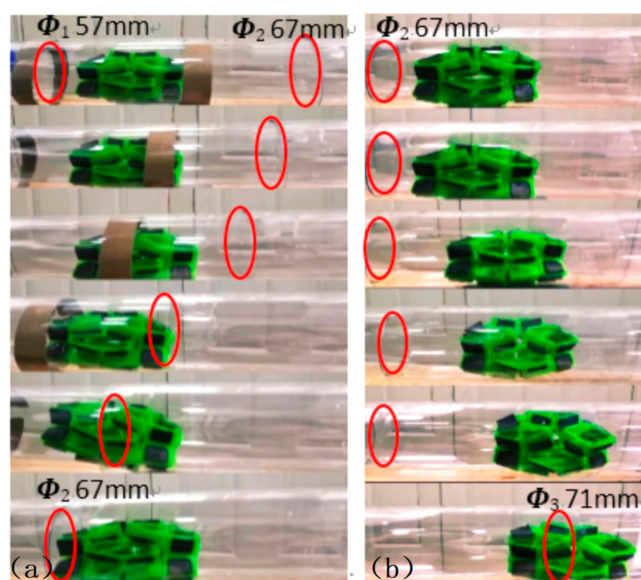


Figure 11. The origami flexiball robot crawls through variable diameter pipes (the nested connections of variable diameter pipes are marked using red circles): (a) from $\varnothing 57$ mm pipe to $\varnothing 67$ mm pipe; (b) from $\varnothing 67$ mm pipe to $\varnothing 71$ mm pipe.

Obviously, although our origami flexiball-inspired in-pipe robot prototype looks a little simple, it provides a new alternative. Besides its good adaptability to various pipe sizes, it has many other potential advantages. For instance, due to its fully soft nature without any rigid parts, it can work in pipes with fragile walls. Further, it can be easily expanded to different scales, or reconfigured into many segments by assembly. Admittedly, there is much room for its full robotization, including self-sensing, long-range control strategy and a more complex deformation mechanism.

4. Conclusions

In recent years, origami-inspired structures, origami-inspired mechanisms, origami-inspired metamaterials and even origami-inspired robotics have primarily demonstrated their promising potential for innovative inspirations for engineering solutions. In this research, origami flexiballs configured with rhombic cells are investigated from underlying metamaterial mechanisms to robotized possibility.

In light of the definition of a mechanical metamaterial, and further referring to the similarly origami-inspired metamaterials, this type of origami flexiball could be exactly regarded as a shape-shifting metamaterial mechanism owing to multiple degrees of freedom, switchable rigidity and large volumetric deformations. Further, we redesigned and fabricated the soft origami structures considering 3D printability and foldability. Furthermore, we introduced a magnetically driven soft actuator with rhombic deformations different from soft bionic deformations like bending, stretching, twisting, spiraling, etc. Lastly, an applicable attempt was presented through robotizing the soft origami flexiball as an in-pipe crawling robot. Locomotion through variable diameter pipes and a cleaning task clearly suggested the presented origami flexiball robot has good adaptability to various pipe sizes,

and can also be easily expanded to different scales, or reconfigured into more complex metastructures by assembly.

Although this exciting and illuminating research may contribute to the new soft robotics paradigm, admittedly, there is much room for the full robotization of origami metamaterial polyhedra, including self-sensing, long-range actuation methods and more controllable complex shape-shifting mechanisms like hopping, rolling and self-assembly. Besides robotic fields, many more applications in other interesting fields are expected, such as soft deformation sensors, transformable buildings, optical instruments with foldable long-focal-length and multiset lenses, reconfigurable dampers, lightweight haptic devices [53], constrained devices [54], etc.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data generated or analyzed during this study are included in this article.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

DOF	Degree of Freedom
FDM	Fused Deposition Modeling
MAE	Magnetoactive Elastomer
PLA	Poly(lactic Acid)
RHD	Rhombic Hexahedron
RDD	Rhombic Dodecahedron
RTD	Rhombic Triacanthahedron

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