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An overview on the applications of mechanisms in architecture. Part I: bar structures

I A Doroftei¹, C Bujoreanu², I Doroftei³,*,

¹,²,³Mechanical Engineering, Mechatronics and Robotics Department, “Gheorghe Asachi” Technical University of Iasi, Romania

*E-mail: idorofte@mail.tuiasi.ro

Abstract. Transformable structures in architecture have the ability to change morphology and readjust in response to varying conditions and needs that can include changing environment and climatic conditions, different functional requirements and emergency situations. Depending on how the transformation is carried out, transformable structures can be deployable or demountable, as a kit-parts system. Deployable structures can also be classified in four main groups: spatial bar structures consisting of hinged bars; foldable plate structures consisting of hinged plates; tensegrity structures; and membrane structures. In this paper, a review on the deployable structures based on rigid bar mechanisms will be performed.

1. Introduction

Transformable structures in architecture can adapt their shape or function offering dynamic answers to modern problems, such as deployment for creating temporary spaces, responsiveness to climatic influences and change of use, in a society which embraces the concept of sustainable design [1], [2]. Based on how this transformation is realised, two groups of transformable structures can be distinguished: the transformation of the structure is primarily done by either incorporating a kinematic mechanism (mechanism that enables the structure to deploy from a compact configuration to a larger, expanded state in which it can fulfil its architectural function) or by designing the structure as a demountable kit-of-parts system (with dry, reversible connections between the constitutive components, enabling the structure for disassembly, whereby all components can be reconfigured, replaced or reused) [2]. In our review we will focus our attention on the first category, which are also called deployable structures.

According to their structural system, deployable structures can be classified in four main groups: spatial bar structures consisting of hinged bars; foldable plate structures consisting of hinged plates; tensegrity structures; and membrane structures. Because of their wide applicability in the field of mobile architecture, their high degree of deployability and a reliable deployment, two sub-categories are studied in greater detail: bar structures, generally, and pantograph (scissor-like) structures, especially, and foldable plate structures, respectively [3], [4].

In this paper, an overview on the deployable structures based on rigid bar mechanisms will be performed.

2. Pantographs (scissor-like elements) based structures

Scissor structures are lattice expandable structures consisting of bars, which are connected through revolute joints, allowing them to be folded into a compact bundle. Although many impressive
architectural applications for these mechanisms have been proposed till now, due to the mechanical complexity of their systems during the folding and deployment process, few of them have been constructed at full-scale [5].

Scissor-Like Elements (SLEs), sometimes denominated as scissor units, pantographs or Nuremberg mechanisms are the most widely used mechanism type in larger-scale structures, thanks to their reliable synchronous movement, their compactness and their economic use of material. A basic SLE is formed by bars that are interconnected along their length by one or more revolute joints – the Intermediate hinges - allowing one free revolution in their (common) plane.

They consist of two straight bars connected through a revolute joint, called the intermediate hinge, allowing the bars to pivot about an axis perpendicular to their common plane. By interconnecting such SLE’s at their end nodes using revolute joints, a two-dimensional transformable linkage is formed. Based on variations in the basic SLE, the shape of the bars and placement of the intermediate hinges, three general subgroups can be identified: translational, polar, and angulated units.

2.1 Translational units

The unit lines are imaginary lines that connect the upper and lower nodes of a scissor unit. In the case of a translational unit these lines always stay parallel one to another. A translational scissor unit can be: flat (figure 1.a) or curved (figure 1.b) unit.

![Figure 1. Translational units: a) flat unit; b) curved unit [3].](image)

The flat unit is the simplest translational unit having identical bars. When these units are linked, a well-known transformable single-degree-of-freedom mechanism is formed, called a lazy-tong (figure 2.2). By varying the deployment angle a linkage is transformed from its most compact configuration (a compact bundle, figure 2.a) to its fully deployed position (2.b).

![Figure 2. Lazy-tong scissor mechanism: a) undeployed position; b) deployed position [3].](image)

The curved unit, named such because it is commonly used for curved structures, has bars of different length. Even though the unit lines of translational elements by definition stay parallel, a curved grid can be formed by varying the point on the bars that the intermediate hinge is connect (figure 3). It should be noted that the compacted bundle retains the original height of the completely deployed mechanism, making it less than ideal for the use in transportable structures.
2.1.1 Translational flat structures
To form spatial structures of SLEs, a multitude of options exist, starting by defining the shape of the formed array. Figure 4 shows the results of choosing a square grid array formed by connecting the edge nodes to each other at straight angles. This results in an unstable structure in the projected-plane, needing additional bracing for the square shapes to make it function optimally in static state [2].

