Towards a Free-form Transformable Structure

A critical review for the attempts of developing reconfigurable structures that can deliver variable free-form geometries

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In continuation of our previous research (Hussein, et al., 2017), this paper examines the kinetic transformable spatial-bar structures that can alter their forms from any free-form geometry to another, which can be named as Free-form transformable structures (FFTS). Since 1994, some precedents have been proposed FFTS for many applications such as controlling solar gain, providing interactive kinetic forms, and control the users' movement within architectural/urban spaces. This research includes a comparative analysis and a critical review of eight FFTS precedents, which revealed some design and technical considerations, issues, and design and evaluation challenges due to the FFTS ability to deliver infinite unpredictable form variations. Additionally, this research presents our novel algorithmic framework to design and evaluate the infinite form variations of FFTS and an actuated prototype that achieved the required movement. The findings of this study revealed some significant design and technical challenges and limitations that require further research work.

Keywords: *Kinetic transformable structures, finite element analysis, form-finding, deployable structures, Grasshopper 3D, Karamba 3D*

INTRODUCTION

Transformable systems in architecture are defined as the systems that can “alter their forms to have different spatial configurations to be employed for space-saving and utilitarian needs” (Fox & Kemp, 2009). These systems are considered a sort of dynamic kinetic architecture, based on Fox’s (2009) classification of kinetic architecture, which has three categories: embedded, deployable, and dynamic, which is also sub categorised to mobile, transformable and incremental.

Transformable solutions can be categorised in different ways as described in the classifications of, for instance, C.J. Gantes (2001), Felix Escrig (2010), Maziar Asefi (2010), and Esther Adrover (2015). These classifications revealed some common mechanisms utilised in deployable (portable) and transformable (i.e. not portable) solutions such as ’spatial bar structures (Asefi, 2010), which are so-called 'scissor-like elements (SLE)' (Escrig & Sánchez, 2010) or 'latticework' (Hanaor, 2009; Adrover, 2015).

Spatial-bar structures mostly share the same features of space trusses; they are composed of linear elements (i.e. bars or struts) assembled in three-dimensional configurations and flexible joints at the ends or intermediate points of these elements (Asefi, 2010; Hoberman, 2006), covered by flexible materials (e.g. PTFE) or lightweight panels (e.g. Polycarbonate) (Gantes, 2001).

Spatial-bar structures have two typologies, 'pantographic' that employs scissor-pair mechanisms with straight or angulated bars and 'reciprocal' structures with bars or plates in closed-loop formations (figure 1) (Asefi, 2010; Hanaor, 2009). The transformation morphologies of spatial-bar structures, according to Escrig (2010), have six typologies (figure 2): 'umbrellas', 'bundles', 'rings', 'polyhedral', 'planes' and 'double-arched.

According to the mentioned classifications and the morphologies mentioned by Escrig (2010), it can be noticed that the possibilities of the form variations achievable by spatial-bar mechanisms are limited and based on the modification of primitive 3D shapes (e.g. box, cylinder) or platonic solids. Additionally, spatial-bar mechanisms are not common in architectural applications; this can be for two major factors, their cost and complexity (Asefi, 2010).

Despite their issues, spatial bar structures offered sophisticated architectural solutions, such as the works of C. Hoberman (figure 2-d&f) and Santiago Calatrava (figure 2-c). Moreover, recently, some designers attempted to extend the possibilities and morphologies of spatial-bar structures. For instance, C. Hoberman (2015) developed a 'kinetic block' that can achieve foldable free-form geometries (figure 3). Additionally, other prototypes were developed to create interactive free-form surfaces, such as the HypoSurface (Dunn, 2012), and the kinetic sculptures of Reuben Margolin (figure 4) [5]. Finally, some precedents attempted to create transformable free-form structures that alter their forms from a free-form geometry to another (figure 5), which is the scope of this research.

