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Radially Expandable Ring-Like Structure with Antiparallelogram Loops

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Abstract
As they constitute a substantial percent of deployable structures, scissor mechanisms are widely studied. This being so, new approaches to the design of scissor mechanisms still emerge. Usually design methods consider the scissor elements as modules. Alternatively, it is possible to consider the loops as modules. In this paper, loop assembly method is used such that antiparallelogram loops are placed along a circle, to construct a deployable structure. The research shows that it is possible to construct radially deployable structures with identical antiparallelogram loops with this method. Then kinematic and geometrical properties of the construction are analyzed. It is found out that the links of such a structure turn out to be similar generalised angulated elements. Furthermore, similar loops are used for the construction and deployable rings are obtained.
Keywords: Deployable ring-like structure, antiparallelogram loop, loop assembly method, radial expansion, angulated scissor element.

1. Introduction

Deployable structures are mechanisms that can go under transformation in order to achieve a compact (stowed) and an open (deployed) configuration [1]. This change in size offers a great advantage in packing and also in mobility, therefore making them suitable for many applications varying from retractable roofs [2-4] to space antennas [5-7].

One of the most important units of deployable mechanisms are scissor-like elements (SLEs). SLE is composed of two straight bars connected with a revolute joint, which is perpendicular to the common plane of the bars, called pantographic elements [8]. In 1960's Pinero published the first academic studies on deployable structures made of SLEs [9]. Later on the foldability conditions of SLEs were defined by Felix Escrig [10, 11]. Kinematics of deployable structures continued to be a research area for many others [12-14].

Angulated elements were first introduced by Hoberman [15, 16]. This new type of SLEs were able to subtend a constant angle. We observe the same property in Servadio's foldable polyhedra [17]. Hoberman's latter work, the Iris Dome [16], is nothing but a circular application of the angulated unit subtending constant angle between the unit lines, therefore capable of radial deployment.

Angulated units were further explored by You and Pellegrino [18] after the invention of Hoberman. They derived the geometric conditions of radial deployment and came up with two types of generalized angulated elements (GAEs): equilateral (type I) and similar (type II) GAEs. After You and Pellegrino, further research was conducted on the kinematics and mobility analysis of angulated elements [19, 20]. Kiper et al. [21] showed that the motion of the angulated elements in a radially expanding structure is the Cardan Motion.

Instead of using the angulated elements as modules for deployable structure design, Hoberman uses rhombus loops as modules [22]. This loop assembly method first places identical rhombus loops along a curve and then the link lengths are determined. Liao and Li [23] and Kiper and Söylemez [24] have found similar results independently from Hoberman.

2. Loop Assembly Method

In the literature there are three types of scissor units: transitional, polar and angulated units. When the scissor hinge is in the middle of straight bars, the result is a translational scissor. Maden et al. [25] have examined the possible arrangements of different types of scissor units and provided formulations for their analysis and design. When several translational scissor units are assembled together in a row, the loops formed are rhombus loops (Fig. 1a). When the scissor hinge is not placed in the middle, polar units with kite loops are formed (Fig. 1b).

