Modeling and analysis of some planar deployable mechanisms. Part 2: curvilinear bar mechanisms

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Abstract. Research in deployable structures increased in the last decade, due to the need of building structures that can change their shape or functionality in response to varying of different aspects: climatic conditions, environment, functional requirements or emergency situations. Depending on how the transformation is doing, transformable structures can be deployable or demountable, as a kit-parts system. These structures can be classified in four main groups: structures based on spatial articulated bar mechanisms; foldable plate structures; tensegrity structures; and membrane structures. In this paper, some geometric design aspects of curvilinear bar mechanisms are discussed and a curvilinear structure mechanism is proposed. More results on the geometric design, dimensional synthesis and simulation of this scissor structural mechanism will be presented in future work.

1. Introduction
Research in deployable structures increased in the last decade, due to the need of building structures that can change their shape or functionality in response to varying of different aspects: climatic conditions, environment, functional requirements or emergency situations [1], [2]. Two sub-categories of these structures are studied in bigger detail, due of their wide applicability in the field of mobile architecture: bar structures and foldable plate structures, respectively [3], [4], [5], [6], [7]. Deployable structures with bar articulated mechanisms are based on translational or curvilinear scissor structure mechanisms [8]. In this paper, some geometric design aspects of curvilinear bar mechanisms are discussed [8] and a curvilinear structure mechanism is proposed. More results on the geometric design, dimensional synthesis and simulation of this scissor structural mechanism will be presented in future work.

2. General geometric design aspects of a deployable scissor structure

2.1. Polar scissor units
A polar scissor unit can be derived from the translational unit by moving the location of the revolute joint away from the midpoints of the bars (Figure 1). By doing this, scissor revolute joints of the planar scissor structural mechanism generate a curvature during deployment. The top and bottom revolute joints and the intermediate scissor revolute joints are placed on concentric circles. As consequence, the unit lines will intersect at the centre of these circles at an $\phi$ angle, which has variable values, depending on the unit deployment. The centre of the circles becomes closer to the unit as the curvature increases [8], [9].
Figure 1. Basic scissor polar unit.

Using polar scissor units, two types of curvilinear scissor structural mechanisms can be generated. The first type has identical bars and scissor revolute joints eccentrically placed (Figure 2). For this type of curvilinear scissor structural mechanism, the deployability condition is as following [8]:

$$\frac{a_{i-1}}{b_{i-1}} = \frac{a_i}{b_i} = \frac{a_{i+1}}{b_{i+1}} = \cdots = \frac{a_n}{b_n}. \quad (1)$$

Because the scissor unit bars are identical, it results:

$$a_{i-1} = a_i = a_{i+1} = \cdots = a_n = l_1$$
$$b_{i-1} = b_i = b_{i+1} = \cdots = b_n = l_2. \quad (2)$$

Figure 2. Curvilinear scissor structural mechanism with identical bars and scissor revolute joints eccentrically placed.

The second type of curvilinear scissor structural mechanism has arbitrary units in its structure (Figure 3). The scissor units used to build such structural mechanism have different bar lengths. Also, these scissor units are characterized by the fact that their scissor revolute joints are not located at the
middle of the bars. For this type of curvilinear scissors structural mechanism, the deployability condition is [8]:

$$\frac{a_{i-1}}{b_{i-1}} \neq \frac{a_i}{b_i} \neq \frac{a_{i+1}}{b_{i+1}} \neq \ldots \neq \frac{a_n}{b_n}.$$  \hspace{1cm} (3)

For this type of structural mechanism, the lengths of bars can be different but, the lengths on both sides of the unit lines are similar, such as the general deployability conditions are respected:

$$a_i = a_{i+1}, \ b_i = b_{i+1}, \ a_{i+2} = a_{i+3}, \ b_{i+2} = b_{i+3}, \ldots, \ a_n = a_{n+1}, \ b_n = b_{n+1}.$$ \hspace{1cm} (4)

