Modeling and analysis of some planar deployable mechanisms. Part 1: translational bar mechanisms

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Abstract. Deployable structures can change their shape and volume in order to dynamic answering to changing needs. 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 general geometric design aspects of deployable bar structures are discussed and some translational bar mechanisms for deployable structures are proposed. More results on the geometric design, dimensional synthesis and simulation of these scissor structural mechanisms will be presented in future work.

1. Introduction

Deployable structures can change their shape and volume in order to dynamic answering to changing needs [1], [2]. These structures can be classified in four main groups: structures based on spatial articulated bar mechanisms; foldable plate structures; tensegrity structures; and membrane structures. Between them, two sub-categories are studied in greater detail, because of their wide applicability in the field of mobile architecture, their high degree of deployability and their reliable deployment: bar structures, generally, and pantograph (scissor-like) structures, especially; and foldable plate structures, respectively [3], [4], [5], [6], [7].

Deployable structures based on scissor structural mechanisms are consisting of articulated bars. Even if many deployable structures based on these mechanisms have been proposed till now, few of them have been realized at full-scale because of their mechanical complexity of their systems during the folding and deployment process [8]. However, during the last years, Ten Fold Engineering company (in UK) has been proposed and developed a series of modular, self-deploying structures: regular mobile homes, mobile hotels, bridges, huts, solar panels, lorries, antennas, stairways, larger halls or road barriers, and so on [5], [6], [7], [9], [10].

The key element of a planar scissor structural mechanism is the scissor unit, which consists of two straight bars. These bars are connected to each other by a revolute joint, which is called as scissor hinge. By changing the location of the revolute joint, three distinct basic unit types can be obtained: translational, polar and angulated units (Figure 1) [11].

In this paper, some general geometric design aspects of deployable bar structures are discussed [11] and some translational bar mechanisms for deployable structures are proposed. More results on the geometric design, dimensional synthesis and simulation of these scissor structural mechanisms will be presented in future work.
2. General geometric design aspects of a deployable scissor structure

2.1. General deployability condition

The most important part of the design process of a deployable scissor structure is its geometric design. It means that not only the choosing phase of a desired geometric shape is important, but also the selection of the type of basic unit. There are some geometric conditions, also called also deployability constraints, for foldability of planar scissor structural mechanisms using translational or polar units. One of these conditions is that the structure is capable to be stored in a compact shape (Figure 2), [11]. As we can see in Figure 2.a, in the compact shape of the structure, all the points $B_1$, $C_1$, $A_1$, $B_2$, $C_2$, $A_2$, $B_3$, $C_3$ will theoretically be collinear. The distance between $B_1$ and $C_1$ can be written using the cosine rule [11]:

$$a_i^2 + b_i^2 - 2a_i b_i \cos \theta_i = a_{i+1}^2 + b_{i+1}^2 - 2a_{i+1} b_{i+1} \cos \theta_{i+1}.$$

(1)

Figure 2. Deployability condition for scissor units.

In the compact shape $\theta_i = \theta_{i+1} = \pi$ and equation (1) become:

$$a_i + b_i = a_{i+1} + b_{i+1}.$$

(2)

Equation (2) was derived by Escrig [12], [13], and according to that the sum of the lengths of bars on both sides of the unit line should be equal. Unfortunately, this equation can be only applied to translational and polar units, which are composed of straight bars, but not to angulated units.
2.2. Translational scissor units

Rectilinear scissor structural mechanisms are consisting of scissor units with straight bars and they can only translate without any rotation. In order to meet this condition, all the unit lines must be parallel to each other before, during and after the deployment process [11]. According to the bar lengths and the location of the revolute joint of the scissor unit, there are various types of rectilinear scissor structural mechanisms. The first type is consisting of scissor units with identical bars and the revolute joint located at the midpoints of these bars (Figure 3) and it constitutes a perfect planar surface. This scissor structural mechanism is called lazy tong [3] and its condition can be formulated as:

\[ a_{i-1} = b_{i-1} = a_i = b_i = a_{i+1} = b_{i+1} = \cdots = a_n = b_n = l. \]  

