SMART TENSEGRITY STRUCTURES FOR THE SWISS EXPO 2001

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Abstract

The Swiss Expo 2001 will be held in 2001 on the three lakes of Neuchâtel, Bienne and Morat. The main events of this exhibition will take place on four platforms protruding from the seashore to the lake and with dimensions of about 400m x 100m. The covering “deck” of these platforms will be created using the Tensegrity concept and will be dismantled and recycled after the event. This kind of structures is composed by a network of cables, struts and reinforced membranes. The resulting structural behavior is highly geometrically non-linear and is relatively complicated to calculate and simulate. This pointed to the necessity of extensive testing and permanent monitoring of the structures as well as to the introduction of active elements able to compensate for quasi-static variable loads such as temperature variations, snow on the membranes, successive construction phases and additional weight of scenic elements. This data will be continuously analyzed and, when corrective actions are necessary, hydraulic actuators placed at key locations will optimize the shape and the tensile state of the whole structure. Tests of this concept are now carried out on 1:10 scale models.

1. Introduction

A national exhibition constitutes a rare event for Switzerland. The last one was held in Lausanne over thirty years ago, in 1964. As its name implies, the next one will be in 2001. Structures for exhibitions are generally and traditionally spectacular, setting technical progress to show. In many cases they have given birth to daring towers, as in the case of the Eiffel tower in Paris, or to new technology as tensile or pneumatic structures.

This contribution aims to give a brief technical description of the planned structures, called “FORUM”, that will host the different events and exhibitions of the Swiss Expo 2001.

These structures are mainly constituted from huge platforms protruding from the shores to the interconnected lakes of Neuchâtel, Bienne and Morat. A new type of tensostructures based on the tensegrity structure principle and covered with synthetic membranes will top these platforms (Fig. 1). A peculiar characteristic of the entire project is that all structure are meant to be the temporary and designed to be re-used elsewhere and under other forms at the end of the event. This leads to the choice of modular structural elements being lightweight, relatively small, easily transportable, easily mounted and dismounted, and allowing a great versatility in their use. Much like in a Meccano toy kit, a few simple base elements will give rise to a great variety of esthetically and technically appealing forms. Furthermore, most of the structures will use innovative materials, technologies and techniques.

The FORUM structures will also be “Smart”, incorporating a fiber optic monitoring network and a series of actuators able to react almost in real time to changes in the dead and live loads acting on these structures.

At the time of writing, a numerical analysis of the different structural elements is under way. At the same time, and during all 1998, static, dynamic and aerodynamic tests will be carried out on scale models to refine the structural design and implement different active control algorithms.

The next paragraphs will describe of the basic structural elements that constitute each of the four planned FORUM structures.

2. Plateforms

The FORUM platforms will cover a total surface of about 150’000 square meters, subdivided in the four sites retained for the exhibition: Neuchâtel, Yverdon, Morat and Bienne. Each platform will have a width between 100 and 120 m and a length of about 400 m.

The platforms are an integral part of the FORUM project. They will host most of the activities and attractions of the Expo.

These platforms are designed to be assembled before the Expo 2001 and dismantled immediately thereafter. All structural parts used in the platforms will be reused for other purposes, for example as roofs for other events or for public and industrial buildings. To facilitate mounting and re-using, most elements will be prefabricated at different sites, than assembled and mounted at the Expo locations.

The platform structure is a space truss composed by bottom crosses (Fig. 2.1), diagonals departing from the cross centers (Fig. 2.2) and top square plates with a 3.0 m sides (Fig 2.3). The bottom crosses and the top plates will be made of HPC (High Performance Concrete) with a compressive strength of 80 MPa. The diagonals are made of steel tubular elements with a tensile strength of 520 MPa.

The entire platform is assembled from this basic 3.0 m by 3.0 m element (Fig. 2.4). The continuity of the structure is guaranteed exclusively by a system of pre-stressing tendons placed inside the concrete elements (Fig. 2.1 and 2.3).

The platform is raised about 2.0 m above the lake level and rests on piles and towers with a raster of about 25 m x 25 m.

The peculiar assembly system relying exclusively on prestressing cables reduces the time and costs required for assembling and disassembling the structure but demands a careful monitoring of the prestressing during these phases and while in service. This monitoring will be carried out using SOFO fiber optic sensors [1] installed at key positions and on heavily loaded elements. The SOFO system was developed at the Swiss Federal Institute of Technology in Lausanne and by SMARTEC in Grancia, Switzerland.

