DESIGN OF BISTABLE DEPLOYABLE SCISSOR STRUCTURES CONSISTING OF TRANSLATIONAL UNITS BASED ON FLAT RETRACTION LOGIC

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Abstract. The subject of this research is the study of the retraction change mode of deployable scissor grids based on the Hoberman mechanism. The retraction logic of this type of flat mechanism can be changed mainly by moving the pivot point of the rod and using bistable deployable scissor structures consisting of translational units. Therefore, the mechanism can remain flat while it retracts, and the irregular translational units allow for a greater variety of surface variations in the shape of the mechanism. Through the study of the scissor system, a simplified mathematical model is used to explore the geometric potential, and a formula for complete flat retraction is derived. Following the input of defined data using digital tools, the remaining translational scissor units that conform to the retraction logic are generated. Then, irregular linkage mechanisms are created that can retract from 3D to 2D, with the opening mode not being limited to the radial sphere or other mean geometries. These results provide a unique retraction mode for deployable scissor grids, thus facilitating the collection and transportation of such mechanisms in practical applications.

Keywords. Flat Retraction Logic, Geometric Design, Translational Units, Pivot Point, Bistable Deployable Scissor Structures.

1. Introduction

1.1. DEPLOYABLE STRUCTURES

Deployable structures are becoming increasingly important as means of addressing the problems posed by the unbalanced distribution of land and the impact of natural disasters on the built environment. One example of this is the use of standard shipping containers as temporary hospitals during the COVID-19 pandemic. These containers can be easily transported by truck, train, or airplane, which allows them to be quickly deployed to areas in need of medical resources.

One notable example of a deployable structure is the Hoberman Sphere

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(Hoberman, 1992), a spherical structure made of polyhedra and scissor-like joints that allow the structure to be collapsed to a fraction of its normal size. The ability to quickly change the geometry and dimension of this type of structure makes it useful for constructing temporary spaces.

1.2. HOBERMAN MECHANISM

The Hoberman mechanism is the theoretical foundation of deployable structures. It allows for the conversion of linear motion into a specific radial motion, enabling deployable structures to retract and reduce their volume while occupying a large space when deployed (Figure 1).

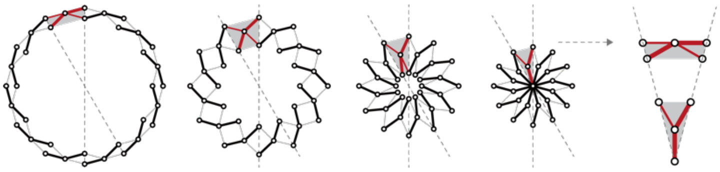


Figure 1. The retraction logic in the simplest Hoberman mechanism.

Hoberman developed a number of deployable structures based on the Hoberman mechanism, which are widely used in the construction field. For example, the Hoberman Arch was used as a mechanical curtain during the 2002 Winter Olympics in Salt Lake City, Utah. Despite its usefulness, the Hoberman mechanism has some limitations, such as limited potential for complex geometric forms and difficulty in the construction of grid systems. These limitations suggest that there is still much potential for innovation in the design and use of scissor structures (Roovers, K., Mira, L. A., & De Temmerman, N., 2013). They were applied by altering the geometry of rods for curvy transformation (Dinevari, N. F., Shahbazi, Y., & Maden, F., 2021) and used in applications to build various grid systems (Roovers, K., & De Temmerman, N., 2017).

1.3. REALISTIC CONSTRAINTS OF THE BASIC HOBERMAN SPHERE

This research takes the basic Hoberman spherical mechanism as the initial subject of observations and discusses the limitations brought by the mechanism. We focus on the effects of the pivot points on the motion of the mechanism and present a unique mode of overall retraction for deployable scissor grids by leveraging the structural characteristics of bistable grids.

- Retraction logic leads to increased difficulty in transportation.

  The retraction logic of the Hoberman Sphere is based on scaling in three dimensions, which allows the mechanism to remain intact after retracting. However, this overall retraction makes it difficult to disassemble structures for transportation. The gaps between mechanisms caused by this limitation are not conducive to the mobility of deployable structures, which is important for addressing building needs during emergencies. We propose using flat retraction logic that allows the flat mechanism to maintain its structural integrity without spatial constraints. The flat mechanism without spatial structure can present a relatively soft property for storage, which is convenient for curling or stacking layers. This makes storage and transportation easier and allows for deployment of more stable structures.