(3)

![Figure 3. Rectilinear scissor structural mechanism with identical bars and scissor revolute joints located at the midpoints of bars.](image1)

The second type of rectilinear scissor structural mechanisms is consisting of scissor units with different bar lengths, but the scissor revolute joints are located at the midpoints of the bars. In this case, the system still translates and unit lines remain parallel during the deployment process (Figure 4) and the conditions for this type can be written as:

![Figure 4. Rectilinear scissor structural mechanism with different bar lengths and scissor revolute joints located at the midpoints of bars.](image2)
$$a_{i-1} = b_i = a_{i+1} = b_{i+2} = \cdots = a_n = b_{n+1} = \ell_1$$
$$b_{i-1} = a_i = b_{i+1} = a_{i+2} = \cdots = b_n = a_{n+1} = \ell_2.$$ (4)

The third type of rectilinear scissor structural mechanisms is obtained by combining the geometric principles of the first and second types (Figure 5). In this case, bar lengths of one scissor unit are different and the scissor revolute joint is located at the midpoints of the bars (as in the case of the second type). The mechanism translates as the one described for the first type, but its construction method is completely different from that of the first two types. It is because the basic scissor unit is not repeated through the scissor structural mechanism. The current unit is connected to the previous one by reversing that unit. But, still, the mechanism forms a planar surface because all unit lines are parallel to each other before, during and after the deployment process. Its condition is that:

$$a_{i-1} = b_i = a_{i+2} = b_{i+3} = a_{i+4} = b_{i+5} = \ell_1$$
$$b_{i-1} = a_i = b_{i+2} = a_{i+3} = b_{i+4} = a_{i+5} = \ell_2.$$ (5)

![Figure 5](image)

**Figure 5.** Rectilinear scissor structural mechanism with different bar lengths and scissor revolute joints located at the midpoints of bars.

By connecting scissor units with arbitrary bar lengths and the scissor revolute joint eccentrically placed, we get the fourth type of scissor structural mechanism (Figure 6).

![Figure 6](image)

**Figure 6.** Rectilinear scissor structural mechanism with arbitrary bar lengths and scissor revolute joints eccentrically placed.
In this case, each unit has different bar lengths and its scissor revolute joint is located randomly. However, the unit lines are still parallel and the mechanism translates without rotation. The condition for the fourth type of scissor structural mechanism can be written as:

\[ a_{i-1} = b_{i-1} = l_0, \quad a_i = a_{i+1} = b_i = b_{i+1} = l_i, \ldots, a_n = a_{n+1} = b_n = b_{n+1} = l_n. \]  

(6)

The rectilinear scissor structure mechanisms presented before may be used for portable furniture elements (foldable chairs or tables) and for deployable structures (tents and canopies). Because these scissor structures are very simple mechanisms, they can easily be adapted to large-scale structures used for architecture applications [11].

3. Proposed translational bar mechanisms for deployable structures

One of the most important goals of the research on deployable structures based on bar mechanisms is to find mechanism structures that can fold the structure into a compact bundle but also deploy it to a maximum expanded configuration, with high rigidity, too. In order to do that, one of the solutions is to find optimum mechanism structure, with a minimum number of actuators necessary to fold/unfold it. Then, the dimensional synthesis problem of the mechanism has to be solved.

A first translational bar mechanism for deployable structures (Figure 10) proposed here is based on a modified translational scissor unit, which consist of a variable location of the revolute joint (scissor hinge), as shown in Figure 7.

![Figure 7](image)

**Figure 7.** Modified translational scissor unit with variable location of the rotational joint: a) totally deployed configuration; b) partially deployed configuration; c) folded (compact) configuration.

The advantage of the modified translational unit, comparing to the classic one (Figure 1.a) is that the vertically distance between the revolute joints of the two bars with the ground remain constant during the deployment/folding process (Figure 8). Thanks to that, the modified translational scissor unit may be used as a driving unit for rectilinear scissor structural mechanisms, which may consist a wall of a deployable house, for example (the wall height will remain constant during the folding and deployment process).