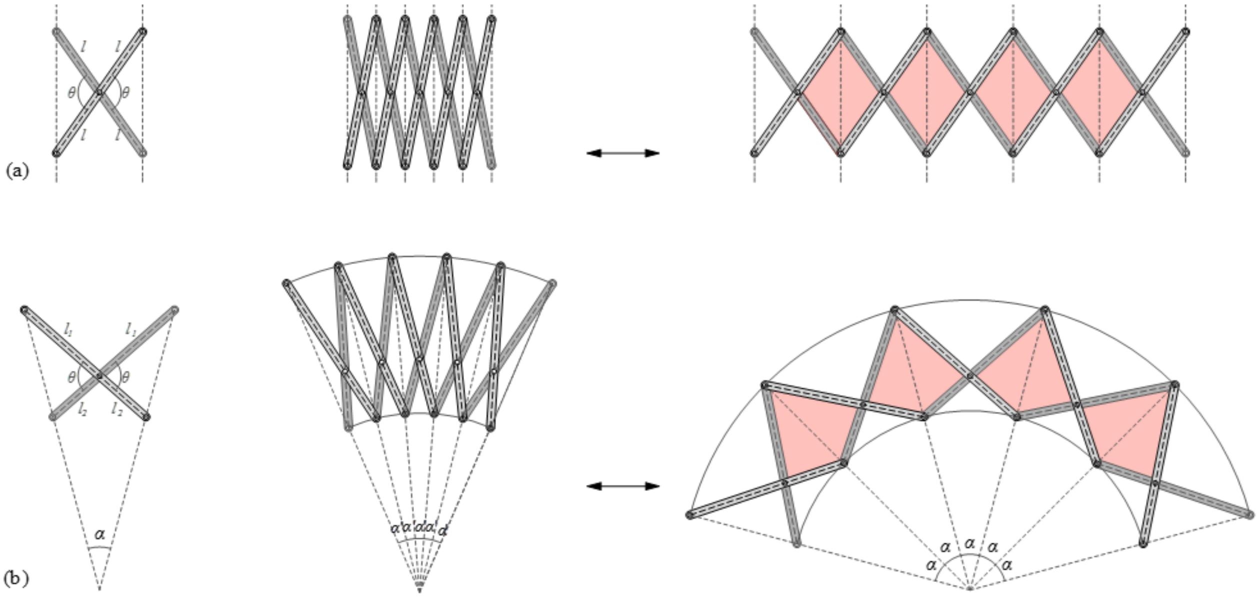


Fig. 1: a) Rhombus loops formed with translational scissor units
b) Kite loops formed with polar scissor units [26]

Hoberman devised a methodology using the loops to find the form of the links. By aligning rhombus loops on a curve, he derives angulated elements (Fig. 2). He also found out that it was possible to achieve deployable structures using different scales of the same rhombus along a given curve. In this study we use another type of loop, antiparallelogram loop, to compose single degree of freedom (DoF) radially expanding deployable structures.

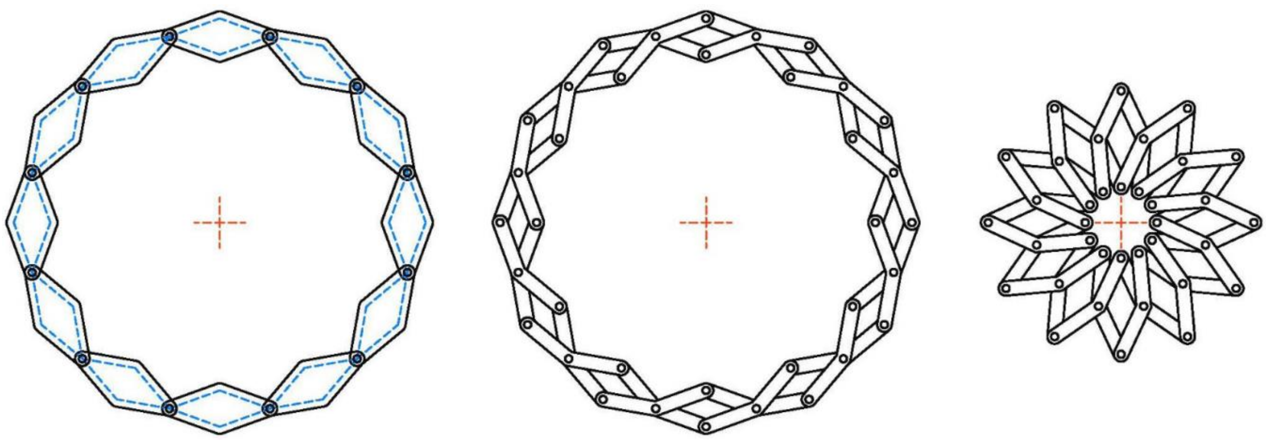


Fig. 2. Assembly of rhombi loops on a circle [22]

An antiparalellogram is also called a crossed parallelogram or a contraparallelogram. It is made up of two equal short and two equal long sides, in which long sides cross each other. During the motion the crossing point moves on the long edges and always stays on the mirror symmetry axis of the loop (Fig. 3).

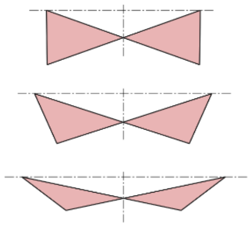


Fig. 3. Motion of antiparallelogram loop

In our study, we align antiparallelogram loops along a circle, similar to Hoberman's method. There are several variations of arrays in order to connect the loops at joints. Placing the loops in alternating order on the circle (sort of glide reflection along the circle) yielded a radially deployable structure (Fig. 4).