Figure 3. Curved scissor mechanism: a) undeployed position; b) deployed position [3].

Figure 4. Square grid array [2], [6].

Figure 5. Hexa-triangular grid array [2], [6].
The hexagonal grid is made up of equilateral triangles. It offers in plane stability and greater strength, but the compact ability is low (figure 5).

When the planes of each of the lazy-tongs no longer cut each other perpendicularly, but obliquely, more complex framework shapes are derived. In this case, the intermediate hinges of two or more SLEs intersect, and fewer bars meet at the end nodes. An example of a triangular oblique grid is shown in figure 6. The intermediate hinge (marked in orange) has to be specifically designed for the three bars crossing each other.

![Figure 6. Oblique triangular grid array [2], [6].](image)

The perpendicular type of grids can be formed as a collection of prismatic elements (figure 7), and the oblique grids from the collection of anti-prismatic elements (figure 8) [7].

![Figure 7. Prismatic modules make up straight grid array [2].](image)

![Figure 8. Anti-prismatic modules make up oblique grid array [2].](image)

### 2.1.2 Translational multi-layered structures

By increasing the number of intermediate hinges for each bar, multi-layered systems can be made from SLEs. Because the number of fixed points and the structural height per SLE are increased, the
whole will be subject to a smaller maximal bending moment. But this has as a cost more material and lesser compactness. That is why a multi-layered structural system is rarely used for deployable structures where a compact bundle is the key. However, the rhombic shapes (see figure 9) can form the basis of elaborate spatial structures, such as ruled surfaces.

![Figure 9. Multi-layered translational scissor mechanism: a) undeployed position; b) deployed position. [2].](image)

**2.2 Polar units**

If in the flat translational unit the intermediate hinge is moved away from the center by a certain eccentricity, the unit lines will move from being parallel to having a polar angle $\gamma$ between them. This angle changes his value from zero (at the completely - theoretical - folded position) to its maximum value (at the fully-deployed position). The maximum value of the angle is proportional to the eccentricity. In this way, a polar unit is formed, which has unequal semi-bars $a$ and $b$ as is shown in figure 10 [3]. It is the eccentricity of the intermediate hinge which generates curvature during deployment. By linking these polar SLEs together, a polar scissor is formed (figure 11).

![Figure 10. Polar unit [3].](image)

**2.2.1 Polar free-form structures**

By varying the size of the bars within each of the SLEs, we may obtain more randomly curved shapes. If the condition of complete foldability (and thus, maximum compactness) is to be achieved, the sum of the partial-bar lengths of two adjoining elements must be equal. This is defined in an equation first given by [8], which is referred as the compactability equation (figure 12):

![Equation figure](image)
Figure 11. Polar scissor mechanism: a) undeployed position; b) deployed position. [2].

Figure 12. Random bar length scissor mechanism: a) undeployed position; b) deployed position [2].

\[ l_i + k_i = l_{i+1} + k_{i+1} \]  \hspace{1cm} (1)

2.2.2 Polar single curved structures
If the arches formed by polar SLEs are repeated in a linear fashion and they are connected by translational SLEs, cylindrical structures can be formed (barrel vaults). They have been first researched by Escrig F. [7], [9] (see figure 13) and, later, geometrically and structurally investigated by Langbecker T. [10] (figure 14).

Figure 13. Barrel vault researched by Escrig F. [7], [9].
2.2.3 Polar double curved structures

By connecting polar units in multiple directions, double curved spatial structures (such as domes) can be obtained. In [8] different ways to form dome-shapes from polar units have been demonstrated. The domes shown in figure 15 and figure 16 can be formed using square and triangular grid, respectively. The advantage of these regular grids is the modularity of the polar units [2].

![Figure 14. Barrel vault investigated by Langbecker T. [10].](image)

![Figure 15. Dome from square modules: a) top view; b) side elevation [8].](image)

![Figure 16. Dome from triangular modules: a) top view; b) side elevation [8].](image)
These domes (formed by these regular grids) deviate from a pure spherical form. To approximate a more constant curvature, the edges of the polygons from any geodesic dome can be replaced by modular polar elements. An example is the geodesic dome shown in figure 17.

