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Deployable Structures

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Introduction

The generic name *deployable* structures is used for a broad category of structures that can be transformed from a closed compact configuration to a predetermined expanded form, in which they are stable and can carry loads. The use of deployable structures is very old, as most of nomadic populations have developed such kind of, sometimes sophisticated, shelters. Talking about tents, it may be for example funny to compare nomadic shelters to contemporary hiking tents (Fig. 1).

Figure 1 – Berbers (left) and American Indians (center) shelters versus a 2-secs-pop-up tent

In modern terms, due to their inherent transformability, deployable structures can be considered a special case within the broader class of adaptive and morphing structures, which are characterized by their ability to change the shape, the mechanical and physical properties, according to the external excitations and the requirements emanating from their use at any given time.

In the context of the present paper, the behavior and purpose of deployable structures are however considered to be quite specific, focusing on the change of shape, which is usually obtained by a single degree of freedom (SDOF) transformation and between only two configurations (start/compact and final/deployed). Moreover, the compact and deployed configurations are defined a priori and thus the structure is not conceived to respond or adapt to real-time changing scenarios, nor is designed to be used with different conditions in a same context.

On the contrary, the conception of a deployable structure looks towards two different uses in two different contexts, the first being the transportation or erection of the structure and the latter its static and functional behavior when deployed.

The interest in deployable structures is then due to their promising applications and to the advantages they offer compared to conventional, non-deployable structures for certain type of applications, particularly for temporary construction and movable roofing systems, or for other needs in the aerospace industry.

For such applications their potential for compact storage, transportability and easy erection and dismantling is of primary importance and outweighs the restrictions imposed by the need for complex design and detailing, which are necessary to achieve deployability.

The deployable system

Since the deployment is specifically related to a morphological variation of the structure, it is useful to look at deployable structures as the combination of two major components, i.e. the *structural system* and the *actuation system*. Both components are fundamental but, while for the actuation system several technical solutions or even the human action can be used, it is in the former where the main conceptual design issues are to be faced.

A deployable structure requires the whole structural system or at least some of its elements to be able to change their geometry. This requirement leads to the field of mechanism-like structures or, in other words, Variable Geometry Structures (VGSs). This kind of structures can be designed such that they possess kinematically indeterminate states.

VGSs can be classified according to their structural system. In doing so, four main groups can be distinguished: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, strut-cable (tensegrity) structures and membrane structures. These structural systems have been classified by their morphological and kinematic characteristics by Hanaor and Levy [1]. This classification is presented in Fig. 2.