Therefore, the platforms will not be truly Smart Structures but will rather implement a health monitoring system or Smart Sensing system. Health monitoring refers to the use of in-situ, nondestructive sensing and analysis of system characteristics, including structural response, for the purpose of detecting changes, which may indicate damage or degradation [2].

3. Tensegrity

The International Journal of Space Structures published in 1992 a special issue devoted to tensegrity systems [3], where many topics related to these systems are treated.

Basically, tensegrity systems are composed of two sets of elements, a continuos set of cables, and a discontinuous set of struts. The whole defines a reticulated 3D structure in state of self-stress such as tension is exclusively carried out by cables and compression by struts. The simplest tensegrity structure is composed of 3 struts and 9 cables (Fig. 3.1).

According to our experience, this basic module is not suitable to be used directly in real structures. The main drawbacks are due to the necessity of very long struts with disadvantageous buckling load and to their extremely complicated geometry. To crate smooth surfaces with large bending radiuses it is necessary to vary the length of all struts and the assembly becomes complicated and requires and almost impossible tensional control of all the elements. Fig. 3.2 shows such a tensegrity structure that was considered in the early stages of this project.

After different optimizations, a new basic module was developed (Fig. 3.3). The main difference from the initial module of Fig. 3.1 resides in the presence of a central node containing an hydraulic jack allowing the regulation of the self-stressing state of the whole module. This hydraulic jack has a double function: to tension the structure during assembly and to monitor and actively control it while in service. Furthermore, the central node almost halves the buckling length greatly reducing the weight and cost of the structure. Varying the inclination of the struts, it is also possible to easily modify the form of the basic element and therefore of the whole structure. This basic module allows the realization of large roofing structures with a great freedom of forms. Fig. 3.4 shows a possible solution. The final form of the four FORUMs will be defined by end 1998 in cooperation with the designers. It is however expected that these tensegrity roofing will have spans over 100 m, heights of 20-30 m and a total length up to 400 m.

The main characteristics of these structures reside in their lightweight, in the possibility of obtaining complex architectural forms and in their new and intriguing esthetics. Compared to more traditional tensostructures, these tensegrity structures do not require any costly earth anchorage of the principal cables. Furthermore, the covering membrane can be attached directly to the cables of the relatively small tensegrity modules (max. 30 m x 30 m) and do not require secondary reinforcing such as a steel cable net. The membranes are therefore very easy to assemble, lightweight and inexpensive.

The price to pay to obtain such light and efficient structures resides in their geometrically nonlinear static behavior requiring relatively sophisticated analysis.

To calculate these structures we use the finite element program MCS/NASTRAN with the pre/postprocessor PATRAN, as well as specific software code developed by our company. These numerical results will be validated and refined by experimental tests on scale models of different sizes. The deformations of the struts, cables and membranes will also be measured with the SOFO fiber optic monitoring system. This same system will subsequently be integrated into a global monitoring and active control system.

4. Smart Structures

Smart structures are defined to be structures that are capable of reacting to changes in their environment (dead and live loads, temperature, etc.) through reference to relevant design criteria and maintenance strategies. Reactions may involve a modification of the behavior of the structure (changes in prestressing, damping, etc.) and/or reductions in service loading. The knowledge that determines such reactions is either explicit (represented in a knowledge bases or an algorithm) or implicit (represented by a neural network or an adaptive algorithm). Explicit representation presents the advantage of having the information accessible in an intelligible form to engineers throughout the lives of structures. These knowledge bases contain knowledge representations that are understandable by engineers and can be easily modified in the field when requirements change. Smart Structures with explicit knowledge representation can be described as “Intelligent Structures”

While there has been much activity related to the development of measurement systems for structures, applications involving the combination of active control systems with knowledge bases for full-scale civil engineering structures have not yet surfaced. At a recent congress of the International Association of Bridge and Structural Engineering [4], some participants observed that active control systems showed “potential” for use in practical situations and that extension to intelligent structures was possible. However, no evidence of practical applications of intelligent structures (as defined above) was identified at this congress. Also, international journals in this area have yet to describe any practical application of intelligent structure.