![Image of geodesic dome](image17a.png)

**Figure 17.** Geodezic dome from triangular modules: a) top view; b) side elevation [8].

A last category of structures mentioned in [8] are the domes generated from a rhombic pattern (called lamella domes). They do not any incompatibilities, and are easily designed (figure 18).

![Image of lamella dome](image18a.png)

**Figure 18.** Lamella dome with identical polar units: a) top view; b) side elevation [8].

Anticlastic surfaces such as hyperbolic paraboloids can also be made by flipping the side of the eccentricity of the intermediate hinge, or keeping a central hinge and using side-by-side compatible translational elements. A geometric and kinematic analysis of single curve and double curve structures has been performed in [10]. The author has used translational units to design several models of positive (figure 19) and negative (figure 20) curvature structures.

![Image of positive curvature structure](image19a.png)

**Figure 19.** Positive curvature structure with translational units in two deployment stages [10].
Figure 20. Negative curvature structure with translational units in two deployment stages [10].

2.3 Angulated units
Angulated elements (figure 21) consist of two rigidly connected semi-bars of length $a$ that form a central kink of amplitude $\beta$ [11]. They are also denoted as hoberman’s units. The main advantage of these units is that, as opposed to polar units, they subtend a constant angle $\gamma$ during deployment. For this reason, the bar geometry has to be such that $\alpha = \gamma/2$ (see figure 21). Angulated units can be used for radially deploying closed loop structures, capable of retracting to their own perimeter, which is impossible to accomplish with translational or polar units. In figure 22 a circular mechanism with angulated units is shown.

Figure 21. Angulated unit [3].

Figure 22. A radially deployable mechanism consisting of angulated units in three stages of the deployment [3].

The previous concept of angulated unit has been extended in [12] and [13] to multi-angulated units, which are units with more than one kink angle, as we can be seen in figure 23. The deployment a
structure composed of two layers of twelve identical multi-angulated units with three kinks is shown in figure 24.

![Figure 23. Multi-angulated unit [3].](image)

![Figure 24. A radially deployable mechanism consisting of multi-angulated units in three stages of the deployment [3].](image)

This concept was extended by the same authors to include generalised angulated elements which allow non-circular structures to be generated (patterns of either rhombuses of parallelograms).

In [14] and [15] was shown that, by providing this type of structure with cover elements, it is possible to employ them as a retractable roof (figure 25). The cover elements provide both in the open and closed position a gap-free, weatherproof surface.

![Figure 25. Multi-angulated structure with cover elements in an intermediate deployment position [3].](image)
By changing both their total length and kink angle, a myriad of different anticlastic shapes can be created using angulated units. In [16] the conversion of any arbitrary continuous surface to a scissor mechanism is described geometrically (figure 26).

![Figure 26. Expansion of anticlastic geometry from angulated units [16].](image)

### 2.4 Architectural applications

Although many impressive architectural applications for these mechanisms have been proposed till now, due to the mechanical complexity of their systems during the folding and deployment process, few of them have been constructed at full-scale. The examples used in this section consist only of real-life structures or models that were used to materialize the discussed geometries.

Spanish architect Emilio Perez Piñero [17] and [18] is considered the pioneer for using of scissor mechanism to make deployable structures. An example is his moveable theatre (figure 27), consisting of rigid bars and wire cables, which would become tensioned to provide the structure with the necessary stabilisation. The links remain unstressed in the compact configuration and the deployed state, except for their own dead weight. Also, the structure is stress-free during the deployment, working like a mechanism.

![Figure 27. Emilio Pérez Piñero and his design for a deployable theatre, in the compact and deployed configurations [19].](image)

Inspired by the work of Pérez Piñero, another Spanish architect and engineer, Escrig F., carried on his legacy to the academic world. Together with Sánchez J. and Valcárcel J. he not only geometrically and structurally analyzed SLE systems, but they realized many new pantographic typologies. One of their designs is the deployable cover of the San Pablo swimming pool in Seville, based on a polar quadrangular grid (see figure 28). Escrig and Sánchez also made use of a curved grid, which allows for large spans to be covered with efficient material use, but goes at the cost of the compactness of the elements and thus requires large-scale transportation (figure 29).

The inventor of angulated units, Hoberman C. used his patent to build several pantographic structures at sculptural-architectural scale, all of them radially deployable, either compacting to a
central position (see the geodesic dome in figure 30), or along their circumference (see Iris dome in figure 31).