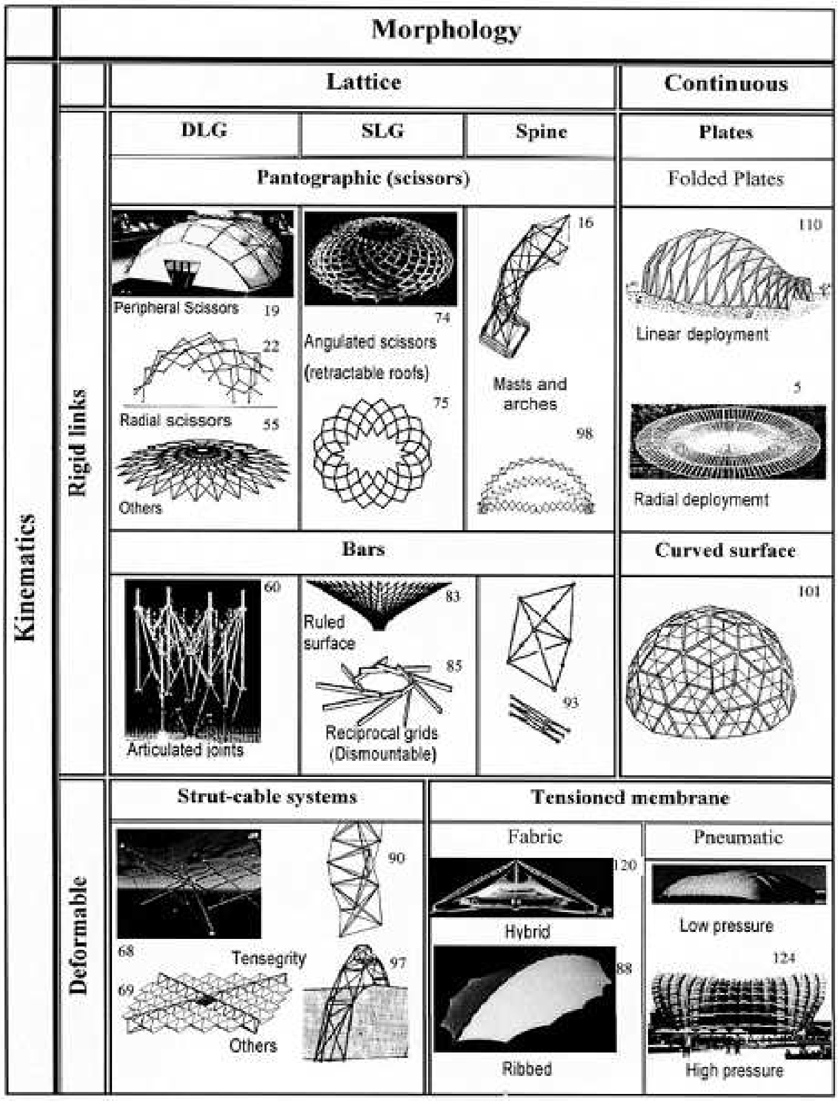

Figure 2 – Classification of VGSs on the basis on their morphological and kinematic characteristics by Hanaor and Levy [1].

In this paper the focus is mostly on kinematics, consequently such structures, according to their process of transformation, can be distinguished into only two main categories. The first category – *deformable* – includes those that rely on the intrinsic property of their material to change configuration, like engineering balloons that are blown up with hot air, whereas the second category – *rigid links* – consists of those that rely on the geometric inter-linking of their elements to change configuration; this latter category usually contains a number of essentially resistant bodies, which are connected by hinges employed to enable movement along one or more degrees of freedom. The two categories will be described in more detail in the following subsections.

Deformable. Structures based on compliant mechanisms, tensegrity and pneumatic structures can be categorized among deformable structures.

a) Compliant mechanisms

Due to their hingeless nature, compliant mechanisms offer numerous advantages over traditional mechanisms. The ability to store strain energy in compliant mechanism eliminates the need of return springs and can be used to design bi-stable mechanisms such as in [2]. The monolithic feature reduces the number of joints and fasteners in the assembly, leading to weight savings. Furthermore, the absence of joints in compliant mechanisms eliminates the backlash seen in kinematic joints, thus providing high precision and highly repeatable motion. The noise and wear associated with kinematic joints are also eliminated, which further reduces the cost for maintenance and enhances performance.

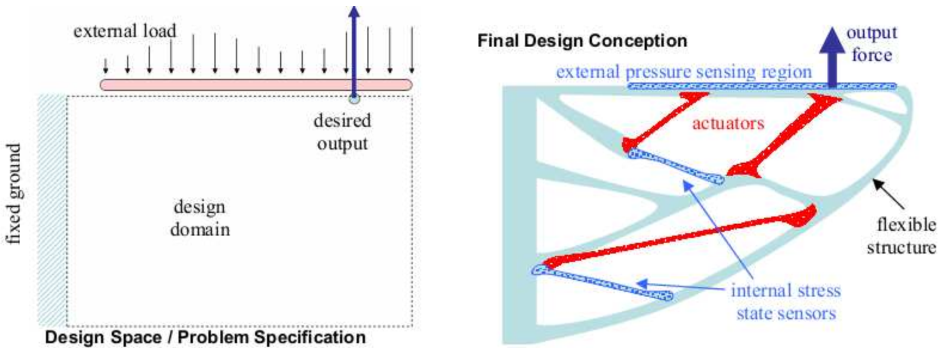

Figure 3 – Design of a fully-compliant system with embedded and distributed actuators and sensors, given a specified design space, external loading conditions, and desired mechanical task [3].