Nevertheless, much related work has been carried out. Research into adaptive structures has concentrated mostly on vibration control of structures in area where earthquake loading may be severe e.g. [5,6]. Other work has studied vibration control of bridges and buildings under wind and service loading using techniques such as active tendon control and tuned mass dampers e.g. [7,8]. Neural networks have been proposed for intelligent structures, e.g. [9,10]. Also, there has been some important work related to reliability aspects of structures with active control e.g. [11,12].

None of this works exactly fits the definition for intelligent structures as defined above. However, there is evidence that important researchers are moving in this direction. In his report of the Task force on Intelligent Control, Antsakis [13] notes that an important difference between intelligent and traditional control is the “separation” between the controller and the system to be controlled. Also intelligent control tasks include adaptation, learning, planning and coping with large amounts of data in order to act appropriately in uncertain environments. In structural field, researchers in the area of structural monitoring (smart structures) have recognized that applications of results from artificial intelligence research will have an important impact on their future research [14].

5. Deployment Of Smart Structures At Expo 2001

Because of the importance, dimensions and complexity of the Expo 2001 FORUM structures, the very few existing applications of tensegrity structures in the world as well and the security and cost issues related to this project, we intend to proceed in a very pragmatic way. In a first phase, on the base of the results obtained by numerical simulation, static verification will be carried out on 1:10 scale models using the SOFO system for monitoring. These tests will also include the verification of the structural behavior under collapse of single elements.

At the same time, aerodynamic simulations and wind tunnel tests will be carried out in cooperation with prof. Deville and prof. Hertig at EPFL.

In a second phase, the global active control and adaptive structure concept will be introduced, tested and refined. The hydraulic jacks installed at every tensegrity node and used to tension the cable during assembly will constitute the actuators of these smart structures.

The most important elements of the structure (cables, struts, membranes) will be monitored with SOFO sensors. The obtained data will be recorded in the adaptive control database. From this data it will be possible to determine if a corrective action is possible and how the jacks should be operated to achieve the desired goal. Different control methods and strategies will be developed and tested on the 1:10 models in collaboration with Prof. Smith at EPFL, Prof. Del Grosso at Genoa University, Dr. Inaudi at SMARTEC and the Institute of Material Mechanics (IMM, Grancia, Switzerland).

The implementation of the active control concept demands the following steps that will be tested on the reduced-scale models before being implemented on the real structures:

- Installation of the required measurement systems.
- Installation of the required actuation systems and their driving.

- Reliability studies to ensure that mal-function of the active control does not reduce structural reliability to unacceptable levels.
- Implementation details such as power sources, accessibility, etc.

Possible application of active control include:

- Changing actuator forces in the nodes and structural cables according to variations in temperature and/or wind in order to minimize cover-structure attachment stresses
- Changing actuator forces according to changes in lateral and vertical loading in order to minimize structural stresses and deflections. Expected loads include the weight of other structural elements, membranes, scenic elements, equipment, visitors, rain and snow.
- Changing stiffness of selected tensegrity cables (hydraulic pistons) according to loading in order to reduce dynamic effects such as excessive flapping/vibration of the cover membrane.
- Opening vents in the membranes to reduce aerodynamic pressure in case of strong winds.
- Making active control macroscopically visible to the public, thus increasing public participation with the physical elements of the exhibition.
- Interaction of the structure with specialized exhibitions in order to enhance their impact.

Besides its direct usefulness for the realization of the Expo 2001, it is expected that this project will serve as a demonstration of the active control concept. Apart from the enhanced functionality of the structures, additional benefits might include:

- Potential to demonstrate that additional design savings on future structures are possible.
- Ability to show that maintenance of structure is facilitated.
- Possibility to obtain explicit knowledge from the structure and ease of its representation and re-use in future structures.
- Facilitation of the recycling of the elements.

6. Conclusions

The Swiss Expo 2001 national exhibition will be one of the first large-scale applications of tensegrity structures. This type of structures, although very lightweight and material efficient, present a highly nonlinear behavior and therefore require careful design and monitoring. An additional increase in their efficiency can be achieved by active control, implemented with hydraulic jacks installed at key locations and driven in almost real-time by a suitable elaboration of the data obtained by the monitoring system. It is expected that the FORUMs at the Swiss Expo 2001 will constitute a large-scale example of how an appropriate combination of effective design, monitoring and active control can help to crate new daring, efficient and attractive structures for the next century.