The driving unit based on the modified translational scissor may use two actuators (placed on A and E joints, Figure 9.a), when it consists in a RPRPR (rotational-prismatic-rotational-prismatic-rotational) five bar mechanism, or a single actuator (placed on A joint, Figure 9.b and Figure 9.c), when it consists in a RPRPRPR or a more complex bar mechanism.

These driving units can be used in building different rectilinear scissor structural mechanisms, which can consist in deployable structures. The first mechanism based on the modified translational scissor, is shown in Figure 10 and Figure 11. Based on the mechanism structure, it can have one driving link (Figure 10.a and Figure 10.b) or two driving links (Figure 10.c).
Figure 8. Modified translational scissor unit with variable location of the rotational joint vs. classic translational scissor unit, as driving unit of rectilinear scissor structural mechanism: a) modified unit in two different deployed configurations; b) classic unit in two different deployed configurations.

Figure 9. Actuators number of the driving unit based on translational scissor unit with variable location of the rotational joint: a) with two actuators; b) with one actuator; c) with one actuator and locked in a deployed configuration.
Figure 10. Rectilinear scissor structural mechanism based on the modified translational scissor unit: a) with one actuator and locked in a deployed configuration; b) with one actuator; c) with two actuators.

Figure 11. Rectilinear scissor structural mechanism with one actuator and locked in a deployed configuration, based on the modified translational scissor unit: a) compact configuration; b) partially deployed configuration; c) totally deployed configuration.
The mechanism shown in Figure 10.a is a twelve bar mechanism and it has less prismatic joints comparing to the mechanisms shown in Figure 10.b and Figure 10.c and it is supposed that its reliability is better comparing to the two others. It can have a very compact folded configuration (Figure 11.a) and, also, may be locked in a deployed configuration (see Figure 11.c). For these reasons, this mechanism will be considered for further research.

Comparing to a similar folding mechanism (having rotary joints only) developed by Ten Fold Engineering company and discussed in [7], the mechanism shown in Figure 11 has a bigger rigidity, thanks to the prismatic joints, even if this one is more complex in terms of practical achievement.

To find the degree of freedom of the mechanism, Grubler formula may be used,

\[ F = 3(n - 1) - 2g_1, \]  
(7)

where \( n \) is the number of links (including the frame) and \( g_1 \) is the number of single revolute joints.

According to this formula, for \( n = 12 \) and \( g_1 = 16 \), we will get:

\[ F = 3(12 - 1) - 2 \cdot 16 = 1. \]  
(8)

It means that a single actuator is needed to actuate the mechanism. This actuator is suitable to be placed to \( A \) joint (the link 1 will be the driver link).

If we consider \( \theta_1 \) the rotational angle of the driver link, the area \( A_1 \) of a wall formed by this mechanism in the deployed configuration will be:

\[ A_1 = 2 \cdot l_{AE} \cdot l_{AE} \cdot \sin \theta_1. \]  
(9)

This mechanism could be used to build a mobile house or a road barrier, for example. Further research should be oriented on the dimensional synthesis of the mechanism. As preliminary conditions, next relations should exist:

\[ l_{AE} = l_{OP}; \quad l_{AI} = l_{EG} = l_{GP} = l_{IO}; \quad l_{FG} = l_{IN}; \quad l_{FI} = l_{GN}. \]  
(10)

The second mechanism based on the modified translational scissor is shown in Figure 12 and Figure 13. Based on the mechanism structure, it can also have one driving link (Figure 12.a, Figure 12.b and Figure 12.c) or two driving links (Figure 12.d).

Based on the same considerations as before, the mechanism shown in Figure 12.a and Figure 13 will be considered for further research. To find the degree of freedom of the mechanism, Grubler formula may also be used.