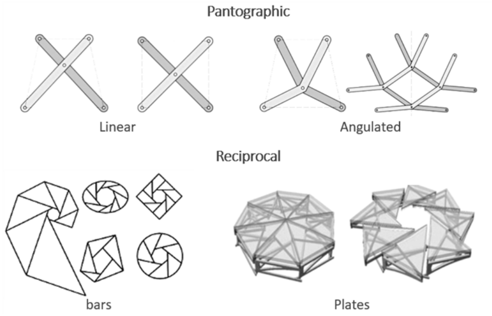


Figure 1
Typologies of spatial-bar structures: pantographic (linear and angulated) and reciprocal (bars (Larsen, 2008) and plates (Rodriguez, et al., 2009)).

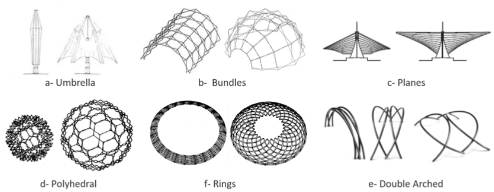


Figure 2
Transformation morphologies of spatial-bar structures: umbrella (Escrig & Sánchez, 2010); bundles (Ibid); planes (Schumacher, et al., 2010); polyhedral (Hoberman, 1991); rings (Ibid) and double-arched (Escrig & Sánchez, 2010).

This unique morphology of transformable structures is named in this research as "free-from transformable structures" (FFTS). They share similarities with space trusses which are supported by their corners or edges and are not fully supported/attached/suspended by/to another structure, unlike the HypoSurface or Margolin's sculptures (figure 6).

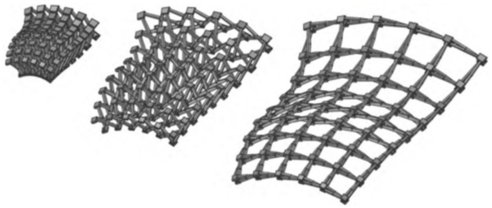


Figure 3
An expandable free-form surface with angulated scissor-bars (Hoberman, 2015).

Figure 4
Contour kinetic sculpture made by Reuben Margolin [5]

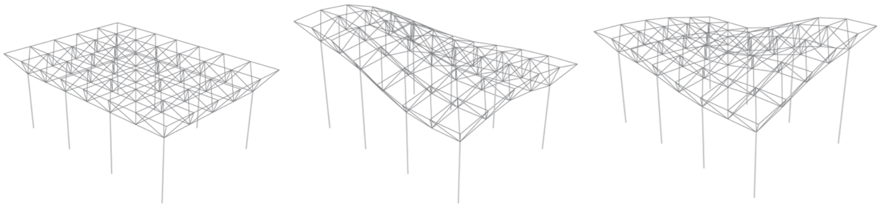


Figure 5
Forms that can be achieved by FFTS as described in this research.

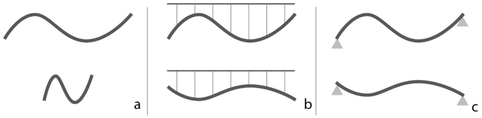


Figure 6
The possible transformation of free-form surfaces: a) expandable; b) supported by another structure; c) supported by its ends, which is the scope of this research.

The main concern with FFTS systems is their capability to deliver infinite form variations which may make their design and evaluations process more complicated and challenging compared to common transformable structures, which move within a predefined series of states (e.g. from compacted to expanded).

Therefore, this research aims to highlight the essence and possible functions of FFTS and define the techniques employed to achieve this kind of movement and reveal the key design and evaluation challenges and considerations. Thus, Why is the free-form transformation of spatial-bar structures needed? How can this transformation morphology be achieved? How these precedents faced the design and technical challenges of FFTS?

In order to answer these questions, the research investigated eight precedents with six different approaches sorted chronologically. Each approach is presented in two sections: the first is a brief description of the precedent (e.g. structure system, mechanism, materials), and the second is a critical review and evaluation.

PRECEDENTS OF FREE-FORM TRANSFORMATION

Tetrobots

In 1994, G. Hamlin and A. Sanderson (1998) proposed a robot that can walk within rough terrains based on the tetrahedral modules of space-trusses, and they called it Tetrobot (i.e. tetrahedral robot) (figure 7-a). The motion is achieved by changing the lengths of struts using linear actuators and flexible joints called CMS (Concentric Multilink Spherical), which were based on scissor mechanisms to achieve concentric movement of the struts.

