Advances in Architectural Geometry
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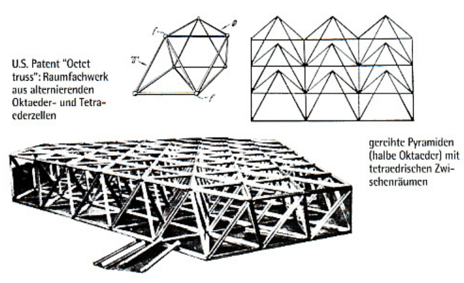
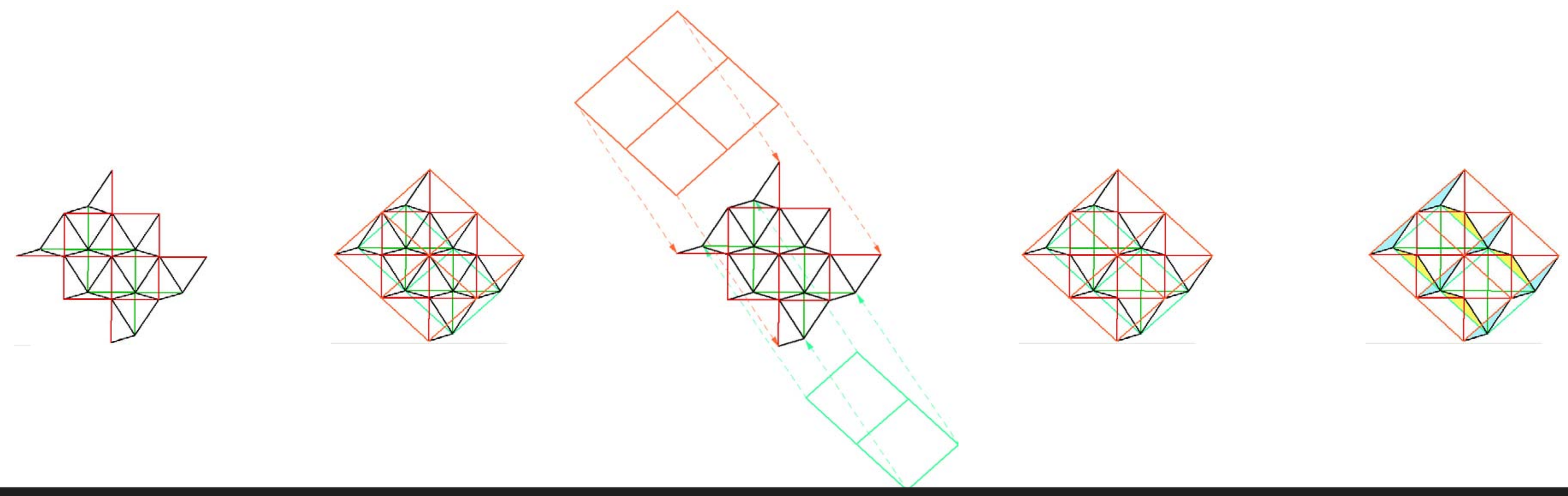
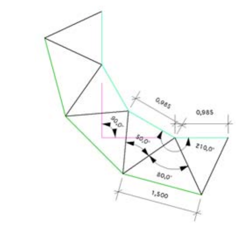
Octet Truss, R. Buckminster Fuller