If the compliant mechanism is a *fully distributed* one (Fig. 3), there is also a sensible reduction in stress concentration and a smooth deformation throughout the structure is possible and particularly attractive to shape morphing applications [4]. Moreover, due to the absence of backlash and wear, a compliant mechanism is particularly effective to work with small displacements (1-100 μm) usually provided by smart actuators [5]. Despite the potential advantages and a consistent number of studies and applications in fields like precision engineering and aircraft engineering, there are no relevant studies related to applications in architecture.

b) Tensegrity structures

Tensegrity structures have a long history [6] and, being composed by rigid bars and cables as bones and nerves in the body, they are also belonging to the class of bio-inspired structures. Acting on the cables it is possible to modify and optimize the shape of the structure and even obtain fully deployable systems [7]. Fig. 4 illustrates a prototype of an actuated tensegrity type space structure. Different types of applications have been proposed in aerospace engineering and robotics. Small and large structures have also been proposed in the civil engineering field. A large scale example is described in [8]. The study of the shapes is one of the crucial aspects in the design of tensegrity structures and in some cases instabilities can arise. These situations can be overcame by adding active control, as proposed in [9]. Tristan d'Estree Sterk of The Bureau for Responsive Architecture and Robert Skelton of UCSD have been working on shape-changing *building envelopes* using *actuated tensegrity* structures, i.e. a system of rods and wires manipulated by pneumatic *muscles* that serve as the building skeleton, forming the framework of all its walls [10]. Within the project sensor/computer/actuator technologies are used to produce a series of intelligent building envelopes that seek fresh relationships between *building* and *user*. These responsive buildings are covered by skins that have the ability to alter their shape as the social and environmental conditions of the spaces within and around each building change. Although extensively studied for application to architecture and subject of different patents, no significant realizations have been performed to date.

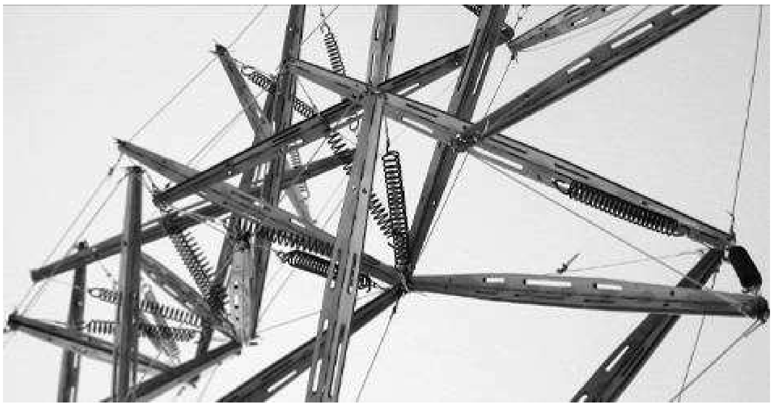

Figure 4 - Actuated tensegrity prototype by Tristan d'Estree Sterk and ORAMBRA, 2009.

c) Pneumatic structures

The lighter the structure the easier and the more precise can be the movement. If the proper movement can also be achieved by air pressure, i.e. if costly and heavy mechanisms can be avoided, literally light-weight movements can be achieved. Pneumatic structures fulfill these requirements of light weight and flexibility. In structural engineering pneumatic structures are known as air-inflated and air-supported structures. While in air-supported structures the air pressure is applied between the surface and the ground, in air-inflated structures the air pressure is enclosed in a cushion or a tube.