In 2015, Robert Read commenced a project called 'The Gluss' (figure 7-b), which aimed to make the Tetrobots mechanisms cheaper and smaller, and easier to control using Arduino [3]. He employed Actuonix L16 actuators for the adjustable struts, and 3D printed adjustable turret joints, which were previously invented by Song, Kown and Kim (Song, et al., 2003). Read made an open-source parametric digital model of the turret joints, which can also be easily fabricated by 3D printing.

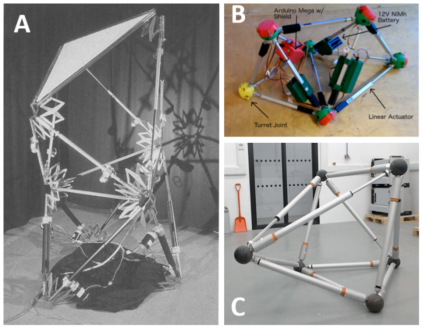


Figure 7
The Tetrobots : A) The tetrobot (Hamlin & Sanderson, 1998, p. 142); B) the Gluss [3]; C) Morphs [2].

Afterwards, in 2015, a team from BMADE Robotics Lab at UCL proposed an interactive tetrahedral model called 'Morphs' (figure 7-c) [2]. It was designed to move within public spaces and respond to its environment. The structure has 12 linear actuators and spherical cast polyurethane joints, which enables the structure to shift its CG, making it able to crawl.

In terms of design, tetrobots were mainly proposed to make robots that can move over terrains that wheeled machinery cannot access. They have similarities with space trusses and can be employed to obtain a structure with free-form transformation. However, Tertobots technically have two major issues: first, they rely on a large number of linear actuators, which may increase the complexity of the structure's compositions and its operation, which can negatively affect its maintenance cost and life expectancy. Second, The proposed joints have many small pieces which may require an intensive maintenance plan (e.g. lubrication), especially if these joints were exposed to dusty, rainy or snowy environments.

Topo-Transegrity

In 2002, the '5subzero' design group, founded in London, presented a prototype in the Latent Utopias Exhibition, Graz, 2002 of a structure called topo-transegrity that can reconfigure itself based on the changing conditions (figure 8) [1]. The structure was proposed to renovate the courtyard of the Barbican Arts Centre in London as a responsive surface for this public space that can offer a real-time transformation to host changing activities, events, and behaviours (Neumayr, 2006).

Figure 8
Topo-Transegrity prototype (Neumayr, 2006).

The presented prototype was a 1:10 scaled model for a manipulatable space-frame structure with adjustable struts using 'Festo' pneumatic actuators. The structure's modules can be considered deformable boxes, and accordingly, its joints are simple; each is a cross with four one-degree of freedom (DOF) revolute joints. The designers claimed that the structure could transform into stairs, walls with adaptive louvres, roof openings or changeable routes and deliver a network of included planes that allow access from every point of the public space to another. The designers also suggested that the structure's operation process is self-learning as it could adapt to the changing needs of its users (Luciana, 2013).

In terms of design, topo-transegrity offered a simple approach to achieve free-form transformable structures. Within the transformation process, the modules remain rectangular from the plan-view, and the structure elevates upwards without any unwanted deformation. However, the structure only offers forms that look like steps and cannot offer smooth free-form surfaces. Additionally, there are many concerns in employing pneumatic actuators, as they are not reliable nor convenient in structural applications due to the compressibility of air when subjected to loads (Hamlin & Sanderson, 1998) and their complicated technical requirements.

Actuated Tensegrity

In 2003, T. Sterk proposed a reconfigurable structure system based on tensegrity structures called actuated tensegrity (figure 9). He presented that system in some conceptual projects such as the 'Frais' [6] and the 'Prairie House' [7]. Additionally, he presented a prototype of this system in 2004 made of cast aluminium and wires of shape memory alloys actuated by pneumatic actuators (Schumacher, et al., 2010). The designer claimed that the structure could transform to control its aerodynamics, respond to the changing loading conditions (e.g. wind), control solar gain, and reduce the CO_2 emission (Sterk, 2015). Additionally, he also claimed that the structure could shake itself to drop any accumulated snow on its surface.

