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TRANSFORMING ARCHITECTURE MADE WITH SCISSOR-HINGED DEPLOYABLE STRUCTURES: ALHAMBRA PAVILIONS IN CAMBRIDGE MARKET SQUARE

Esther Rivas-Adrover
University of Cambridge
Department of Architecture, 1-5 Scroope Terrace, Cambridge, CB2 1PX, U.K., e-mail: er460@cam.ac.uk

Abstract

Deployable structures can transform, expand and contract due to their geometric, material and mechanical properties. This technology enables an architecture that can be transportable, mobile, adaptable, rapidly built, reusable and that makes efficient use of space and materials. Scissor-hinged deployable structures, made by units of bars joined by a pivot, can generate large complex lattice structures that can expand and contract. In this field an advancement is made when a new structure is created that can achieve optimal deployment. The 'form generation method of relative ratios for two-bar scissors' formulated by the author of this research can be applied to infinite combinations of lines, and therefore allows for infinite scissor structures to be made with optimum deployment. The aim of this research is to test the allowances of this method, and therefore extend the theory and our knowledge on what can be achieved by this technology.

Keywords

Deployable, transformable, scissor-hinged, Alhambra, Cambridge

1 Introduction

Transforming architecture can be generated by the manipulation and design of deployable structures, which allow a maximum motion, expansion and contraction with the minimum energy input. These structures are light, adaptable and reusable. All these qualities therefore enable deployable structures to fully embrace the concept of sustainability. In an age where society evolves in unpredictable ways, were programmatic possibilities for architecture change rapidly, the emerging field of deployable structures is receiving increased interest as it offers a novel and versatile field for research and innovation for both its theory and practice.

There are many different types of deployable structures [1]. This research will focus on the scissor-hinged type, which is made by units of bars joined by a pivot. These scissor units are then replicated and joined by hinges generating large complex lattice structures that can expand and contract. These structures have a fluid motion and are stable and durable.

Scissor surfaces were pioneered by Pérez Piñero in the 1960s for prototypes as well as applications such as transportable pavilions [2, 3]. Other scissor structures include the swimming pool cover in Seville by Escrig, Valcárcel and Sanchez [4], and the Iris Dome by Hoberman [5]. The author of this manuscript developed the 'form generation method of relative ratios' (FGMORR) [6] which can generate infinite scissor-hinged deployable structures, and it is enunciated in the following chapter. In order to test the allowances of this method, the FGMORR will be here applied here to a combination of lines inspired from the Alhambra in order to make a scissor-hinged pavillion. A pattern from the Alhambra has been chosen because it is part of the culture of the country of origin of the author of this manuscript, and for its great tradition of geometry.

2 Form generation method of relative ratios (FGMORR)

Scissor-hinged surfaces have been made by grids that make triangles or squares [2, 3, 4, 5]. In this field an advancement is made when a new structure is created that can achieve optimal deployment. The 'form generation method of relative ratios' (FGMORR) [6] can be applied to infinite combinations of lines, and therefore allows for infinite scissor structures to be made with optimum deployment.

The FGMORR states: in any given combination of lines, a ratio for a scissor unit (or various ratios for different sizes of scissor units with equal angles of motion) can be found as the relation between segments and sub-segments, with respect to the number of times the ratios are contained in the segments and sub-segments. This method enables for the scissor structure to be made with the minimum number possible of different sizes of bars, as well as achieving an optimal expansion and contraction. In order to apply this method to any given combination of lines, the first step is to identify the smaller sub-segment and to divide it in a series of equal ratios for scissor units; the first ratio is denominated C1. In some situations the smaller sub-segment can be made of one single ratio for one scissor unit, however when the combination of lines has a certain level of complexity, dividing the smaller sub-segment into three ratios (3 x C1) for instance allows a greater manoeuvrability when transferring this initial ratio to the rest of the segments and sub-segments. The smaller sub segments will dictate the mobility of the structure, therefore this first operation is critical. The next step is to transfer this initial ratio C1 throughout the segments and sub-segments of the structure, and by doing this, other ratios for other scissor units can be generated in order to develop a scissor hinged deployable structure with optimal deployment. The FGMORR always seeks to find ratios in which the smaller bars are at least half (and ideally bigger than half) the size of the original bars in the first ratio C1; this will allow an optimal deployment of the structure made with a reasonable ratio of thickness and length of bars. For translational scissor units, the bars of all scissor units from the central node to the end nodes must mirror another scissor unit with equal lengths to guarantee an optimum deployability, by doing this the geometric deployability constrain is guaranteed [Escrig 96]. Another property of the FGMORR is that it is not restricted to any given combination of lines, but one could add (or remove) segments or sub-segments; this is particularly relevant when seeking to reinforce and optimize a structure. The FGMORR has so far been tested with 2-bar translational scissor units, further research will test this method with different types of units such as polar units, and with different number of bars.