The development of pneumatic structures started with air-supported structures, but they have to deal with several problems like a big air volume and a comparable low air pressure, which is restricted because the interior is used by people. On the other side the air-inflated structures enclose the pressure with a continuous membrane so that the interior is decoupled from the pressure. Looking at the adaptive potential of pneumatic structures, air-inflated structures seem to be more suitable [11] as there will be a smaller amount of air volume which has to be handled, a wider range of different air pressures are possible and no compatibility with human restrictions, i.e. influence of air pressure to the human body, is necessary. Hence the pressure difference is both the stabilizing and the form giving parameter.

The structure is therefore very sensible to pressure changes. The above mentioned need for regulation of pneumatic structures leads to the idea of implementing the desired motion by the same mechanism without any extra motors or cable pulls. Ideas like this go back to designs from the '70s when T.Oki & Associates designed in 1969/70 a flexible umbrella with a central movement and are today the focus of several research projects as the movable roof in Fig. 5 from Böegle et al. [12]. One more interesting aspect we just want to mention here is the possibility, given for example by materials as ETFE films, to allow transparency, which consequently and very easily drives to lighting and energy considerations.

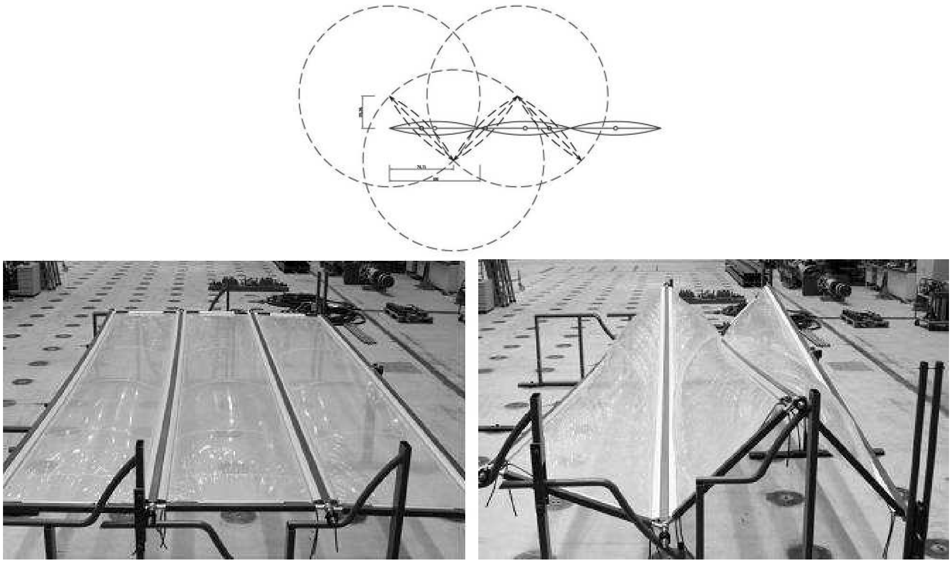

Figure 5 - Kinematic scheme and two different configurations of an adaptive pneumatic structure prototype model (courtesy of A. Böegle et al.).

Rigid Links. Mutually supported elements, rigid foldable origami, morphing truss and scissor like structures are among this category of structures.

a) Mutually supported elements

Mutually supported elements (MSE) arranged in closed circuits create MSE modules. These modules are also known as reciprocal frames [13] or nexorade fans [14]. MSE circuits may be connected one to another to generate much larger space structures. Such configurations are generally 3-dimensional and non-traditional in form and differ from better known truss assemblies because elements join each other not only at the ends but even at intermediate points. There are various ways of connecting circuit elements together, bolting being one of the most simple and effective methods [15]. Space structures assembled and connected in this way have the potential advantage of eliminating complex ball-joint type connectors traditionally used in lattice type assemblies. One of the most interesting aspects of this structural system is the possibility to manage restraints in order to allow a frame to change the position of its supporting point by sliding on another frame (Fig. 6). This particular kinematic behavior of MSE is fascinating for many researchers [16] who consider such structural system promising for applications in the field of adaptive structures.

