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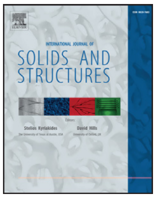

Deployable scissor grids consisting of translational units

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ABSTRACT

Deployable scissor grids can quickly transform between different configurations, making them particularly fit for mobile and temporary applications. Their ability to deploy typically comes along with a high design complexity and a limited freedom of shape. However, we've found that by using so-called translational scissor units it is possible to generate a myriad of curved spatial grids through a design process that can be simplified into a set of two-dimensional problems. The resulting scissor grids are mechanisms with a smooth and stress-free deployment behaviour. Due to their qualities they have formed the topic of previous research, but nevertheless we've noticed that a large part of their design potential has remained unexplored. By for the first time unravelling the general principles that govern the motion and shape of this scissor grid type, we've managed to reveal various new and interesting design possibilities. This paper presents these new proposals together with the existing ones in order to form a comprehensive overview of the geometric potential and kinematic behaviour of deployable scissor grids consisting of translational scissor units. It covers the mathematical concepts needed to analyse and generate this scissor grid type, ranging from a single scissor unit to large assemblies. In addition, the paper introduces multiple methods to include joints in the line models without modifying their deployment behaviour. This work therefore broadens the design space and compiles the main characteristics of this scissor grid type in order to improve their accessibility and applicability in design.

1. Introduction

Deployable structures can rapidly transform in shape and volume in order to answer to changing needs. Scissor grids are a type of deployable structure consisting of articulated bars (Fig. 1). They have enjoyed much attention in past research for their ability to achieve large volume expansions through an easy to control deployment process. This feature makes them broadly applicable in architecture, engineering and design. Applications include mobile and temporary structures for recreational purposes or disaster relief, portable furniture and panels, deployable solar arrays or antennae for outer space, and adaptable roof and shading systems in static constructions (Alegria Mira et al., 2014; Gantes, 2001; Bernhardt et al., 2008; Buhl et al., 2004).

A deployable scissor grid can be considered as a kinematic linkage of *scissor units*, also known as pantographs or scissor-like elements (SLEs). A scissor unit consists of a pair of bars crosswise interconnected by a revolute joint, allowing a relative rotation about an axis normal to the *unit plane* (i.e. the plane containing the scissor bars). The imaginary lines running through the upper and lower end point at both sides of the unit are called the *unit lines*. Depending on how these lines vary during deployment, different types of scissor units can be distinguished (Fig. 2), each offering a unique range of geometric possibilities and kinematic behaviour. The scissor units considered in this work consist of straight bars and have unit lines that are parallel throughout deployment. They are commonly referred to as translational scissor units. Other scissor grid concepts make use of scissor units with intersecting unit lines (e.g. the polar unit of Fig. 2b) and can even consist of kinked bars (e.g. the angulated unit of Fig. 2c).

Scissor grids are created by interconnecting multiple scissor units at their end points. First, scissor units are combined to form single closed loops, called scissor modules (Fig. 3). Afterwards, multiple scissor modules are combined to form scissor grids. Stacking modules of an equal amount of units gives rise to *single-layer grids*. Well-known examples include the Iris Dome by Hoberman (1991) (Fig. 4a) and the multi-angulated grids by You and Pellegrino (1997b). *Double-layer grids* are formed by tessellating modules along a surface. They exist in a broader variety of shapes and are interesting for their ability to deploy towards compact bundles of bars (Fig. 4b) (Hanaor and Levy, 2001).

When linking scissor units to form scissor modules or grids, various geometric constraints need to be met in order to obtain a deployable assembly. A well-known example is the *deployabil-*

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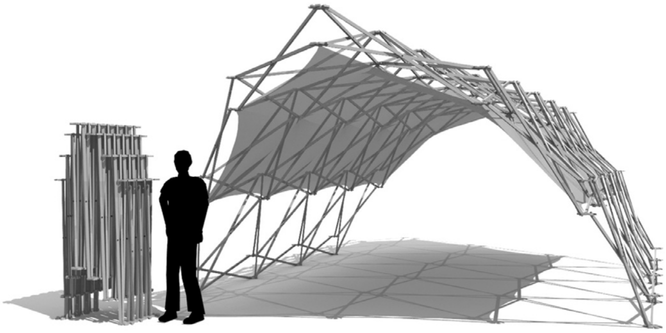

Fig. 1. Singly curved deployable scissor grid in two deployment stages.

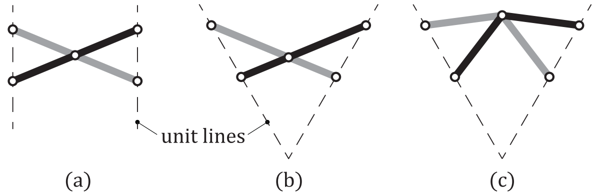

Fig. 2. (a) A translational, (b) polar and (c) angulated scissor unit in its simplest form.