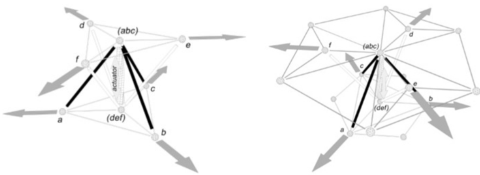


Figure 9
the kinetic blocks of Actuated Tensegrity (Sterk, 2003).

Sterk's approach was ambitious, and he presented multiple functions and advantages of free-form transformable structures. Additionally, his selection for tensegrity structures can reduce the total structural weight and reduce the power needed for operation accordingly. However, there are many concerns about the reliability and durability of tensegrity structures in architectural applications (Motro, 2003; Asefi, 2010). Moreover, there are many issues with using pneumatic actuators, as explained before. Finally, his proposed kinetic modules can increase the movement limitations as each module changes its size in all directions within the actuation process, which can be limited by the movement of its adjacent modules.

HybGrid

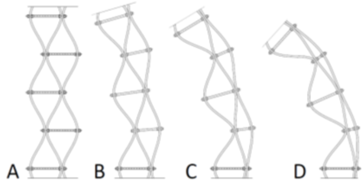


Figure 10 Transformation of the HybGrid

In 2003, Jordi Truco Calbet and Sylvia Felipe Marzal, the founders of Hybrida studio in Barcelona, proposed a structural system called HybGrid in their MArch study at the Architecture Association (Hensel, et al., 2010), and they registered this structure system as a patent in 2007 (Marzal & Calbet, 2007). The HybGrid system can deliver free-form surfaces by tesselating the surface into a rhombus-shaped grid. Each line of the grid consists of three strips of flexible fibre composite, and between these strips, the actuators were placed. By adjusting the actuator, the form of the gridline can be changed (figure 10), and the configuration of the structure changes accordingly.

The system was firstly proposed for fixed structural configurations, and it was employed in projects such as the 'Hybermembrane' pavilions at the Design HUB museum in 2013 and the Belloch Parc, Santa I Cole, in 2016 [8]. Additionally, the team presented some 3D renderings and proposals for transformable HybGrid structures, and they suggested some application like controlling solar gain.

In terms of design, the HybGrid geometry and composition were simple and subtle; they did not employ complex joints nor struts. The structure's simplicity can also enable mass production of the components and reduce its cost accordingly. Unfortunately, the number of actuators necessary to achieve the required transformation is huge and can increase the complexity of the operation process and maintenance. Additionally, the structure's span can change during the transformation process, which means that this kind of structures is not feasible in structures with fixed spans or supports.

Double Scissor-Pair structures

In 2009, D. Rosenburg, in his PhD at MIT, developed a transformable structure mechanism based on pantographic structures for a partition that responds to the unexpected user's needs (Rosenberg, 2010) and control the flow between two spaces and can be controlled either manually or using AI system. His proposed structure can achieve multiple curvatures by shifting the mid joint of the scissor mechanism of the pantographic structure (figure 11). Each module of the mechanism has eight scissor compositions, two for each side; that is why this approach called a double-scissor pair structure.

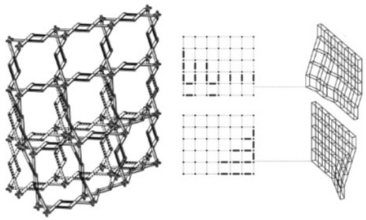


Figure 11 Double SLE (Rosenberg, 2010)

In terms of design, the double-scissor pair mechanism was entirely made of simple 1-DOF joints; However, the structure's composition itself is complex. Additionally, according to the available documentation, the designer focused on the structure's responsiveness to the users' needs and its operation rather than the technical issues of his solution, as there are some concerns and doubts about the ability of the utilised servo motors to shift the pivots as their torque may not be sufficient to make the required movement.

Modified Scissor-Like elements M-SLE

Y. Akgün (2010) proposed a structural mechanism that improves the flexibility of pantographic structures and reduces the actuators required to achieve this transformation (figure 12). His approach to achieving this is by dividing the structure into a number of deployable arc-shaped segments using Modified scissor-like elements (M-SLE). Each M-SLE has four bars instead of two, with one intermediate pivot. He made studies, calculations and finite element simulations on his proposal of M-SLE on a vault structure with three arc-shaped segments and dealt with it as a four-bar linkage (Akgün, et al., 2010). He suggested some applications for his structure, such as making adaptive interactive roofs and control solar gain.