3 Diamond origami-scissor hinged structure

This chapter illustrates a new technology created using the FGMORR [6], and it is also an example of a built prototype derived from this geometry theory method. Throughout the history of deployable structures origami and scissor-hinged have been two different types out of many others that exist [1]. Rivas-Adrover made a diamond origami-scissor hinged structure, which signifies the birth of a hybrid new type of deployable structure: origami-scissor hinged [7]. This was achieved by combining two methods: 'origami of thick panels' by Chen, Peng and You [8], and the 'form generation method of relative ratios' (FGMORR) [6] applied to 2-bar scissor-hinged structures. If the FGMORR could indeed be made with infinite combinations of lines, then the segments that determine the geometry of the thick origami could be made into a scissor structure. This is done with two-bar scissor hinged translational units. Where in the diamond thick origami, one triangulated face is made of two panels, in the diamond origami-scissor structure one triangulated face is made of 77 bars and 124 nodes (2). Figure 1 displays the deployment of the diamond origami-scissor prototype made of six triangulated faces. This prototype is made of 744 nodes and 462 bars (with six different types of bars). The prototype is structurally stable and has a fluid motion. While the diamond origami of thick panels has one degree of freedom, the origami-scissor structure has two degrees of freedom.

4 The language of geometry and the art of the Alhambra

This chapter introduces geometry and some of its branches, including architecture and art. The aim here is to choose a combination of lines inspired from the art of the Alhambra, and in the following chapter it will be tested to establish whether this Alhambra pattern can be made into scissor-hinged pavilion with the FGMORR.

Geometry, a field of knowledge dealing with spatial relationships, can be defined as the mother of the sciences and the arts. In its origin and through the works of Euclid's 'The Thirteen Books of the Elements' [9] 300 B.C., it was regarded as a theoretical entity. Despite this, geometry continuously branched in numerous fields of knowledge, including practical applications. Geometry was used by Eratosthenes to prove that the Earth was a globe and to calculate its circumference 235 B.C. in Alexandria [10]; and before him geometry had been used by Aristarchus of Samos and to propose the first heliocentric model of the Solar System [11] 1800 years before Copernicus. Geometry could also radically transform architecture and art: to calculate earth movements to build cities [10], to set up the building foundations and to determine its space, geometry could be in the walls in tiles, in the floors as mosaics, in drawings, sculpture, furniture and artefacts. Art could express the infinite possibilities that can be generated with geometrical relationships. Such meaning, truth and beauty could be derived from geometry that culturally in some instances it became an expression of divinity. Pythagoras 500 years B.C. was not only a polymath, but a spiritual leader [12]. Geometry as an expression of divinity also resulted in the art of the Islam.

Figure 2A displays the chosen combination of lines inspired from the Alhambra [13]. A square with an inscribed circle and dodecahedron determined by star formation that radiates towards the centre marked by another star formation inscribed in a dodecahedron, from which lines part that make four set of squares inscribed inside the original grid; this operation is then repeated by rotational symmetry and the lines generated can generate