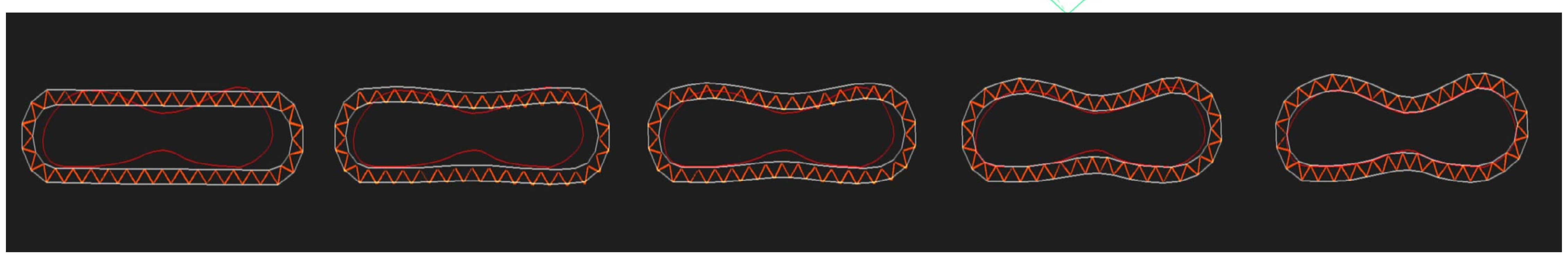


Figure 2: IK-Model simulating approximation

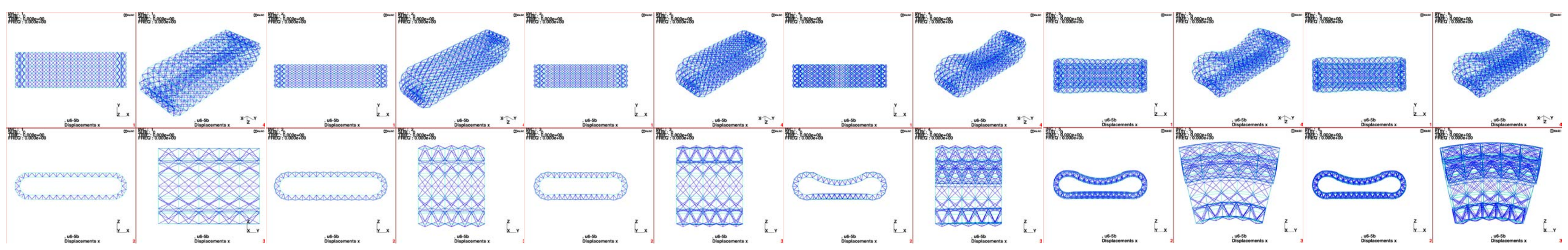
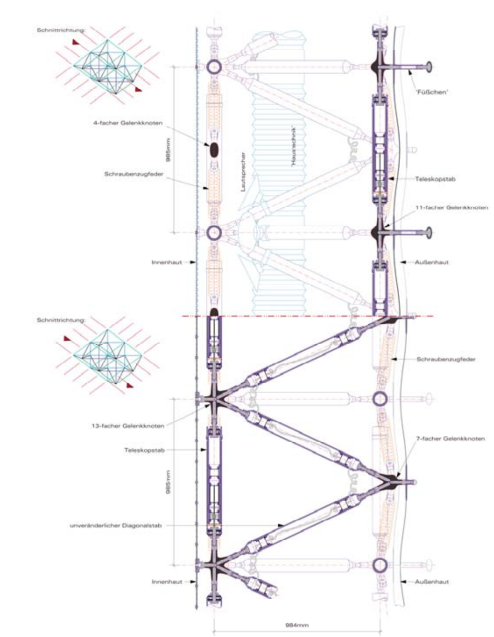
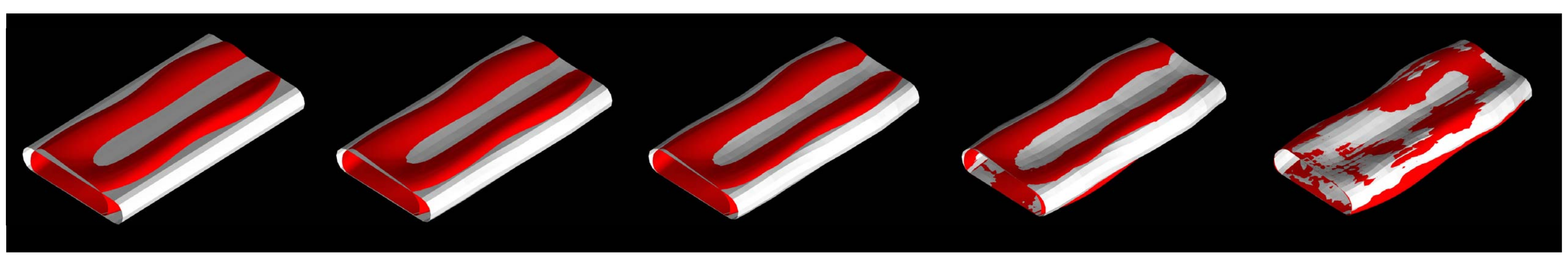