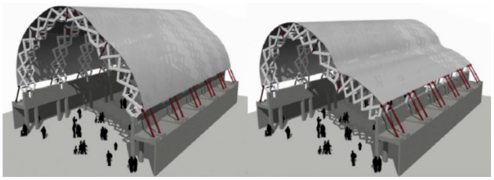


Figure 12
A 3D view for a pavilion with M-SLE

In terms of design, the M-SLE approach has two advantages: they offer structures with simple joints and the lowest number of actuators, which accordingly could decrease the overall cost and the complexity of the construction, operation, and maintenance of the structure. Unfortunately, the supports of the structure cannot move upwards, which can limit the structure's flexibility. Additionally, his proposed solution only fits the case he proposed; the calculation he presented cannot be generalised for structures with more than 2 M-SLEs. Finally, according to the documented structural simulation results of this precedent, the structural simulations were performed on three presumed form variations for four actuator configurations (12 forms in total), which are not sufficient to reveal the worst-case scenarios and maybe not accurate.

FREE-FORM TRANSFORMABLE STRUCTURE (FFTS)

According to the previous investigation of the precedents, and their issues, a novel approach to design and evaluate free-form transformable structures was developed. This approach is formulated into an algorithmic framework and a Grasshopper script (figure 13) that organises the development process of these structures and perform the required simulations seamlessly and effectively. The proposed framework was developed in multiple iterations; the first one was presented in eCAADe 2017, based on an investigation on the available design and evaluation frameworks (Hussein, et al., 2017). The final version of this framework and script, presented here, was validated by testing it on the design and evaluation of an arbitrary 10x10 meters FFTS. The script was also employed in operating a physical model of a single active linear element ALE of FFTS.

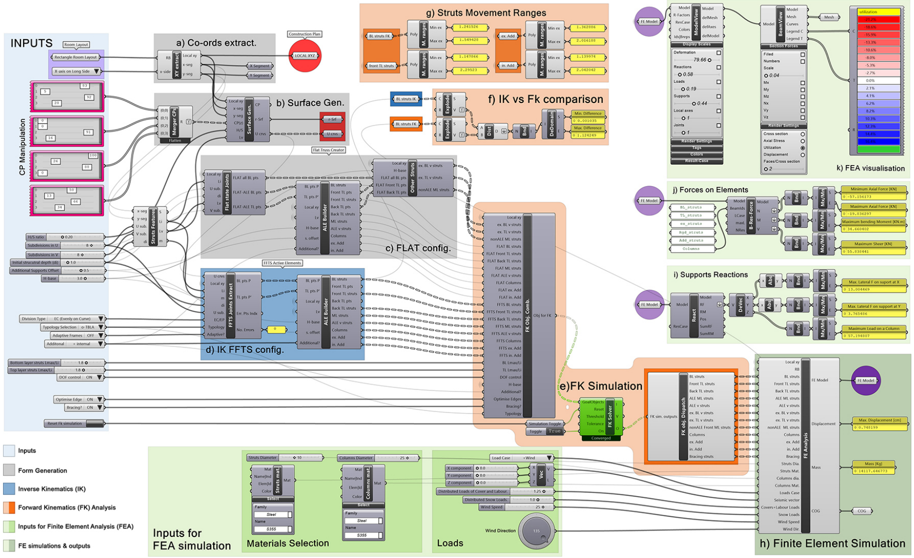
The FFTS design and evaluation processes have two approaches, top-down and bottom-up. The top-down approach aims to define the design concept and perform the evaluation processes to extract the components' design data (e.g. maximum required length of a strut); Then, the bottom-up approach aims to build and operate the physical model of the structure based on the extracted data.

The top-down approach

The research focused on making an FFTS for a pavilion with a rectangular layout (figure 5), which is based on the mechanisms of Tetrobots as they are similar to space trusses and can be employed for various architecture applications. The structure's supports are by its edges, and it can be subdivided into a number of active linear elements (ALEs) that can control the form and the movement of the structure (figure 14).