**Figure 28.** Deployable swimming pool from rectangular modules [20].

**Figure 29.** Deployable swimming pool from multi-layered curved bars [20].

**Figure 30.** Expansion of triangulated geodesic dome from angulated units [2].
Hoberman exhibited a model for a dome, which was continuously retracted by an actuator, at the Expo 2000 in Hannover (figure 32). In 2002 he designed and built a semi-circular retractable mechanical curtain for ceremonial purposes at the Winter Olympics in Salt Lake City (figure 33).

A system based on the angulated mechanism shown in figure 24 was proposed by Kassabian P. E. [22] to form a retractable roof by adding plates to the bar structure. Later, Jensen F. V. and Buhl T. [23] improved this system by using only the plates as rigid elements, instead of a combination of multi-angulated elements and cover plates. A stadium designed by Lake Associates used this system. In figure 34 is shown a retractable dome with plates having fixed points of rotation, the plates providing a gap-free surface in the open and closed position. A retractable dome with modified boundaries is shown in figure 35.
Pérez Piñero E used another method of covering pantographic systems using separate foldable plate elements that join in completely deployed state, in the design of glazing panels for the Dali museum in 1970 and later improved upon by Valcárcel V. P. [20] (see figure 36).

De Temmerman N. [3] combined the know-how of pantographic systems and tensile substructures to design quickly deployable structures in which the fabric works actively on a structural level (figure 37 demonstrates some new tent typologies designed by him).

Alegria Mira L. [24] bridged the gap between translational-, polar- and angulated units by designing a Universal Scissor Component. The basic Universal Scissor Component, together with an icosahedral variation, are shown in figure 38.
Figure 37. New tent typologies: a) textile substructure in barrel vault from variable polar units; b) textile structure attached to central mast from angulated units [3].

Figure 38. Universal Scissor Component (USC) and icosahedral variation [24]

A last group that can be shaped by the use of SLEs is that of the ruled surfaces. A one-sheet hyperboloid type structure has been proposed by Escrig F. and Sánchez J. [20] (see figure 39).

Figure 39. Deployable hyperboloid from multi-layered grid [20].

Hyperbolic paraboloids [25] can also be formed by using multi-layered scissor units. Figure 40 demonstrated the possible use of six independently mobile saddle-surfaces used for shading in a public space.
3. Ten Fold Engineering structures

Ten Fold Engineering is an UK-based company, which has developed a series of modular, self-deploying structures that can be instantly unfolded without the need for builders, cranes or foundations.

The Ten Fold initiative innovates by creating and designing various relocatable buildings and structures. Its enormous self-deploy mechanism generates various combinations of space and facilities and it works by using a hand-held battery-powered drill. Different designs have already been imagined in order to meet the needs and desires of the customers, but the process is fully reversible, whenever you feel the need for a change of scenery [26].

Ten Fold’s family of counterbalanced folding linkages are designed to bring mobility, speed, ease and reliability to the products [27]. Based on the main folding mechanism (figure 41), many other folding linkages are proposed (figures 42-45). Their lever-based patent is simple, but it underpins an amazing variety of extremely useful mechanical movements that confer advantage on the products that use it.

The structure is ultimately easy to run and to maintain, it is fully equipped and powered up from the very beginning and it is also stackable and connectable in order to form larger structures. The shelters that are unfolded into the final structure are easy to operate, rigid, strong and sustainable, while the entire building is easily adaptable to the environment.

The business opportunities and the applications of this system are virtually unlimited. Besides your regular home (you can see an example in figure 46), the Ten Fold mechanism can offer bridges (figure 47), huts (figure 48), solar panels (figure 49), lorries (figure 50), antennas, stairways, larger halls (figure 51) or road barriers (figure 52), and so on.

Mobile shelters for film crews, festivals, sports events or leisure could also definitely be additional uses. Besides representing an entirely innovative concept for mobile housing, it also represents an opportunity for mobile hotels (see figure 53) or portable construction structures, providing the owners with increased safety and agility.

Figure 40. Adaptable hypar surfaces from multi-layered grid [25].

Figure 41. The main folding mechanism patented by Ten Fold Engineering, in compact, partially deployed and totally deployed configurations [27].
Figure 42. Folding mechanisms family, in deployed configuration [27].

Figure 43. Folding mechanisms family, in deployed configuration (continued) [27].

Figure 44. Folding mechanisms family, in deployed configuration (continued) [27].
Figure 45. Folding mechanisms family, in deployed configuration (continued) [27].

Figure 46. Mobile house based on Ten Fold technology [27].

Figure 47. Mobile folding bridge based on Ten Fold technology [27].
Figure 48. Mobile deployable cabin box based on Ten Fold technology [27].