However available studies involve mainly the static behavior of MSE and no significant realizations in the field of adaptive systems have been performed to date.

b) Rigid foldable origami

Several applications of folded surfaces can be found in architecture. However, only in the last years the kinematic behavior of origami has been taken into consideration for adaptive architectural envelopes [17]. Non-static examples of origami structures mainly come from space engineering where deployable surfaces have been studied since a long time ago. A particular kind of origami is the so called *rigid foldable origami*, extensively studied in mathematical theory [18, 19] and also successfully applied in space engineering [20]. A rigid-foldable origami is a piecewise linear developable surface that can realize a deployment mechanism if its facets and fold lines are substituted with rigid panels and hinges, respectively.

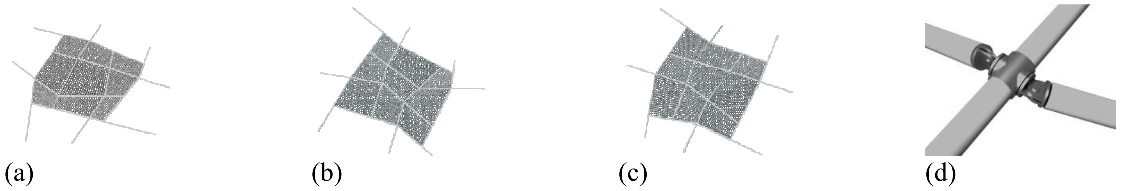

Figure 6. (a, b, c) Different spatial configurations of MSE obtained by sliding frames one on another and (d) a node detail.

A deployable double corrugation surface, which is rigid foldable as well as deployable and flat-foldable, is the Miura-ori [21] and it is for example utilized in the packaging of deployable solar panels for use in space or in the folding of maps. The rigid-foldability of Miura-ori is due to the singularity in its pattern, where a single vertex is repeated but it has been demonstrated by Tachi [22] that it is possible to achieve rigid-foldability in quadrilateral mesh origami without the trivial repeating symmetry (Fig. 7). The resulting one-DOF finite rigid motion which characterizes this kind of opening mechanism is suitable for low-energy actuation while the possibility to switch between general shapes allows an unconstrained design. A generalized controlled finite rigid motion with more than one-DOF is one of the next steps to be investigated but still a today unachieved result.

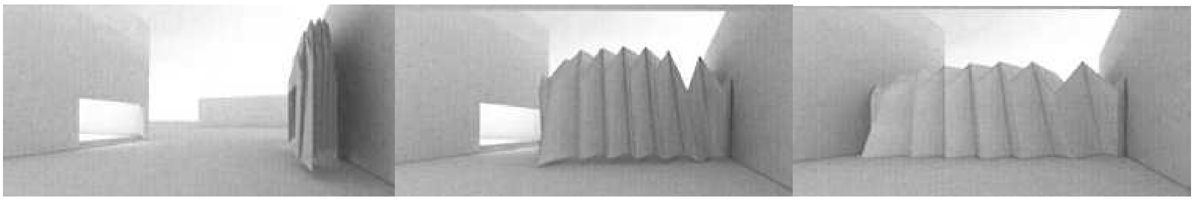

Figure 7 – Model of 1DOF deployable rigid-foldable quadrilateral origami envelope, courtesy of T. Tachi.

c) Morphing truss structures

Shape morphing can be easily fabricated from well-known traditional truss structures by replacing some of the trusses with linear displacement actuators [23]; on the other side joints represent one of the main challenges [24]. The first application of an adaptive structure using a Variable Geometry Truss (VGT) mechanism was showed at the International Expo 2005, Aichi, Japan [25]. The presented movable monument (Fig. 8), composed of three identical movable towers; each tower comprises four actuating truss members and the monument's shape can be changed variably by controlling the length of each of its extensible actuators.