- Simple geometry of the mechanism.

  The diameter of the Hoberman Sphere changes from 13 cm to 30 cm when it is stretched, a factor of approximately 12-13 times. This significant change in volume and shape is useful for deployable structures. However, in architectural applications, there is often a need for more diverse and complex curvatures. Many of the geometric models of scissor structures proposed in recent years are based on simple curved shapes, which limits their potential for use in real-world applications. There is a need for more diverse ways of changing the form of deployable structures rather than simple transformations between similar forms (Roovers, K., & De Temmerman, N., 2017).

1.4. RESEARCH OBJECTIVES& RESEARCH TOPICS

This study aims to provide a unique retraction mode for deployable scissor grids and explore alternative retraction modes for deployable structures with large shape variations. By using a flatter retraction mode, we can reduce the gaps between mechanisms and make the retraction mechanism much smaller in height and easier to transport. Additionally, by moving the pivot points of the scissor units, we can create irregular structures with greater geometric potential. So that the deployable grids can get a high degree of design freedom of the shape making it easier to design such mechanisms for practical applications. The study is divided into three parts:

- The influence of the position of the middle pivot point of the scissor structures.
- The characteristics of translational units in bistable deployable scissor structures.
- A test of bistable deployable scissor structures consisting of translational units based on flat retraction logic.

2. Deployable scissor structure

2.1. GEOMETRIC CONSTRUCTION METHOD

Deployable scissor structures are mechanisms that are capable of deploying and retracting in a single linear direction. The pivot point in the middle of the link rod is typically located at the center of the rod (Figure 2). The control units of the motion track of the scissor structures can be divided into three main parts: (1) the position of the pivot point in the middle of the link rod, (2) the angle of the link rod itself, and (3) the length of the link rod under the same projected area. This study focuses on the first category, specifically on how changing the position of the pivot point can alter the movement track of the rod.

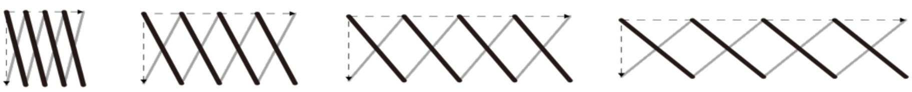


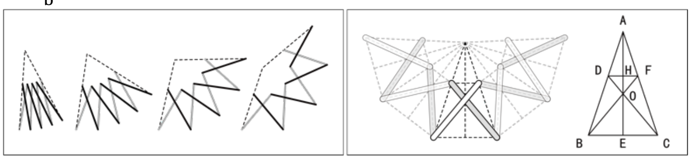
Figure 2. Motion track diagram of the simplest translational scissor structures.

2.2. EFFECT OF THE PIVOT POINT DEVIATION ON THE MECHANISM

When the rod is symmetrical, the center point of the rod deviates, and the motion track of the mechanism changes, causing the original linear motion to become a radial deployment and retraction track. We set DO=FO=a, BO=CO=b, AE bisection ∠BAC, ∠AOD=β, line CD and BF intersect at point A, and the relationship between the intersection point of the moving rod and the motion track can be explored by calculating the length of AO (Figure 3).

Using a simplified mathematical model, we can calculate the intersection point of the deployment line formed by the end point of the long side of one rod of a group of scissor units and the endpoint of the short side of its mirror rod. This calculation allows us to determine the length of the intersection point of the two rods:

$$AO = \frac{2a\cos\beta}{1-\frac{a}{b}} \tag{1}$$



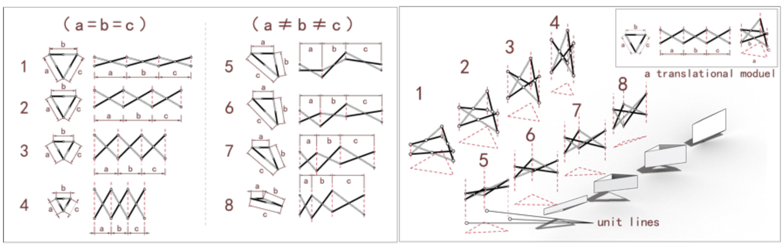
(a) (b) (c)

Figure 3. (a) Diagram of the mechanism deviating from the center point of the rod. (b) Simplification of the mechanism. (c) The simplified mathematical model.