Figure 49. Ten Fold self-deploying solar panel [27].

Figure 50. Ten Fold falling off a lorry [27].
Figure 51. Ten Fold self-deploying stadium tribune [27].

Figure 52. Ten Fold road barrier [27].

Figure 53. Mobile hotel formed by modules based on Ten Fold technology [27].
4. Conclusion
Transformable structures in architecture can adapt their shape or function offering dynamic answers to modern problems, such as deployment for creating temporary spaces, responsiveness to climatic influences and change of use, in a society which embraces the concept of sustainable design. Based on how this transformation is realised, two groups of transformable structures exist: the transformation of the structure is primarily done by either incorporating a kinematic mechanism, when the structure is called deployable, or by designing the structure as a demontable kit-of-parts system, when the structure can be disassembled and all the components can be reconfigured, replaced or re-used. According to their structural system, deployable structures can also be classified in four main groups: spatial bar structures consisting of hinged bars; foldable plate structures consisting of hinged plates; tensegrity structures; and membrane structures. Because of their wide applicability in the field of mobile architecture, their high degree of deployability and a reliable deployment, two sub-categories are studied in greater detail: bar structures and foldable plate structures, respectively. In this paper, a review on the deployable structures based on rigid bar mechanisms has been performed.

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 VII(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] 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.
[6] Escrig Pallárés F 1993 Geometría de las estructuras desplegables de aspas Arquitectura transformable pp. 93-125, Escuela Técnica Superior de Arquitectura.
[7] Escrig Pallares F and Pérez Valcárcel J 1986 Introducción a la geometría de las estructuras espaciales desplegables de barras Boletín Académico Escuela Técnica Superior de Arquitectura, Coruña 3 pp 48 -57.
[8] Escrig Palláres F and Valcárcel V P 1988 Expandable curved space bar structures IETCC, Escuela Técnica Superior de Arquitectura, Sevilla.
[9] Escrig Palláres F, Sanchez J, and Pérez Valcarcel J 1996 Two way deployable spherical grids International Journal of Space Structures 11(1-2) pp 257-274.
[10] Langbecker T and Albermani F 2001 Kinematic and non-linear analysis of foldable barrel vaults Engineering Structures 23(2) pp 158-171.
[11] Hoberman C 1990 Reversibly expandable doubly-curved truss structure U.S. Patent No 4,942,700.
[12] You Z and Pellegrino S 1996 New solutions for foldable roof structures WIT Transactions on The Built Environment 24.
[13] You Z and Pellegrino S 1997 Foldable bar structures International Journal of Solids and Structures 34 pp 1825-1847.
[14] Pellegrino S, Kassabian P E and You Z 1997 Retractable structures based on multi-angulated elements Proceedings International Colloquium on Structural Morphology: Towards the New Millennium pp 92-99.
[15] Kassabian P E, You Z and Pellegrino S 1999 Retractable roof structures Proceedings of the Institution of Civil Engineers-Structures and Buildings 134(1) pp 45-56.
[16] Roovers K, Mira L A and De Temmerman N 2013 From surface to scissor structure. Proceedings of the First Conference Transformables, Seville, Editorial Starbooks, Seville,
Spain Vol. 2.

[17] Pinero E P 1961 A reticular movable theatre The Architects’ Journal 134 pp 299.
[18] Pinero E P 1962 Expandable space framing Progressive Architecture 12 pp.154-155.
[19] Robbin T and Wrede S 1996 Engineering a new architecture pp. 25-37. New Haven: Yale University Press.
[20] Eserig Pallarès F 2012 Modular, ligero, transformable. Un paseo por la arquitectura ligera móvil. Universidad de Sevilla.
[21] http://www.hoberman.com.
[22] Kassabian P E 1997 Investigation into a type of deployable roof structure. Final year project, University of Cambridge, Engineering Department.
[23] Jensen F V 2005 Concepts for retractable roof structures PhD dissertation, University of Cambridge.
[24] Alegria Mira L 2010 Design and Analysis of a Universal Scissor Component for Mobile architectural Applications Master’s thesis, Free University of Brussels, Faculty of Engineering.
[25] Maden F and Teuffel P 2013 Development of transformable anticlastic structures for temporary architecture Proceedings of the First Conference on Transformables pp. 251-256 Starbooks.
[26] http://urbanizehub.com/ten-fold-mobile-house-future/
[27] https://www.tenfoldengineering.com/