7. References

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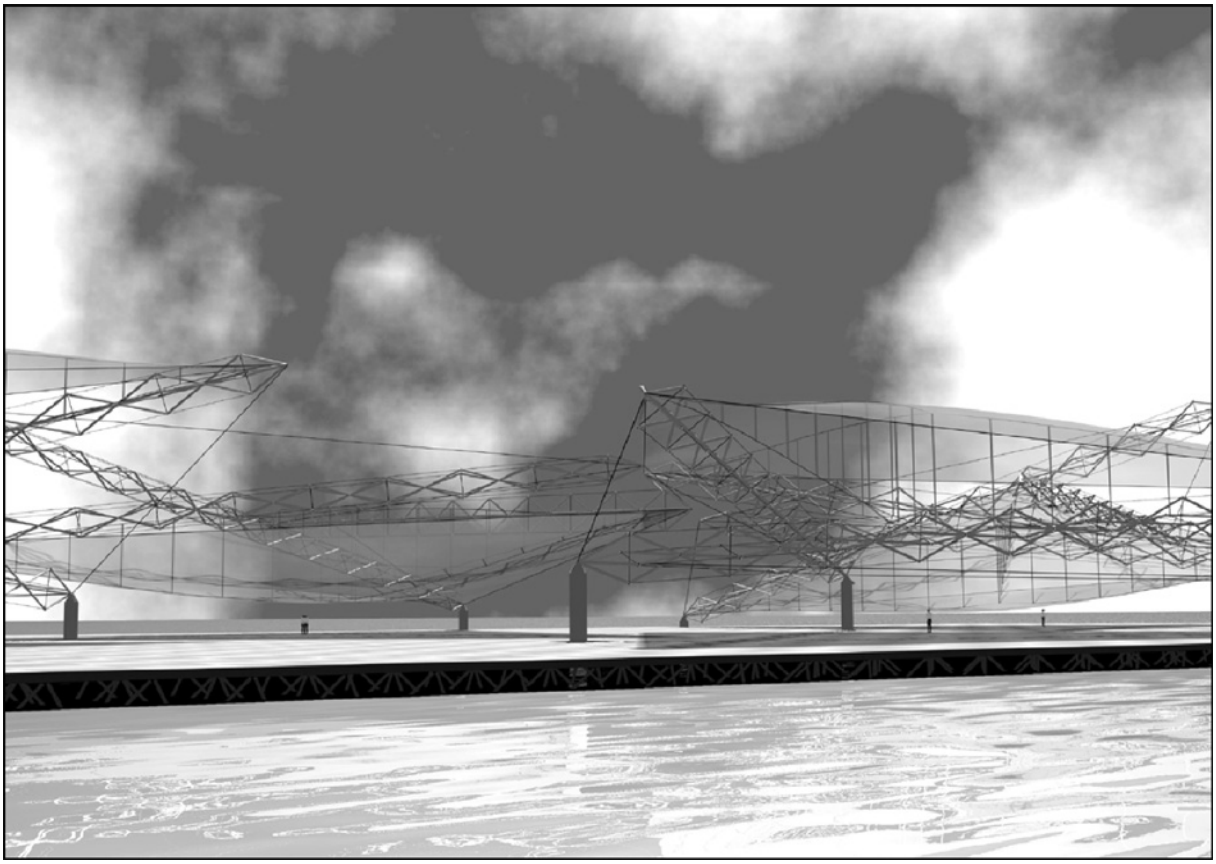