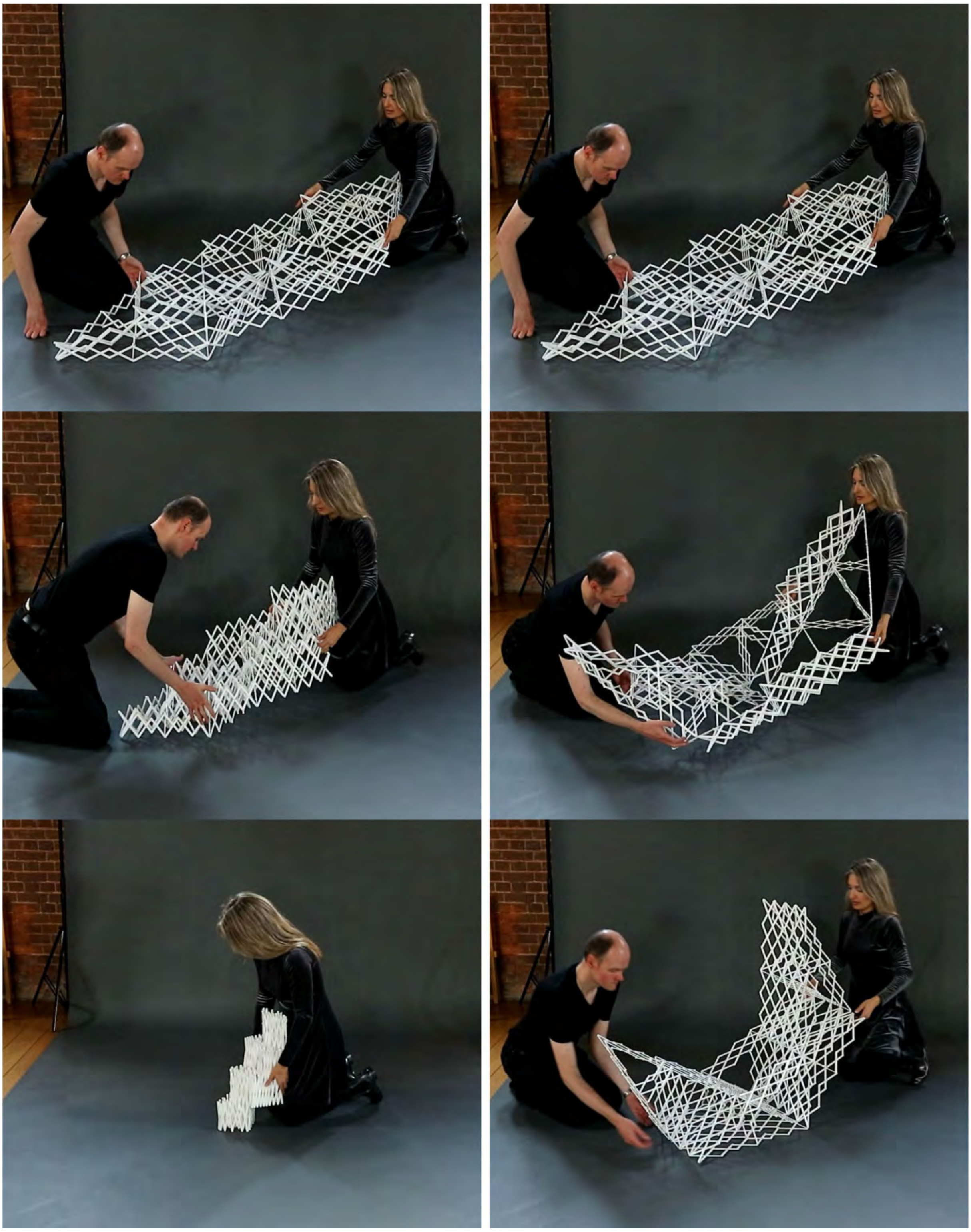

Figure 1. Diamond origami-scissor hinged deployable structure. Deployment sequence of six faces: scissor deployment and origami fold.

multiple further connections within the grid. In the centre, three sets of lines whose vertices would make an equilateral triangle (vertices 3) have been chosen to generate a triangulated central support for the pavilion.