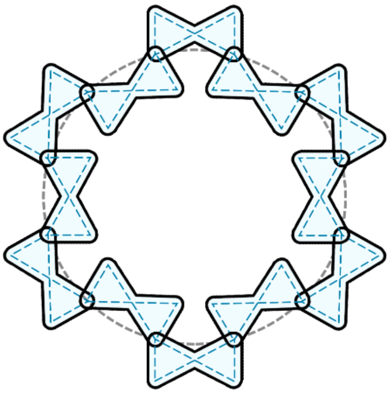


Fig. 4. Antiparallel loops along a circle

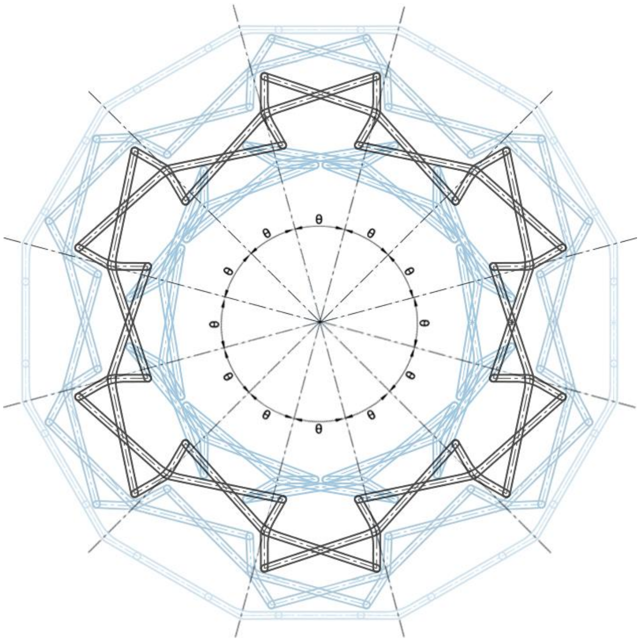


Fig. 5. Deployable antiparallelogram ring mechanism

In Fig. 5 it is seen that there is only one joint on each radial axis from the center, unlike the angulated scissor ring-like structures developed by Hoberman. Therefore it is not possible to locate the center with a single loop, but two loops are necessary so that the positions of three joints defines a circle. The relation between the subtended angle θ and kink angles α + β of the links can be observed with a geometrical analysis (Fig. 6). Also, due to alternating order of the loops, there are always even number of loops in the assembly.

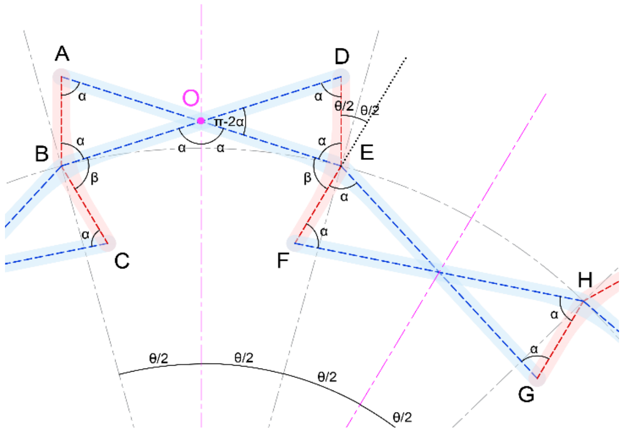


Fig. 6. Geometrical analysis of antiparallelogram ring mechanism

Initially AB arm of link ABC and DE arm of link DEF are parallel to each other. Let ∠EAB = α. Since |AB| = |DE| and |AE| = |BD|, all inner angles of ABDE antiparallelogram are equal to α. Let ∠AEF = β. It is seen from Fig. 6 that ∠DEF = ∠AEG = α + β, i.e. the kink angles of both types of angulated elements, DEF and AEG, are equal to each other. ∠BOE = 2α, being an outer angle of triangle OAB. A line through the intersection point O and parallel to AB and DE divides ∠BOE and also the subtended angle θ into two. The loop has mirror symmetry about this line. Such lines will be called unit lines. Since DE is parallel to the unit line through O, the angle between the radial axis through E and DE is equal to θ/2. Similarly one can conclude that the angle between EF and the radial axis through E is equal to θ/2. So, θ/2 + α + β + θ/2 = π, that is, the kink angles are α + β = π – θ.

Since identical loops are used to construct the mechanism, the two type of angulated links DEF and AEG have link lengths |DE| = |EF| and |AE| = |EG|. Also the kink angles of both type of angulated elements are equal. Therefore, the angulated elements are similar (type II) GAEs (Fig. 7). When the desired number of loops and the circle radius at the initial configuration is specified, one of the side lengths can be chosen freely and the other side length is dependent.