3. Flat retraction logic

This study aims to develop a mechanism that can retract flatly, which is useful for practical applications that require retraction of flat structures and spatial structures during deployment. Thus, it is necessary to minimize the height of the mechanism in the Z-direction when retracting and ensure the deployed mechanism's stability.

3.1. USE OF BISTABLE GRIDS CONSISTING OF TRANSLATIONAL UNITS TO TRANSFORM 2D AND 3D FORMS



(a) (b)

Figure 4. (a) Top view and expansion diagram of the translational modules. (b) Perspective view of translational modules.

Deployable structures are both mechanisms and structural systems. As mechanisms, they transform between multiple predetermined configurations, and as structural systems, they must bear loads in their stable configurations. (Arnouts, L. I., Massart, T. J., De Temmerman, N., & Berke, P. Z., 2019). Bistable grids have the advantage of being structurally weak in the direction of the flat surface, which makes them easier to store and transport. When deployed, bistable grids can instantly achieve structural stability and are self-locking, which eliminates the need for external locking devices when subjected to small external loads (Roovers, K., & De Temmerman, N., 2017). In this study, we use a closed-loop assembly consisting of three translational scissor pairs as the module of bistable deployable structures. This configuration allows us to consider the stability of triangles, making the resulting structures more robust.

3.2. KINEMATICS OF TRANSLATIONAL SCISSOR MODULES

This section discusses the basic geometric and kinematic concepts of translational scissor units and the grids they form. We also develop mathematical rules for generating scissor structures consisting of translational units.

Basic translational units are characterized by parallel unit lines during deployment. (Roovers, K., & De Temmerman, N., 2017). In this basic motion, the link rod is composed of identical straight rods, and the pivot point is located in the middle of the rod. The two ends of the rods are connected to form a closed loop, and the motion track of the unit lines is always maintained in the same direction, which is perpendicular to the maximum projection plane formed by the rod enclosure. If the rods have no thickness, they eventually collapse into a straight line when the loop is closed. This causes the length of the projections of the rods to decrease and the enclosed area of the triangle to decrease (Figure 4).

Irregular translational units are necessary for practical applications where the structure must be adjusted to different surfaces. Triangle segmentation of the mean value limits the design of the model. When the three sides of the control projection are different, more triangles can be formed. Therefore, we focus on the linkage of translational scissor units with different pivot points in the following explanation.

When the rod length is different and the position of the central pivot point changes, the unit lines are no longer perpendicular to the maximum projection plane formed by the surrounding molding of the rods. The maximum projection plane is no longer equally scaled in the retraction process. The rods theoretically retract into a 2D plane (Figure 4). From the previous sections, we know that the position of the central pivot point of the rods affects the motion track of the intersection pivot points between the end of the rod and other rods. If the straight lines connected by the motion track intersect, the rods collide in the motion process. Therefore, we must prevent the motion track of the intersection pivot points at the end of the rod from intersecting in space while moving the central pivot point of the rod. This allows us to design scissor structures with more complex and varied geometry.

3.3. THE GENERAL FORMULA FOR THE MOVEMENT OF THE TRANSLATIONAL SCISSOR MODULES

The module is simplified into a mathematical model (Figure 5). We propose that when $h_1+h_2=h_3$, the mechanism can retract in a flat form to the minimal state.

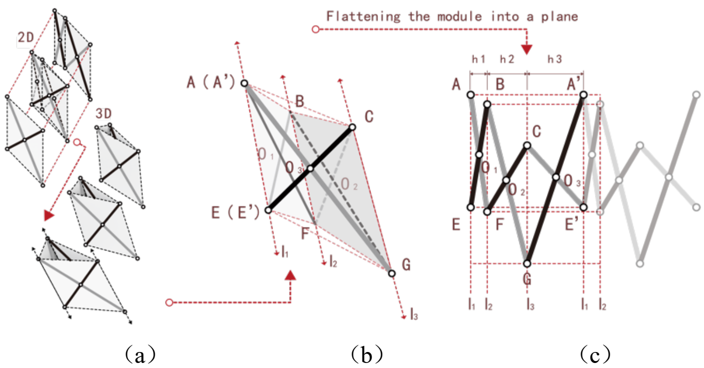


Figure 5. (a) The transformation of a module from 2D to 3D. (b) 3D spatial mockup of the module. (c) 2D tiled view of the module along l_1.