5 FGMORR applied to Alhambra combination of lines

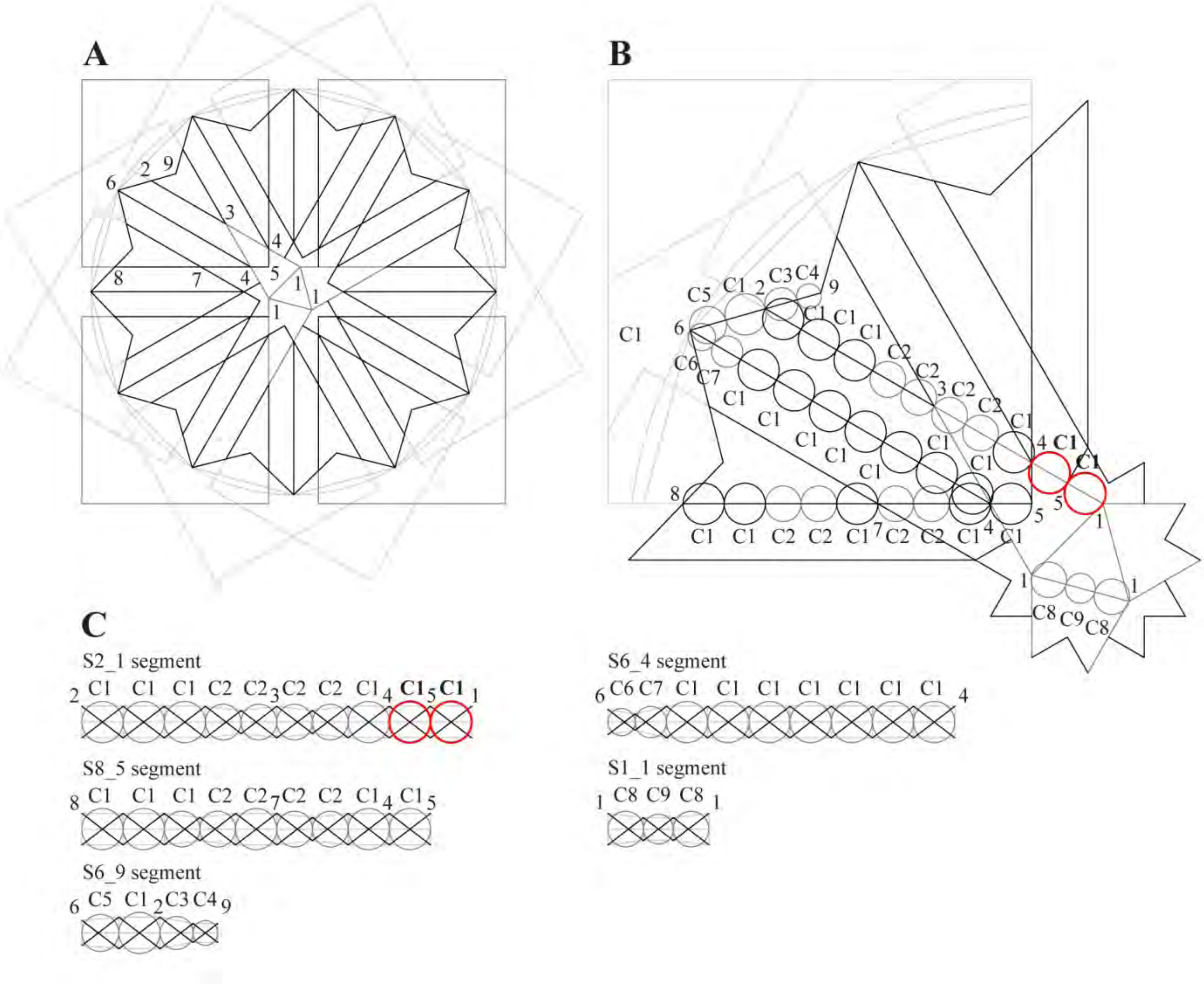

Figure 2. Alhambra combination of lines made into a scissor-hinged deployable structure. (A) Alhambra combination of lines, determination of its segments. (B-C) Applying the 'form generation method of relative ratios' for two-bar scissor units to the Alhambra segments.