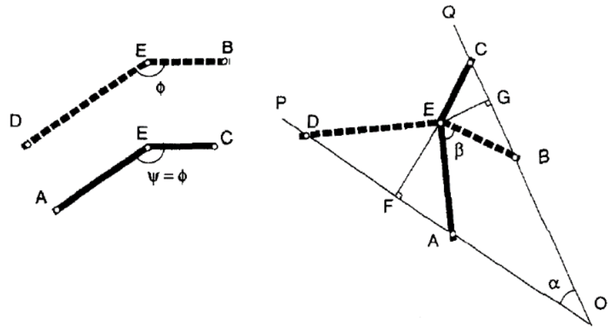
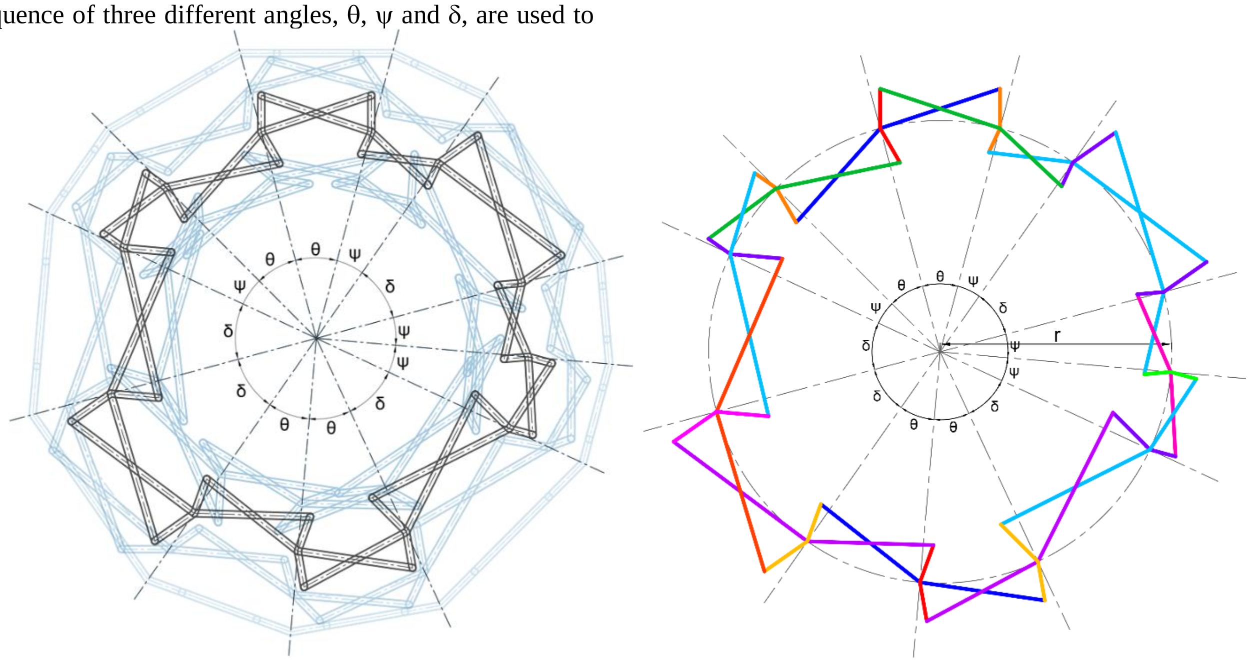


Fig. 7. Similar (type II) GAEs - |AE|/|DE| = |EC|/|EB| and $\psi = \phi$

Next, we construct a ring with similar loops, instead of identical loops. For this construction, a random sequence of three different angles, θ, ψ and δ, are used to divide the circle into sections. When the mechanism is drawn in Solidworks® it is seen that this construction also yields a deployable ring structure (Fig. 8).

Geometric principles of the mechanism can be found similar to the construction with identical loops (Fig. 9). The short edges of each loop are parallel to the unit lines passing through the center of the circle and crossing point of the loop. The unit lines bisect the corresponding subtended angles θ, ψ and δ. Again, similar GAEs are used with identical kink angles. This time, the kink angles are determined by two adjacent subtended angle values. For example, $\angle FED = \angle AEI = \alpha + \beta_2 = \pi - (\theta/2 + \psi/2)$. For the example in Fig. 8, there are 6 different pairs of angulated elements (Fig. 8b). Within each pair, two angulated links have the same kink angle and proportional arm lengths, i.e. they construct a similar GAE.



a) b)

Fig. 8: a) Deployable antiparallelogram ring mechanism with similar loops b) Link typology of the mechanism

3. Conclusions

Our study showed that it is possible to achieve deployable rings using antiparallelogram loops in alternating order on a circle using loop assembly method. The links resulted from the assembly are Type I GAE's with identical kink angles. Furthermore, the kink angles can be represented in terms of the subtended angles. It is seen that only one of the side lengths is independent when the number of loops and circle radius are given for the initial configuration. Unit lines of the loops do not pass through joints, but they are the symmetry axes of the loops.