Suppose: $l_1 \parallel l_2 \parallel l_3$, $\angle AO_1E = \alpha$, $h_1+h_2=h_3$

$\because S\Delta AO_1E = \frac{1}{2}|AO_1| \cdot |EO_1| \cdot \sin\alpha$

$S\Delta EO_1F = \frac{1}{2}|O_1E| \cdot |O_1F| \cdot \sin(\pi-\alpha)$

$S\Delta FAE = S\Delta AO_1E + S\Delta EO_1F$

$\quad = \frac{1}{2}|AO_1| \cdot |EO_1| \cdot \sin\alpha + \frac{1}{2}|O_1E| \cdot |O_1F| \cdot \sin(\pi-\alpha)$

$\because S\Delta FAE = \frac{1}{2}|AE| \cdot h_1$

$$\therefore h_1 = \frac{|AF|\cdot|EO_1|\sin\alpha}{AE} \tag{2}$$

Similarly,

$$\therefore h_2 = \frac{(|BO_2|\cdot|FO_2|+|FO_2|\cdot|GO_2|)\sin\angle BO_2F}{BF} \tag{3}$$

$\because \cos\angle BO_2F = \frac{BO_2{}^2+FO_2{}^2-BF^2}{2BO_2\cdot FO_2}$

$\because \sin\angle BO_2F = \cos(\pi-\angle BO_2F) = -\cos\angle BO_2F$

$$\therefore h_2 = \frac{|BG|\cdot(|BF|^2-|BO_2|^2-|FO_2|^2)}{2|BF|\cdot|BO_2|} \tag{4}$$

Summarizing the above derivation yields:

$$\frac{h_2\cdot|BF|}{|BG|} = \frac{|BF|^2-|BO_2|^2-|FO_2|^2}{2|BO_2|} \tag{5}$$

3.4. THE TRANSLATIONAL SCISSOR UNITS IN GRASSHOPPER

The solution of Formula (5) involves intricate calculations of the square. To model the flattening of bistable deployable scissor structures, we utilize Grasshopper as our parametric platform. The Galapagos Evolutionary Solver within Grasshopper handles complex mathematical computations. The genetic algorithm (GA) is a metaheuristic algorithm modeled after natural selection, and is an efficient, parallel, and global search method that adaptively regulates the search process to find the best solution. In this study, by using the genetic algorithms within the Galapagos component, we can calculate the difference between the two sides of the formula. If the difference cannot be 0, it is made as close to zero as possible by reducing the number of significant digits after the decimal point in the calculation and setting the fitness property to the minimum value, to improve the accuracy in practice. The Galapagos component also helps us generate optimal results automatically and rapidly when inputting information about multiple modules.

By examining Formula 5, we can determine the conditions under which the translational scissor units retract flatly. To use the formula in Grasshopper and enable parametric controls of its arguments, we need to input the following information (as shown in Figure 6): (1) Four points A, B, E, and F, which define a set of translational scissor units according to the requirements. (2) The vertical distance from G to AA', designated as Y, which affects the curvature of the surface produced by the combination of multiple modules. (3) The value of h_3, which determines the perimeter and area of the projection triangle of the closed-loop mechanism. By inputting the above information, we can determine the position of pivot point O_2 on the BG line segment and obtain a complete set for the module.

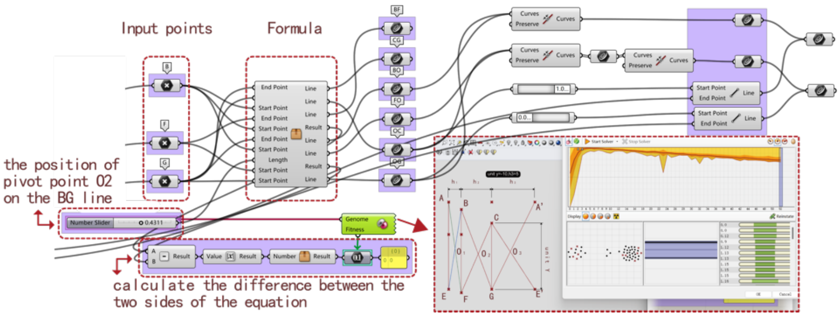
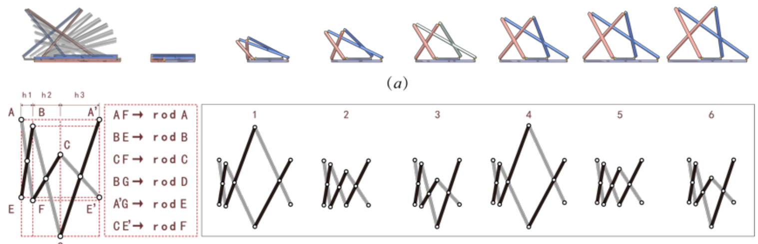