If the FGMORR [6] could indeed generate infinite scissor-hinged structures from infinite combinations of lines, then the segments that determine this geometry derived from the Alhambra (Figure 2A) could be made into a scissor-hinged structure. The scissor unit types used here are translational, in which a vertical line connecting the end nodes is perpendicular to the horizontal plane. Figure 1B displays a quarter to the geometry and its determination from vertices 1 to 9; by joining these vertices five segments are generated: S2_1, S8_5, S6_9, S6_4 and S1_1 which have sub-segments determined by the vertices. These five segments are repeated through the pattern: there are 6 S2_1 segments, 18 S8_5 segments, 24 S6_9 segments, 12 S6_4 segments and 3 S1_1 segments. Figure 2C displays how nine ratios are established to make this combination of lines into a scissor hinged surface: C1, C2, C3, C4, C5, C6, C7, C8 and C9. The first ratio C1 is marked by the smaller sub-segments in S2_1, S1_5 and S5_4. The geometry of the segments and their sub-segments is defined by the relative ratios C1 to C9, which are described by the following geometrical relationships described by the following set of equations in (1) and (2):

S2_1 = (C1 x 6) + (C2 x 4)
S8_5 = (C1 x 5) + (C2 x 4)
S6_9 = C1 + C3 + C4 + C5 (1)
S6_4 = (C1 x 7) + C6 + C7
S1_1 = (C8 x 2) + C9

S1_5 = S5_4 = C1
S6_9 = (S2_1 - S8_5) + C3 + C4 + C5
S6_4 = ((S2_1 - S8_5) x 7) + C6 + C7 (2)
S8_5 = S2_1 - C1

The resulting Alhambra inspired scissor-hinged surface can be seen in Figure 3. Figure 4 displays how the central triangle has been repeated in order to make a central support with further triangulation at the base and junction with the surface for stability and for structural efficiency. Figure 5A, 5B and 5C display three different stages of the deployment capability of the Alhambra scissor-hinged pavilion; Figure 5B the desired position for the pavilion.

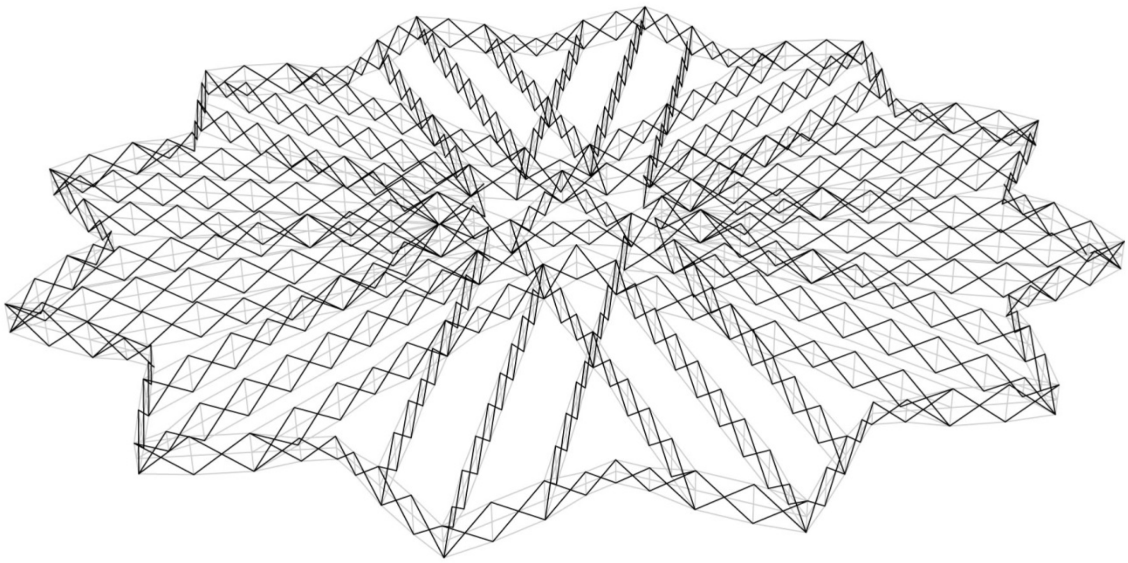

Figure 3. Resulting scissor-hinged deployable Alhambra surface.