Figure 4: FEM model





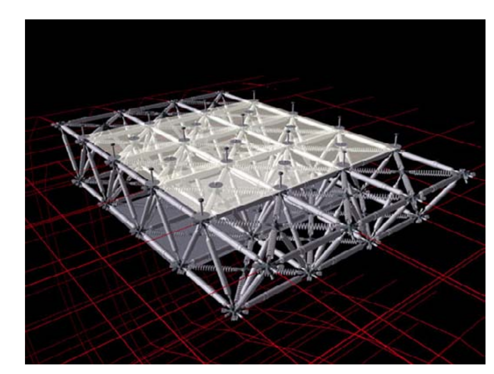


Figure 3: transformer 1 structure

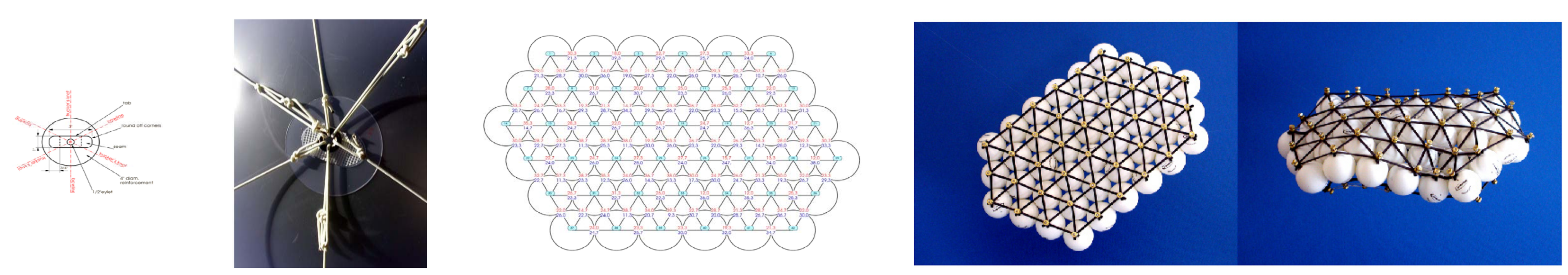
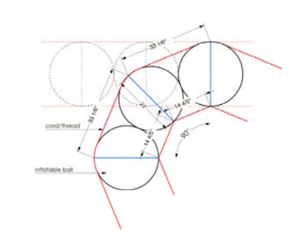
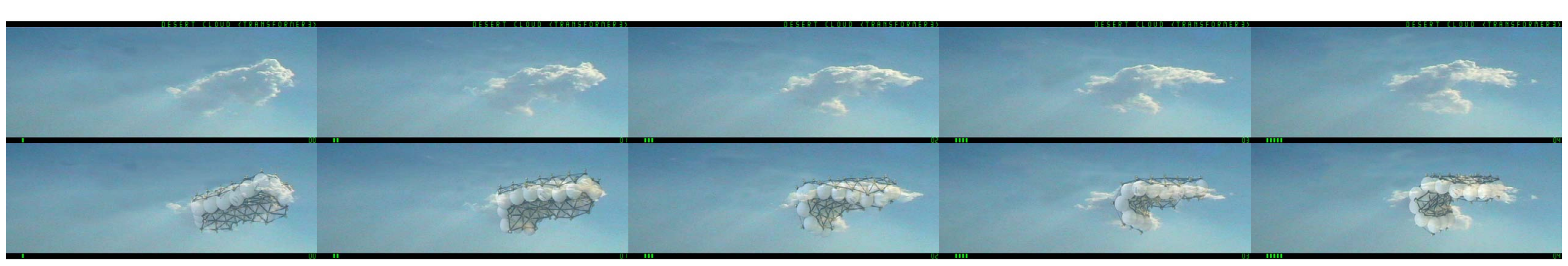
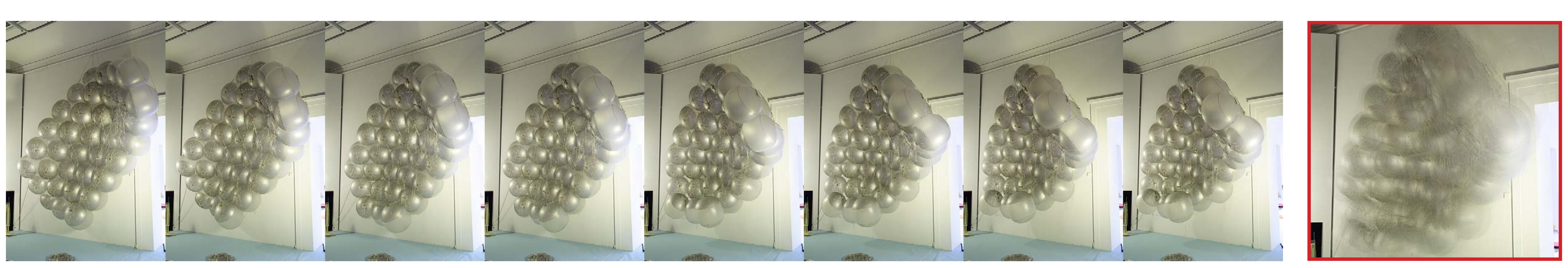