Fig.1

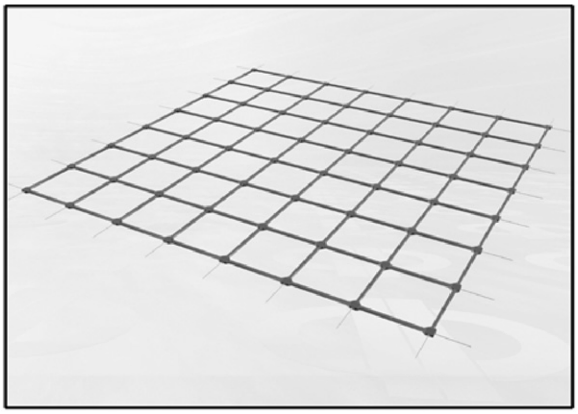


Fig.2.1

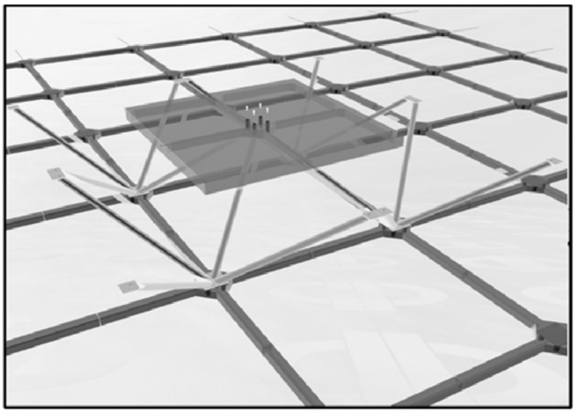


Fig.2.2

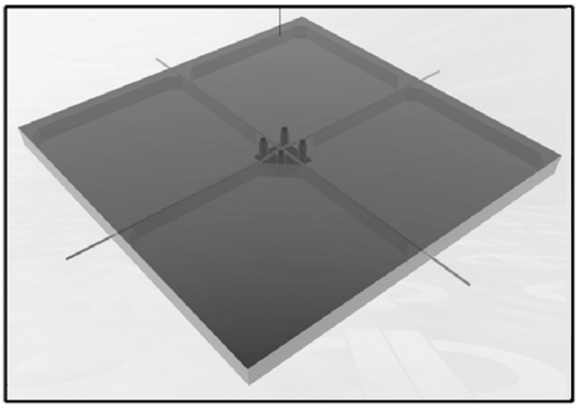


Fig.2.3

Fig.2.4

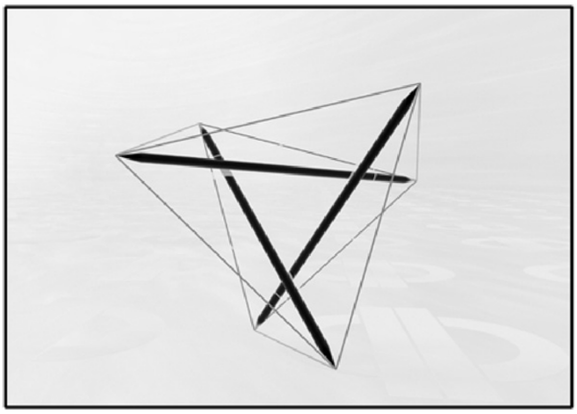


Fig.3.1

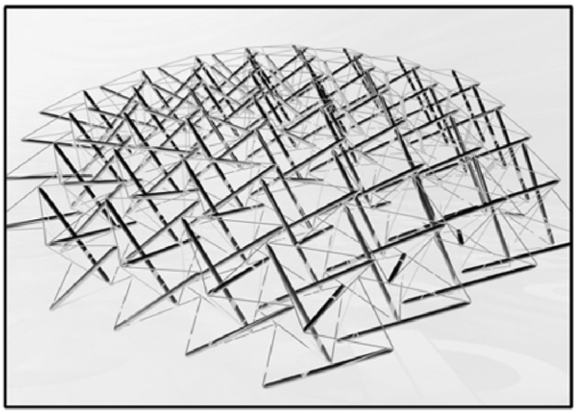
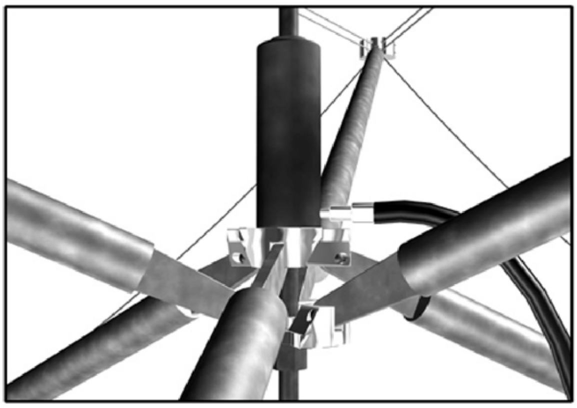