According to this formula, for \( n = 14 \) and \( g_1 = 19 \), we will get:

\[ F = 3(14 - 1) - 2 \cdot 19 = 1. \]  
(11)

It means that a single actuator is needed to actuate this mechanism, too. This actuator is suitable to be placed to \( A \) joint.

If we consider \( \theta_1 \) the rotational angle of the driver link, the area \( A_2 \) of a wall formed by this mechanism in the deployed configuration will be:

\[ A_2 = l_{AE} \left[ 2 \cdot l_{AI} \cdot \sin \theta_1 + l_{FL} \cdot \cos \left( \frac{\pi - \beta}{2} \right) \right]. \]  
(12)

As we see in equation (12), for similar dimensions used for the mechanism shown in Figure 11, this mechanism allow building walls with bigger horizontal dimension, which has as effect a bigger area of the wall surface. Further research should also be oriented on the dimensional synthesis of the mechanism. As preliminary conditions, next relations should exist:

\[ l_{AE} = l_{ST}; \quad l_{AI} = l_{EG} = l_{KT} = l_{LS}; \quad l_{FL} = l_{IK}; \quad l_{FH} = l_{LN}; \quad l_{IH} = l_{KN}. \]  
(13)
Figure 12. The second rectilinear scissor structural mechanism based on the modified translational scissor unit: a) and b) with one actuator and locked in a deployed configuration; c) with one actuator; c) with two actuators.
Figure 13. The second rectilinear scissor structural mechanism with one actuator and locked in a deployed configuration, based on the modified translational scissor unit: a) partially deployed configuration; b) totally deployed configuration.

4. Conclusion
Deployable structures can change their shape and volume in order to dynamically answering to changing needs. 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 general geometric design aspects of deployable bar structures have been discussed and some translational bar mechanisms for deployable structures have been proposed. More information on the geometric design, dimensional synthesis and simulation of these scissor structural mechanisms will be the subjects of near future research.

5. References
[1] De Temmerman N, Alegria Mira L, Vergauwen A, Hendrickx H and De Wilde W P 2012 Transformable structures in architectural engineering High Performance Structures and Materials VI(124) pp 457-468.
[2] Bouten S 2015 Transformable Structures and Their Architectural Application Master’s dissertation Ghent University.
[3] De Temmerman, N 2007 Design and analysis of deployable bar structures for mobile architectural applications PhD dissertation, Vrije Universiteit Brussel.
[4] Doroftei I and Doroftei I A 2014 Deployable Structures for Architectural Applications—A Short Review Applied Mechanics and Materials 658 pp 233-240.
[5] Doroftei I A, Bujoreanu C and Doroftei I 2018 An overview on the applications of mechanisms in architecture. Part I: bar structures IOP Conference Series: Materials Science and Engineering 444 pp 052018.
[6] Doroftei I A, Bujoreanu C and Doroftei I 2018 An overview on the applications of mechanisms in architecture. Part II: foldable plate structures IOP Conference Series: Materials Science and Engineering 444 pp 052019.
[7] Doroftei I A, Bujoreanu C, and Doroftei I 2019 Structural and kinematic aspects of some bar mechanisms for deployable structures IOP Conference Series: Materials Science and Engineering 591(1) pp 012077
[8] Asefi M and Kronenburg R 2006 An Architectural Evaluation of Transformable Roof Structures Proceedings of The International Conference On Adaptable Building Structures pp 85-90.
[9] http://urbanizehub.com/ten-fold-mobile-house-future/
[10] https://www.tenfoldengineering.com/
[11] Maden F, Korkmaz K and Akgün Y 2011 A review of planar scissor structural mechanisms: geometric principles and design methods Architectural Science Review 54 pp 246-257
[12] Escrig F 1985 Expendable space structures *International Journal of Space Structures* **1**(2) pp 79–91

[13] Escrig F. and Valcarcel J 1986 Analysis of expandable space bar structures in K. Heki (ed), *Proceedings of IASS Symposium on Shells, Membranes, and Space Frames* vol. 3 Osaka, Elsevier Science Publishers pp 269–276

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