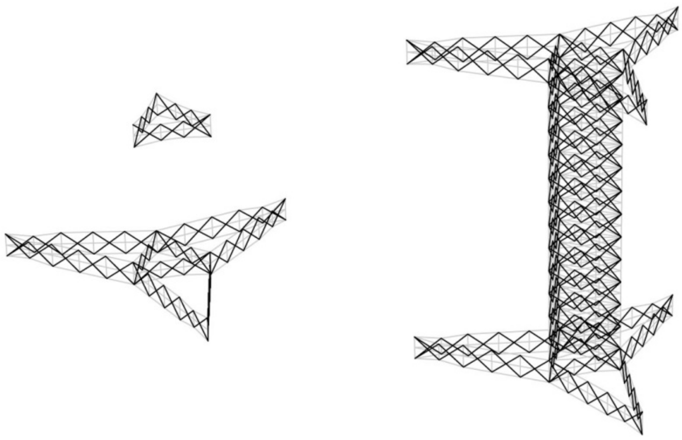

Figure 4. Central support.

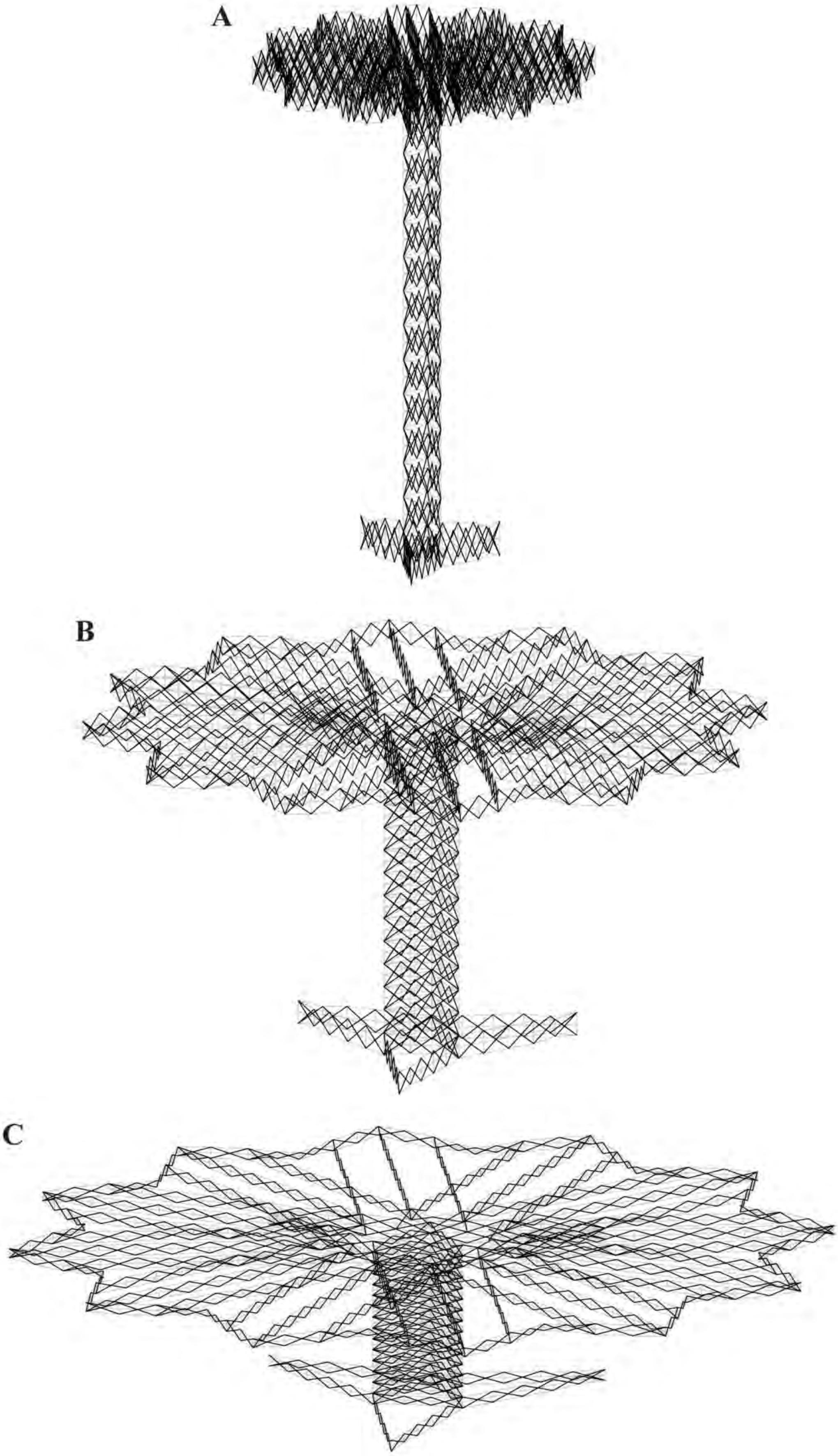

Figure 5. Deployable Alhambra pavilion. (A-C) Three stages of deployment.

6 Alhambra pavilions in Cambridge Market Square

The Alhambra pavilions can have multiple functions (for instance for travelling exhibitions, temporary events) and could be assembled in multiple sites. The following is an outline of a potential intervention in Cambridge Market Square as market stalls that sell from food to local arts and crafts. An intervention would be an opportunity to carry out a design development of this scissor-hinged technology theory investigation, with considerations such as choosing how to attach a weatherproof layer to the structure, or adding wheels to the base of the structure to facilitate deployment, or to consider different market layouts based on circulation: for instance east to west, or semi-random layout. A crucial aspect for an intervention is its assembly and deployment on site.

By understanding the deployment of the pavilion illustrated in Figure 5, the strategy can be outlined for its assembly and deployment on site. While the surface is packaged, the central support is extended (Figure 5A); and while the surface is extended, the central support is packaged (Figure 5C). While this may appear as a challenge, it could be turned into an advantage. Firstly all the different parts are carried on site in their packaged state to use the minimum space during transportation. Once on site, the central support is assembled vertically in its packaged state. The surface can then extended and placed on the central support. This has many advantages: the deployable structure is always perpendicular to the ground therefore it won't suffer stress is by being inclined during assembly; also, this is done at ground level therefore the parts can be assembled manually without the need of a crane. Once the surface is attached to the central support, it can be deployed by applying pressure inwards towards the centre of the pavilion which raises the upwards the pavilion, which can also be done from the ground. Once the pavilion reaches the desired position it can be locked. This assembly process is sketched in figure 6.