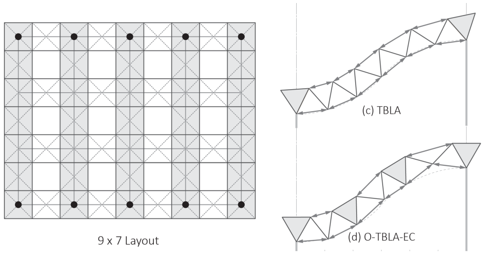
The form of the ALEs can be controlled by adjusting the lengths of the columns and the top and bottom-layer struts to maintain the span of the structure. There are two approaches for actuation: top/bottom-layer actuation (TBLA) and opti-

Figure 13
The developed GH script



mised TBLA with a reduced number of actuators, as shown in figure 14.

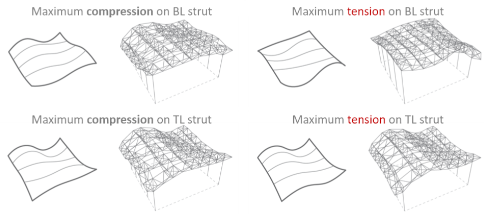
Figure 14
The Active linear elements (ALE) of FFTS.



Afterwards, a parametric model was created using Grasshopper 3D; the script was necessary to generate the form variations of FFTS and seamlessly integrate the inverse & forward kinematics analyses (using Kangaroo 2 plugin) and the finite element simulations (using Karamaba 3D) within a user-friendly interface to easily generate, manipulate and evaluate the FFTS.

By employing the developed GH script and genetic algorithms (GA) solvers (e.g. Galapagos), the designers can determine the design data of the components, such as the maximum or minimum length required for the linear actuators of the struts and the maximum tension or compression stress applied to these actuators (figure 15). Then the designers can move to the bottom-up approach and build the actuated physical model.

Figure 15
A sample of the worst-case scenarios extracted from the GH script and the GA solver.



The bottom-up approach

After extracting the components' design data, designers can design and fabricate the FFTS components, i.e. the adjustable struts and the flexible joints. Due to some limitations in this research project, an actuated model for one active linear element with five pyramid modules of the FFTS was created based on the design data extracted from an arbitrary 10x10 meters pavilion used to validate the functionality of the GH script.

The joint design was based on the turret joint investigated in the tetrobots section, and so it was named as the MT (modified turret) joint (figure 16). This joint achieved the concentric rotation of the struts around the joint's centre, and it controls the movement ranges and behaviours of the struts. The digital model of the MT joint was parametric, and it was fabricated using 3D printing.

Figure 16
The MT joint after fabrication

For the adjustable struts, Actuonix actuators L16-R with a gear ratio of 1:150 were utilised in the actuated prototype of FFTS, the ones with stroke length 100 mm for the struts and 140mm for the columns. These actuators were controlled using the developed GH script and Arduino boards using the Firefly plugin.

Afterwards, some modifications were made to the parametric model and the GH script to match, for instance, the prototype scale, actuators' movement ranges and adding the calculations necessary to calibrate the actuators.

Then, the FFTS model was assembled and operated, and the operation process revealed some issues. The most critical issue was that the structure's span was changing, which was solved by a python script to control the actuators' speeds to have a more stable and consistent movement and maintain the structure's span.

Finally, the structure was operated effectively and achieved form variations and moved smoothly from each configuration to the other (Figure 17); a video recording for the prototype movement is uploaded to the link [4].

CONCLUSIONS

This research investigated six approaches that attempted to create free-form transformations of spatial-bar structures. The study highlighted the essence of these structures as they can be employed as (1) Roof structures with customisable form variations (e.g. M-SLE), interact with users (e.g. Actuated Tensegrity), control solar gain (e.g. M-SLE) and achieve structural stability in different loading conditions (e.g. HybGrid) (2) Partitions that respond to the unexpected users' needs (e.g. Double Scissor-pair) (3) Flooring that controls the users' flow in architectural or urban spaces (e.g. Topo-Transegrity) (4) Interactive elements that interact with users within urban spaces (e.g. Morphs).