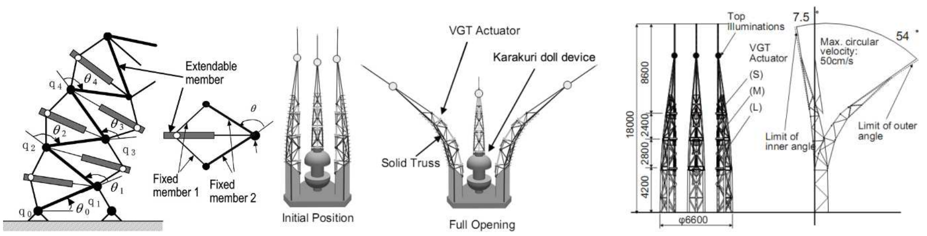

Figure 8. Scheme of the three morphing towers showed at the International Expo 2005, Aichi, Japan (courtesy of F. Inoue).

d) *Scissor-like mechanisms*

Most of the already developed kinetic structures have *open-closed* or *extended-contracted* body shapes based on scissor-like elements [26-29], [9]. Recently, proposals for adaptive kinetic structures using scissor-like elements, i.e. structures where transformations occur between more than two different shapes to constitute more flexible shape alternatives, have been also presented [10]. Scissor hinge structures possess unique extension and rotation capabilities, and the modified scissor unit developed by Akgün, et al. [30, 31] greatly increases the form possibilities for the structure. This modified scissor unit differs from common scissor units in the addition of two joints at a specific point in the mechanism. With the development of this modified unit, it is possible to change the shape of the whole system without changing the dimensions of the struts or the span. The proposed scissor structure is two-dimensional (Fig. 9), but it is also possible to combine structures in groups to create three-dimensional systems.

Recent proposals [32,33] concern scissor-like mechanisms coupled with springs to achieve *zero stiffness* (energy free) systems as the one reported in Fig. 10.

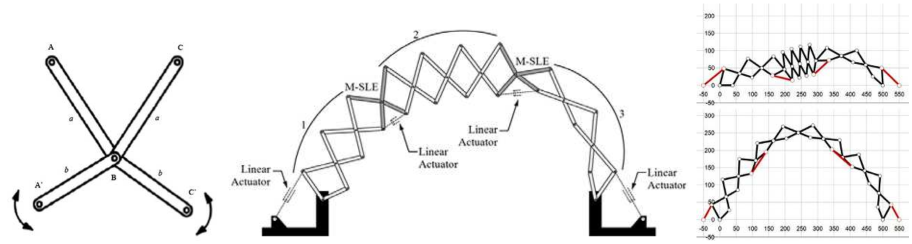

Figure 9 - From left to right: (a) – modified Scissor-Like Element (M-SLE), (b) – locations of M-SLEs and actuators on a scissor-hinge structure at a random geometric configuration and (c) – successive geometric configurations of the structure (courtesy of Y. Akgun et al.).

Figure 10 – Practical implementation of a gravity equilibrator using the parallelogram storage spring principle with zero-free-length spring [32].

Application examples

Modern deployable structures are considerably different from, and more extensive than, in ancient times. Housing has acquired a more permanent character, therefore it does not benefit of what are the main advantages of deployable structures. As a result, applications of deployable structures on earth are found today mostly in relation to recreational purposes or temporary shelters for victims of natural disasters, or for the construction industry. In addition, space related application have emerged, which impose additional requirements. The consequent differences in assumptions that are adopted for design, including types of loading, values of factor of safety, requirement for reliability, degree of automation of the deployment and dismantling process, etc. have made other authors referring to earth-based and space-based deployable structures applications as two distinct categories.

Figure 11 – Emergency deployable shelters.