Figure 6. Grasshopper simulation process.

3.5. RETRACTABLE CHARACTERISTICS OF THE MODULES

By comparing the modules, we see that the range of height and volume variations is greater for the first module than for the second module and greater for the second module than for the third module (Figure 7).

This indicates that the mechanism that retracts in a flat form can be flattened to a large extent in terms of height. For a single module, the retraction rate in a flat form and its volume are affected by three parameters: (1) the length of rods A and B, (2) the value of Y, and (3) the length of h_3. Under constant conditions, the values of rods A, B, and h_3 are positively correlated with the retraction rate of a flat form, where the value of Y is negatively correlated with it. The change in h_3 is particularly significant.



(b)

	rod A	rod B	rod C	rod D	rod E	rod F	flattening of angulated units: h1	h2	h3	Y	range of theoretical changes: height	volume
1	10.496	9.27	15.588	18.926	19.123	17	1.468	6.532	8	15	0-6.65	0-428.416 cm^3
2	10.496	9.27	9.811	8.707	9.068	11.18	1.468	3.532	5	10	0-6.05	0-136.374 cm^3
3	10.496	9.27	14.587	6.871	7.433	7.433	1.468	3.532	5	15	0-5.08	0-125.438 cm^3
4	10.047	8.822	15.588	18.902	19.1	17	1.468	6.532	8	15	0-6.38	0-406.052 cm^3
5	10.047	8.822	9.811	8.726	9.085	11.18	1.468	3.532	5	10	0-5.86	0-130.092 cm^3
6	10.047	8.822	14.587	6.85	7.415	15.811	1.468	3.532	5	15	0-4.91	0-118.969 cm^3
							(h1+h2=h3)					

Unit: cm round to 3 decimal places

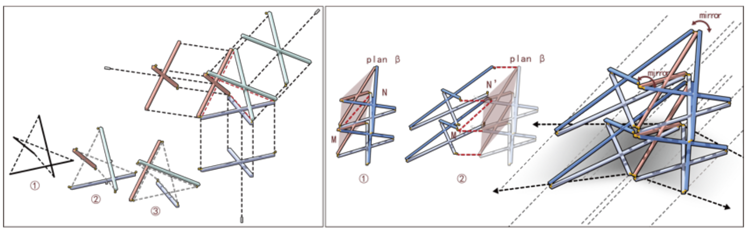
(c)

	length①-length②					
Control group(①&②)	rod A	rod B	h1	h2	h3	Y
Module 2 and module 3	=	=	=	=	=	-5cm
Module 1 and module 4	>	>	=	=	=	=
Module 1 and module 3	=	=	=	=	+3cm	=

(d)

Figure 7. (a) Retraction change diagram for a module. (b) Experimental modules with different rods. (c) The range of height and volume variations for different modules and their corresponding adjustment parameters. (d) Control group.

3.6. ASSEMBLY LOGIC



(a) (b)

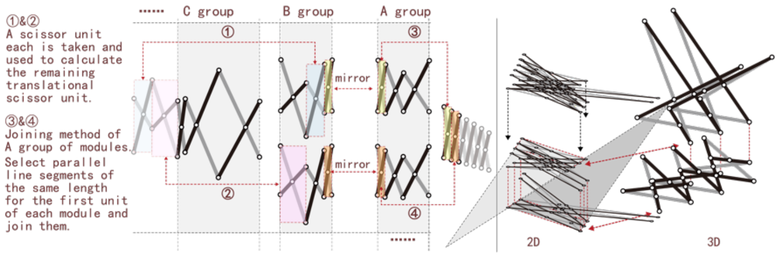
Figure 8. (a) Assembly logic of a single module. (b) Assembly logic of multiple modules.