In the second stage of the study, we used similar loops to construct and that also yielded a deployable mechanism, again resulting with Type I GAE's. In this construction the subtended angles varied. Once again, the kink angles can be represented in terms of the subtended angles.

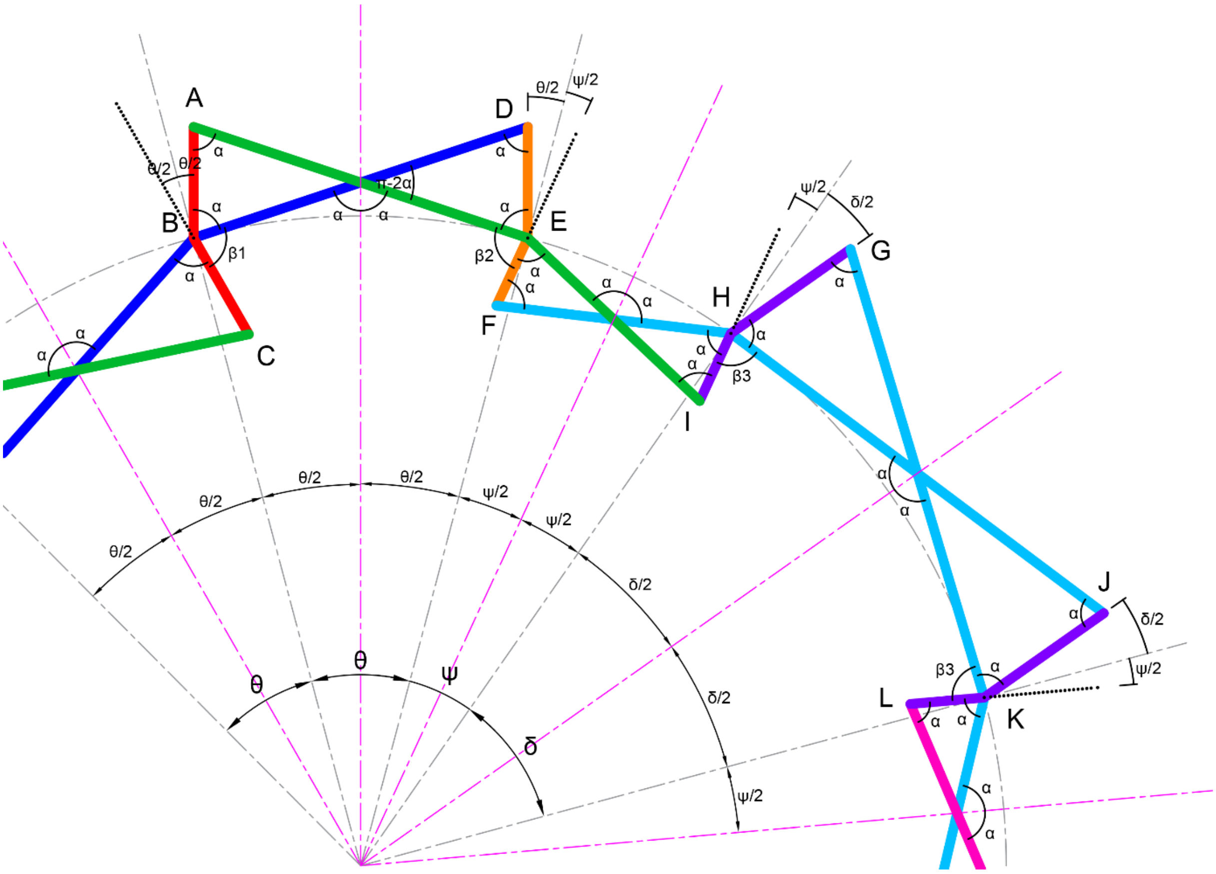


Fig. 9. Geometrical analysis of antiparallelogram ring mechanism with similar loops

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