It means that, for the structural mechanism shown in Figure 3, the deployability condition is:

$$a_i = a_{i+1} = l_2, \ b_i = b_{i+1} = l_3, \ a_{i+2} = a_{i+3} = l_4, \ b_{i+2} = b_{i+3} = l_5, \ a_{i+4} = a_{i+5} = l_6,$$

$$b_{i+4} = b_{i+5} = l_7, \ a_{i+6} = a_{i+7} = l_4, \ b_{i+6} = b_{i+7} = l_5, \ a_{i+8} = a_{i+9} = l_2, \ b_{i+8} = b_{i+9} = l_3.$$ \hspace{1cm} (5)

![Figure 3. Curvilinear scissors structural mechanism with arbitrary scissors units.](image)

2.2 Curvilinear scissors structural mechanisms with mixed units

Using different types of scissors units in different combinations, it is possible to get scissors structural mechanisms in different forms. Such planar mechanisms could be used to design 3D scissors structures for further architectural applications.

One example of such mixed structure is composed of two scissors structural mechanisms with different curvatures (Figure 4), [8]. For both scissors structural mechanisms the bar length \(L\) is the same, but the location of scissors revolute joint is different. The bar length of the scissors structural mechanism with the centre \(O_1\) is \(L = l_1 + l_2\) and the bar length of the scissors structural mechanism with the centre \(O_2\) is \(L = l_3 + l_4\). The curvatures of these scissors structural mechanisms depend on the lengths \(l_2\) and \(l_3\). For our example, \(l_2 > l_3\). To respect the general deployability condition, we have:

$$l_1 + l_2 = l_3 + l_4.$$ \hspace{1cm} (6)
The scissor structural mechanisms with mixed units may be used for deployable roof structures or portative walls that can offer different curvilinear geometries [8].

3. Proposed curvilinear bar mechanism for deployable structures

The curvilinear bar mechanism for deployable structures proposed here (Figure 6) is based on combining two different polar scissor units. As driving unit, in this case is using the same modified scissor unit used for the translational bar mechanisms discussed in the first part of the paper (Figure 5).

Because the two alternated scissor units have the revolute joint different placed on the bars (Figure 7), their unit lines are not intersecting in the center of the circle described by the structure revolute joints, \( C_d \). Despite this, the curvilinear structural mechanism can be used to describe circular structures. Also, the deployability condition, starting with joints \( I \) and \( H \), is:
Figure 6. Curvilinear scissor structural mechanism: a) totally deployed configuration; b) partially deployed configuration.
Because the scissor unit bars are identical but the unit revolute joints are different placed for the two types of scissor units, it results:

\[
\begin{align*}
\frac{a_{i-1}}{b_{i-1}} &= \frac{a_i}{b_i} = \frac{a_{i+3}}{b_{i+3}} = \frac{a_{i+4}}{b_{i+4}} = \frac{a_{i+7}}{b_{i+7}} = \frac{a_{i+8}}{b_{i+8}}, \\
\frac{a_{i+1}}{b_{i+1}} &= \frac{a_{i+2}}{b_{i+2}} = \frac{a_{i+5}}{b_{i+5}} = \frac{a_{i+6}}{b_{i+6}} = \frac{a_{i+9}}{b_{i+9}} = \frac{a_{i+10}}{b_{i+10}}. 
\end{align*}
\] (7)

\[
\begin{align*}
\frac{a_{i-1}}{b_{i-1}} &\neq \frac{a_{i+1}}{b_{i+1}}
\end{align*}
\]

Comparing to the scissor structural mechanism with mixed units shown in Figure 4, where in the first part of the structure is used one type of unit and in the second part the other type of scissor unit, in the mechanism described here the two different scissor units are alternating in the mechanism structure.

More results on the geometric design, dimensional synthesis and simulation of this scissor structural mechanism will be presented in future work.

4. Conclusion

Research in deployable structures increased in the last decade, due to the need of building structures that can change their shape or functionality in response to varying of different aspects: climatic conditions, environment, functional requirements or emergency situations. Depending on how the transformation is doing, transformable structures can be deployable or demountable, as a kit-parts system. These structures can be classified in four main groups: structures based on spatial articulated bar mechanisms; foldable plate structures; tensegrity structures; and membrane structures. In this paper, some geometric design aspects of curvilinear bar mechanisms have been discussed and a curvilinear structure mechanism was proposed. More information on the geometric design, dimensional synthesis and simulation of this scissor structural mechanism will be the subjects of near future research.
5. References

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