Moreover, the study revealed some design issues, challenges, and considerations; a common issue is the FFTS ability to reconfigure into unexpectable form variations, which can make the evaluation processes more challenging. Additionally, the precedents revealed the following:-

- The tetrobots highlighted the potential of utilising space frame structures to create FFTS; however, their mentioned applications were not relevant to architecture.
- The topo-transegrity offered a sophisticated solution and simple joints, but it was dependent on unreliable pneumatic actuators and could not achieve smooth free-form surfaces.
- The actuated tensegrity presented a lightweight solution with ambitious applications; however, it was also reliant on pneumatic actuators, and there were some concerns about the limitation of its module design and the reliability and durability of its tensegrity system.
- The HybGrid revealed a novel approach and system to achieve FFTS; however, it will be complicated to design and operate due to the number of actuators needed for operation, and the struc-

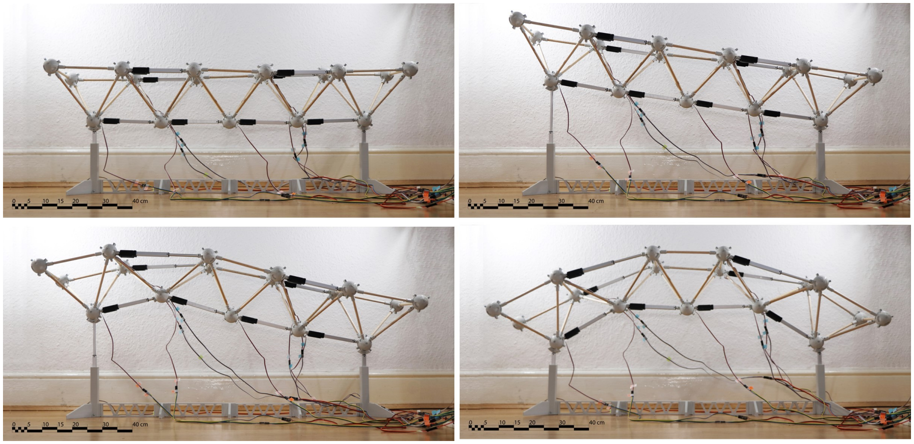


Figure 17
Some of the form variations achieve by the FFTS prototype.

ture span is not fixed, which may reduce its applicability.

- The double scissor pair offered a solution with joints; however, the composition was complex, and they are some concerns about the feasibility of its proposed actuation.
- The M-SLE offered a sophisticated solution with simple joints and a reduced number of actuators; however, the solution has many limitations the affected its flexibility. Furthermore, there were some concerns about the accuracy of the documented structural simulations of M-SLE.

In order to solve these issues, the research presented our approach to achieving FFTS, using a novel algorithmic design and evaluation framework and a GH script that seamlessly integrate the form generation, kinematic analyses and structural simulations in a user-friendly interface. Moreover, genetic algorithm solvers were employed to determine the critical form variations (e.g. worst-case scenarios) and extract the components' design data (maximum stress on a strut).

Based on the extracted design data, the actuated prototype components were defined, such as the linear actuators for the struts and the developed 3D printed MT (modified turret) joints. Afterwards, the developed GH script was modified to operate the structure after assembly effectively.

FFTS achieved a reliable and durable reconfigurable structure with some features of space trusses and their modules, which can be widely employed In architectural applications. Its movement achieved by a lower number of actuators compared to the tetrobots and the gluss project and maintained its span, unlike the HybGrid. Moreover, The structure supports can move vertically and achieved more flexibility compared to topo-transegrity and the M-SLEs. Furthermore, our approach achieved a seamless integration of form generation, kinematic and structural simulations with stochastic investigations to obtain more accurate results compared to the M-SLE.

Although the proposed framework and script dealt with some of the issues and challenges of the design and evaluation of FFTS, Further research work is necessary to improve its reliability and convenience. Additionally, some improvements are necessary for the design of the proposed FFTS to reduce its complexity and enhance its flexibility. Finally, Further research can improve the capabilities and functionality of the proposed system.

Consequently, this research can be considered a base for further research work in the field of transformable structures and can be beneficial in architecture from academic and practical perspectives.

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