Figure 5: transformer 3, photo and schematics







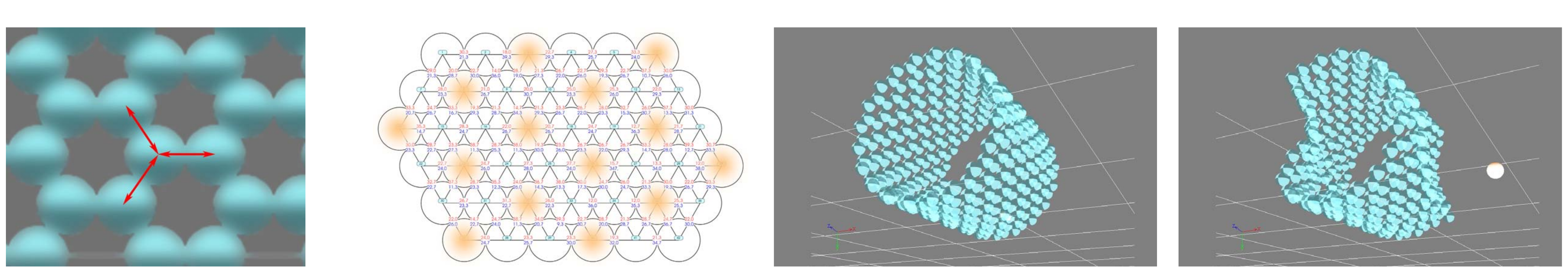
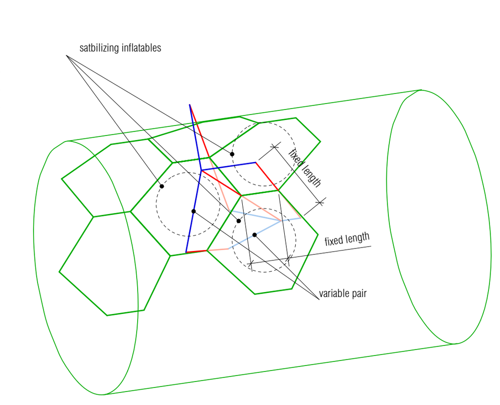


Figure 6: SpaceSeed manipulating the hexagon-based model



Precision of Continuously Variable Structures

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1 Introduction

Design tools, such as animation or scripting techniques allow for rendering nearly any kind of transformation.
Such processes can be used to produce a great variety of design solutions. In more sophisticated applications the software also can choose the „fittest" solution to survive.
However, these designs usually are frozen into one fixed shape before they are built.
As the criteria and the parameters of „fitness" usually keep on advancing, a physically continuously transformable building could take this idea of optimization to its completion.
After some experiments in the 1960ies, especially the work of Mark Fisher and Simon Conolly, the work of Kas Oosterhuis and Hyperbody eventually introduced the idea of a programmable, interactive form and actually transformable buildings more effectively into the architectural discourse.
Meanwhile, there are considerations of how to approach such a difficult design task and especially exciting concepts for an interactive architecture have been developed. At the same time through the progress of processing capacity, optimization by simulation has been taken to an oustanding level.
Yet, there have been rare attempts to investigate the precision of such a structure: how precisely it can approximate to a given form by a control application.