Fig.3.2



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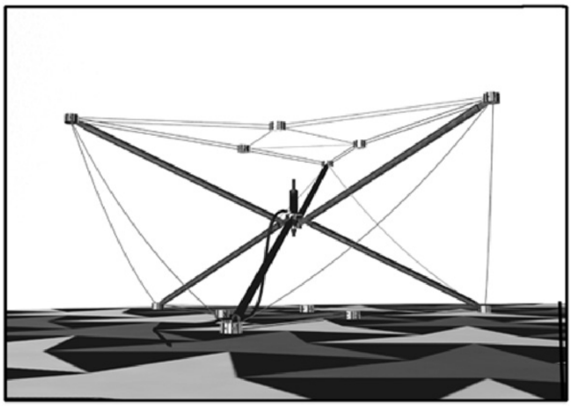

Fig.3.3a

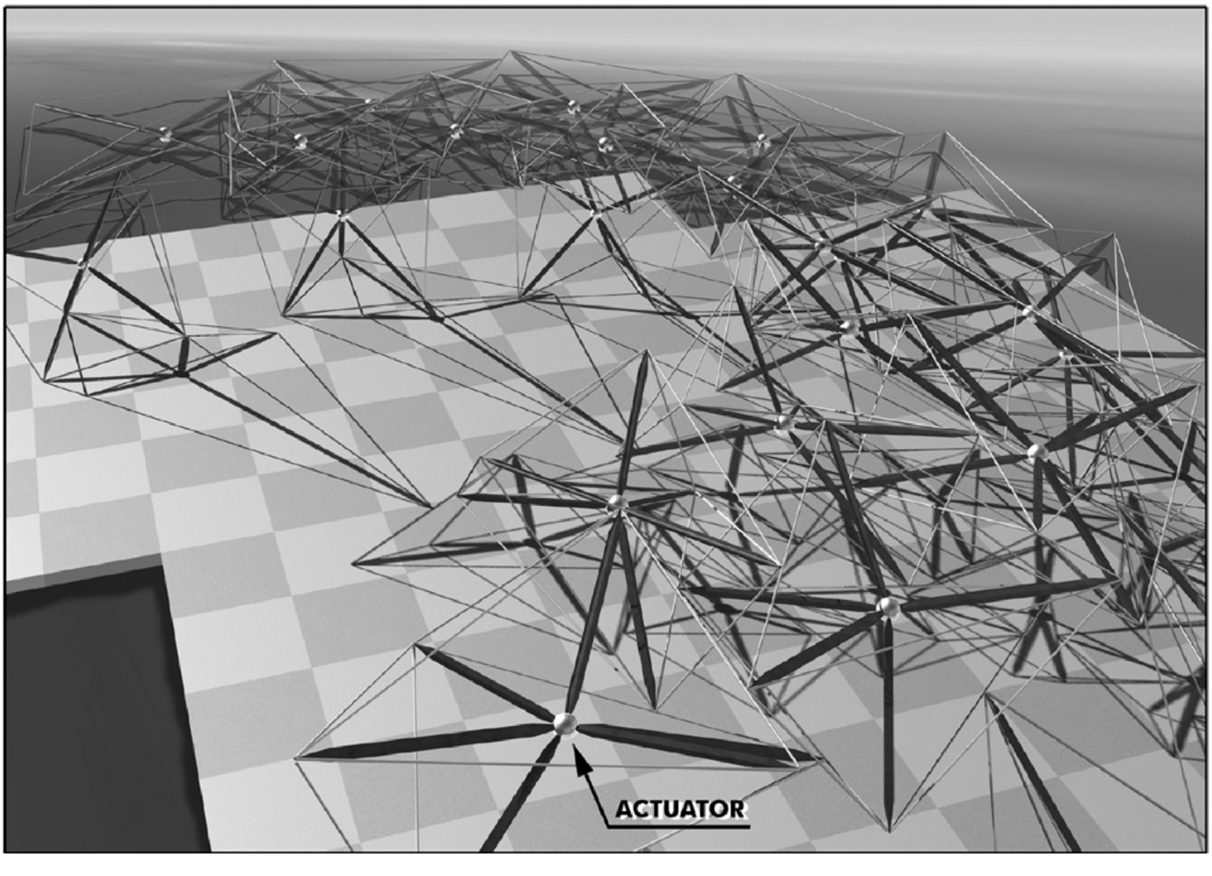

Fig.3.4