- The assembly logic of a single module involves three steps (1) Three disjoint lines are selected, and the rods are placed outward along the line segment to the geometric center formed by the line segment. (2) The other three lines are selected, and the rods are offset along the line segment to the geometric center formed by the line segment. (3) A screw is placed at the central pivot point of the rods, and the rods are connected with joints (Figure 8).
- The assembly logic for multiple modules involves the following steps: (1) The motion tracks of the intersecting pivot points of the rod ends of modules 1 and 2 are

made in the same direction. (2) The MN end of one module in the flattened state is selected and connected to the pivot point of the other module by a joint of the same length. This causes both module 1 and module 2 to fall on plane β when they become flat. (3) The other two modules are found in the same way, and their retractions are in the opposite direction to those of modules 1 and 2. Finally, the four modules are flattened so that the rods all fall on plane β.

3.7. DESIGN EXPERIMENTS

According to the above, the modules were sorted into four groups based on the length of h_3 and the variable Y, resulting in 21 modules with a total of 114 rods with different central pivot points. These modules were assembled according to Section 3.6 to create a nonuniformly deployable surface, which was used to test the rationality of the flat retraction logic. The groups of modules included: Group A with Y=-10 and h_3 =5 (a total of 6 modules); Group B with Y=-15 and h_3 =5 (a total of 6 modules); Group C with Y=-15 and h_3 =8 (a total of 5 modules); and Group D with Y=-15 and h_3 =8 (a total of 4 modules). There are many different geometric relationships between the modules (Figure 9). During the assembly process, the rods must be sorted in advance. Rods that do not intersect in the unfolded 2D planar state are placed on the same layer, and rods of the same color are selected. This ensures that rods of the same color do not intersect in the mechanism. This reduces the problems that incorrect assembly orders can cause during assembly. The retraction characteristics of the structure allowed for further reduction in height through folding after flat retraction. This resulted in height change from 56 cm to 15 cm, and further flatten to 7cm by folding (Figure 10).



(a) (b)

Figure 9. (a) *Relationships between the translational modules.* (b) 2D and 3D states for a module.

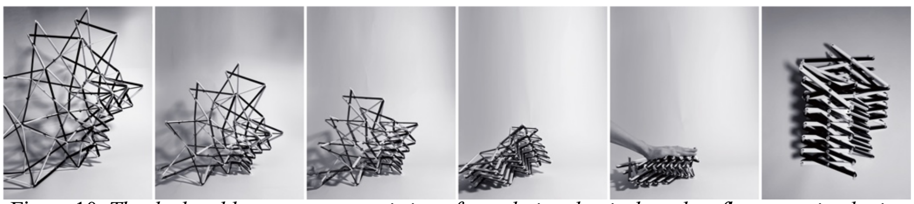


Figure 10. *The deployable structures consisting of translational units based on flat retraction logic.*

4. Conclusions

This study proposes a formula for modeling the flattening of bistable deployable scissor structures. Compared to the Hoberman mechanism, this mechanism fundamentally changes how the mechanism retracts, allowing for fewer gaps during transport.

Through calculations, we quickly generated the special rod lengths and pivot point positions needed to produce bistable deployable scissor structures based on logic for flat retraction. The factors that influenced the mechanism were rod A, rod B, h_3, and Y; h_3 had the most significant effect. The mechanism for retracting flat structures exhibited the following characteristics: (1) high retraction rate, down to a flat plane, (2) the flexible module of the mechanism, which allowed the construction of a variety of surfaces that conformed to the formula. The advantage of this formula is that it breaks the traditional scissor grids with elementary shapes and a high degree of symmetry and uniformity. The maximum projection plane surrounded by the translational scissor modules generated by the formula is no longer limited to regular triangles. It can be adapted to various surfaces that can be divided into triangles. This allows for more possibilities in the geometric form of the mechanism, which enables more freedom in the deployment surface designs in practical applications. The logic of flat retraction improves the mobility of the mechanism and reduces the difficulty of transport.

Potential research directions include the following: (1) A more refined joint design of the retraction mechanism may further minimize its retracted volume and make it closer to the theoretical value. (2) The proportional relationship between the sum of h_1, h_2, h_3, or Y and the curvature of each module can be further studied.

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