According to this distinction, earth based deployable structures are primarily used for temporary and emergency situations and for exhibition purposes. Possible applications include emergency shelters (Fig. 11) or bridges for use after earthquakes or other natural disasters, temporary buildings in remote construction sites, retractable roofs and domes for sport facilities (Fig. 12), travelling theaters (Fig. 13) and concert halls, drawbridges, lightweight camping structures, temporary partitions/screens, scaffolding, forms, skeletons for permanent structures, toys or part of toys, etc.

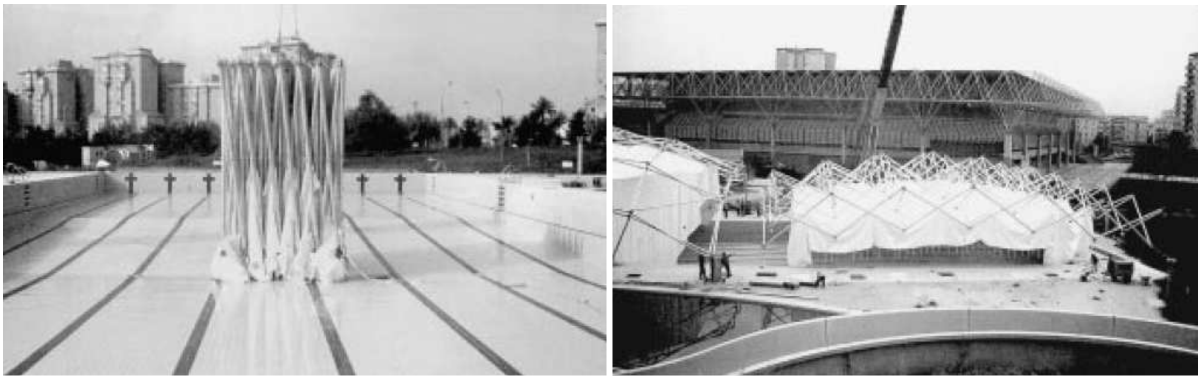

Figure 12 - F. Escrig , deployment of roof elements over a swimming pool in Seville.

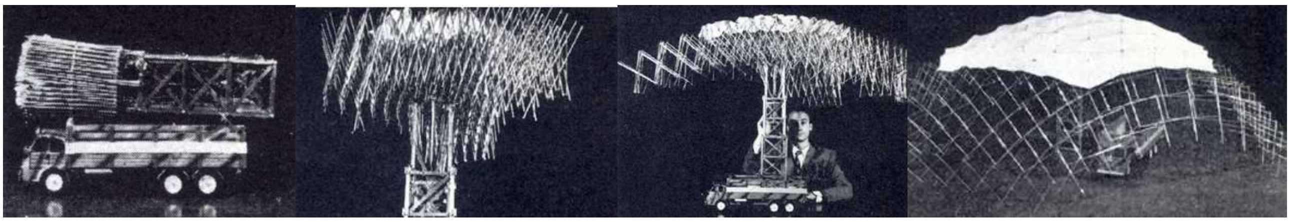

Figure 13 – Emilio Perez Pinero, Mobile Theatre Project, 1961.

Deployable structures are of even greater interest in the aerospace industry, where severe constraints apply to both the payload capacity of space ships and erection in space. Compactly packaged deployable structures are viable solutions for aerospace applications like solar panels, components of space stations, impact protection systems, parabolic reflectors and antennas, etc.

Open problems and future potential

The most issues when dealing with deployable structures design are application specific since, as shown in the previous section, dimensions, load-bearing capacity, actuation process, etc. can vary a lot. Common issues are instead related to the costs of the connections necessary to allow flexible transformations. Specifically for space deployable structures the main challenge remains to ensure high reliability in deployed geometry, stiffness and function. Potential developments in the field of deployable structures may include new bi- or multi-directional deployment processes [34] and multi-DOF schemes [35] thus combining in the design concept some of the features of adaptive and morphing structures.

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