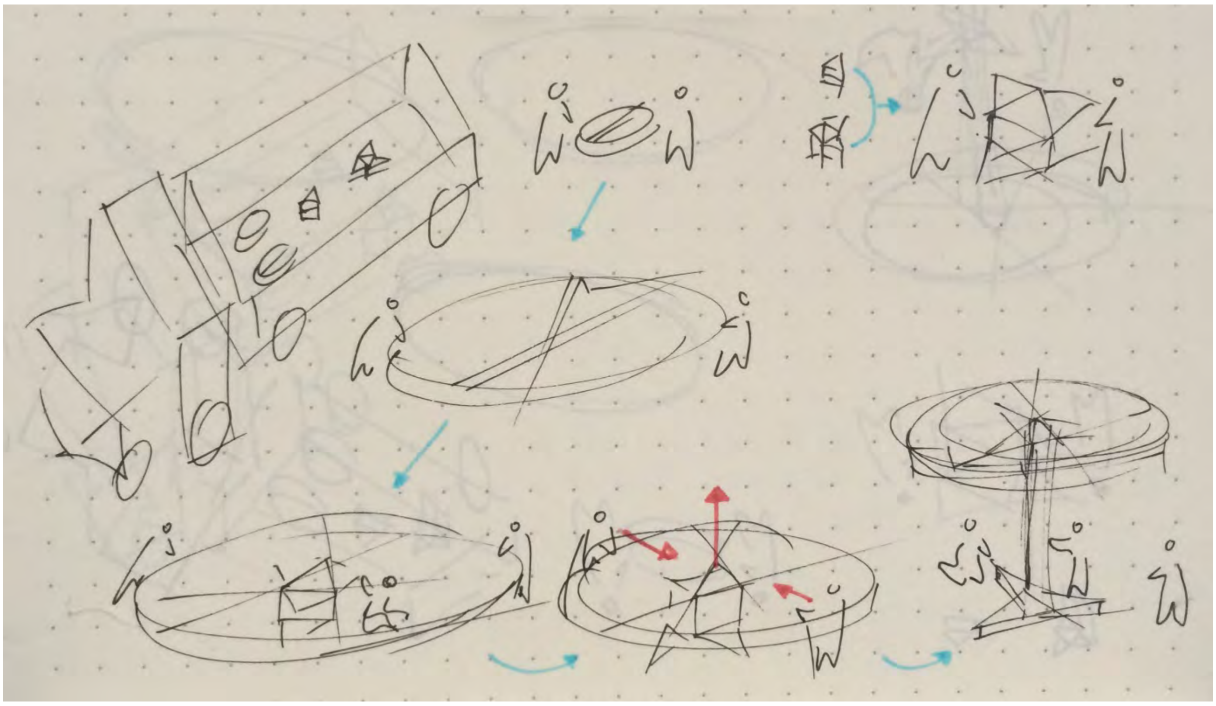

Figure 6. Assembly and deployment of the Alhambra Pavilion.

Figure 7. Alhambra pavilions in Cambridge Market Square.

Figure 7 illustrates the Alhambra pavilions in Cambridge Market Square, where the pavilions are repeated and located following the current layout of the market. Their architectural language is in dialog with the historic site, Great St Mary's Church and Kings College Chapel that can be seen at the background. This could also be an opportunity to reinstate the Gothic fountain most of which was demolished in 1953, and which replaced the Hobson's Conduit fountain following the fire in 1849.

7 Conclusions

This research extends the theory of the FGMORR [6] for scissor-hinged deployable structures. So far scissor-hinged structures had been designed one by one, and scissor-hinged surfaces have been made of grids made of triangles and squares. The 'form generation method of relative ratios' (FGMORR) by Rivas-Adrover can be applied to infinite combinations of lines and can therefore generate infinite scissor-hinged structures. This has been demonstrated by applying the FGMORR to a combination of lines from the Alhambra in order to make a new scissor-hinged surface. Also, while so far scissor-hinged technology has been used to generate surfaces, here it has been demonstrated that the FGMORR allows for creating not only the surface or roof, but also its supports, as demonstrated by the Alhambra pavilion.

The combination of lines chosen from the art of the Alhambra is a two-dimensional geometry of ancient origin. In this research and through the FGMORR it has taken a new meaning: the geometry of the Alhambra pavilion enters the four-dimensional geometry of mechanics, as explained by Lagrange in 1788 [14], as it inhabits the three dimensions of space and the fourth dimension of time, due to its expansion and contraction. This technology enables a connection from theoretical geometry to a physical architectural proposition.

Scissor-hinged deployable structures can be prefabricated with a minimum number of different lengths of bars. They can be packaged and carried easily to the site where they can be assembled. Their lightness and deployability allows them to be mounted and deployed easily on the ground, reducing the need for cranes and on site operations. This significantly reduces the materials, time and cost of assembly and construction. Once on site they can further readapt, expand and contract, and therefore adapt to different weather conditions and changing programmatic possibilities. They can also be packaged in a much smaller spaces and be reused in different locations. Their versatility, reusability and easiness of construction exemplify a sustainable emerging technology.

While this research extends the theory of the FGMORR for scissor -hinged deployable structures, it has also given a clear outline of the assembly and deployment strategy, as well as a potential intervention. The Alhambra pavilions in Cambridge Market Square demonstrate that this sustainable technology can embody cultural symbols, and can embrace the concepts of identity, place and culture; this therefore allows a conversation equally relevant that interacts with contemporary life, future technologies, and historical heritage.

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