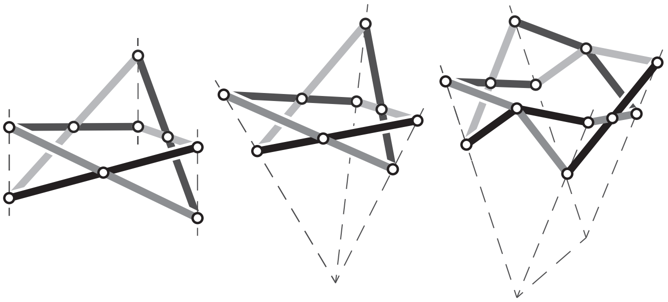

Fig. 3. Examples of scissor modules, i.e. a closed loop of scissor units interconnected side by side.

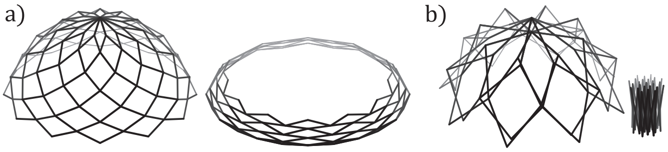

Fig. 4. (a) Single-layer scissor grid based on Hoberman's Iris dome consisting of angulated scissor units; (b) spherical double-layer scissor grid with rhomboid lamella pattern consisting of polar scissor units and based on Escrig (1985).

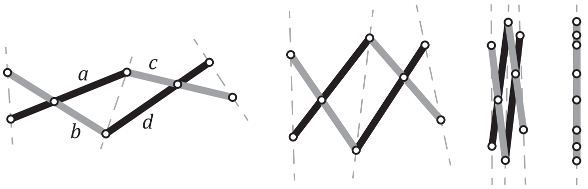

Fig. 5. Illustration of the deployability constraint.

ity constraint, which was proposed by Escrig (1985) and is useful for linkages consisting of scissor units with straight bars. For the two scissor units shown in Fig. 5 which are linked at their ends with *semi-lengths* a, b, c and d (measured between the intermediate hinge point and an end point of a rod) this constraint states:

$$a + b = c + d \tag{1}$$

Hence the sum of semi-lengths coming together in any node of the scissor grid should be equal. It ensures that all scissor units in the linkage simultaneously reach their most compact state and thus the linkage is theoretically reduced to a single line.

The kinematic behaviour of a scissor grid depends on the type of scissor unit used, the geometric constraints that have been applied and the configuration in which the units are assembled. This behaviour is described by the scissor grid's *geometric compatibility* during the two outer deployment stages (e.g. the expanded, functional stage and the compact, stowed configuration) and the transition stage. A scissor grid is geometrically compatible when all its members fit together without deformations. If geometric compatibility exists for all deployment stages, then the grid forms a pure mechanism with a smooth deployment and is referred to as being *foldable*. A foldable scissor grid needs to be locked once erected in order to obtain a rigid load-bearing structure. A contrasting behaviour is displayed by the so-called *bistable* scissor grids, which are compatible in the outer deployment stages and incompatible during deployment (Gantes and Konitopoulou, 2004). These incompatibilities need to be overcome by the actuation forces, inducing strains in the members and resulting in a snap-through deployment behaviour. Bistable grids have the benefit of being self-locking, removing the need for external locking devices after erection when subjected to small external loads. The non-linear effects that accompany this snap-through behaviour however complicate the design process (Gantes, 2001).

Literature mentions a variety of scissor grid concepts. Each concept is formed from a different combination of scissor units using different sets of constraints to ensure a deployable assembly, each time giving rise to a different geometric potential. The geometric design of scissor grids can be straightforward for flat or singly curved shapes with a high degree of symmetry. On the other hand, once three-dimensional grids with double or freeform curvature are desired, the complexity of the design process quickly rises. The resulting low accessibility to generate and explore scissor grid geometry poses a barrier in their design process. However, scissor grids consisting of translational scissor units form an exception to this issue. Indeed, translational units allow constructing spatial double-layer scissor grids with a myriad of shapes and a foldable deployment behaviour, of which the design can be simplified to a set of two-dimensional problems, as all its upper and lower layer nodes are located on parallel lines. A part of the design potential of translational units has previously been demonstrated by Zanardo (1986), Escrig and Valcárcel (1993), Meurant (1993), Pellegrino and You (1993), Sánchez-Cuenca (1996), Langbecker and Albermani (2000) and De Temmerman (2007). Nevertheless, many more design options have remained unexplored.

By for the first time setting up the global mathematical rules to generate scissor grids consisting of translational units, we have managed to uncover its full geometric potential. This paper presents this potential, covering the existing and a range of new scissor grid types. Section 2 discusses the basic geometric and kinematic concepts regarding translational scissor units and the grids that they form. Section 3 will afterwards present the different grid shapes and configurations possible in case the deployment relies entirely on the scissor motion and all other rotations are locked. The possible configurations when additionally allowing the dihedral angles between the planes of adjacent scissor units to vary are presented in Section 4. Section 5 completes this geometric and kinematic overview by presenting multiple methods, including one new method, to incorporate joints with tangible dimensions into these theoretical line models without compromising the kinematic behaviour of the grid.

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