2 Precision of a Continuously Variable Structure

To be fully programmable - in a similar meaning as forms are editible in a computer programm - we have to find a construction which allows for an endless number of forms. Of course, already due to the finite character of the material involved, we face major limitations. Yet, as long as the transformation process is continuous and allows for all three possible kinds of curvatures - single-curved, double-curved synclastic and double-curved anti-clastic -, in more or less arbitrary combinations, a rough approximation to a sufficient number of possible forms can be performed.
The performance of an adaptable construction thus can be seen as its ability to approximate within boundaries to an arbitrary given geometry, and the precision with which this can be achieved. We define variety as the ability to produce different topologies and different geometric properties.
Although, the author also investigated the possibilities of topological change, in this paper only homeomorphic change shall be discussed.
Therefore, there are two major constraints: the underlying topological structure; the restrictions in size, defined by the capacity of the expanded material; finally, the most important constraining parameter regarding precision is the filleting radius when approximating curvature and edges.
The in the following introduced case studies all rely on the change of linear elements for the transformation process. Linear actuators are most simple transformation drivers. It is evident that for feasibility reasons, the number of necessary actuators should be minimized, as well as the cost for these devices.
All structures introduced here, are double-layered structures. In contrary, the Muscle-Projects of Hyperbody, usually applied single-layered structures. There are two disadvantages to these structures: First structurally, a single-layer structure usually is optimized as a grid shell, which is a very specific form. Any deviation from it leads to massively increased member dimensions. Second, for obvious reasons, if such a structure becomes locally flat, a situation is the consequence, where linear length change does not lead to curvature change or to an undecidable situation (Figure 1).
It has to be noted, that all structures introduced in this paper can at best approximate a certain form. The scale of a the form, which should be approximated is taken for being of less importance.

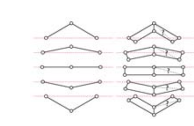

Figure 1: undecidable situation for a single-layer structure

3 Case Study I: A transformable Space-Frame

Transformer 1 was designed to investigate how a large-scale structure can approximate to any arbitrary homeomorphic object. The deviation from the targeted object´s shape has been considered as the degree of precision. Approximation means in this case, that the skin of the original object is as close as possible to the skin of the target object. It also means that geometric qualities such as concave, convex, double-curved, single-curved and so on are emulated. The project aims at a great formal variety, but also at introducing spatial transformation itself as another architectural design concept.
The structure was planned to a highly detailed level to get as many material and geometric properties to enable a proper analysis. It was verified by means of inverse kinematics and finite elements method (using MARC/Mentat).
That the results have been somewhat coarse was not surprising. This is much like the bad resolution of early digital renderings. In Figure 2 the grey skin is manipulated by an IK-model (Inverse Kinematics), which simulates the construction concept of Figure 3. The red skin represents the geometry, which should be approximated.
The structure itself was based on a space-frame construction (Figure 3), with a design suited to reduce actively changing members, relying only on elongation for the transformation process. The actively changing members form two opposing meshes, so that the length differences of opposing members describe a unique shape.
From the IK-model, the different values of the grid net of a specific form could be extracted
Expressed as a percentage of the basic mesh length the data was fed into an FE-Model. By only changing the length of the specified members, the transformation process took place as expected, while specific physical data, such as the strength of the elements or dead loads and live loads, was taken into account (Figure 4).
However, the tested form was not a free form, but a surface of revolution. Any problems related to excentricity were thus avoided. Further the model factored material properties in, yet, geometrically, it assumed that the joints have no physical size. This not realisitic. We tried to approach this problem by conceiving a joint using reinforced rubber and eventually built a prototype. Within limits this prototype seemed to have the desired properties - flexibly connecting the rods with the least possible size. Yet, this does not solve the geometrical problems, which occur during the transformation process: the axis simply do not meet in a single point, when a free from surface should be approximated.

4 Case Study II: Tensile Structures

With Transformer 3 the principle of opposing changeable grids was applied to tensile nets connected by a layer of inflatable balls.
An inner and an outer net of cables was constructed, where only tensile forces apply. These cables were adjustable. They are connected to the poles of the inflatable cushions, which take compression forces. Their skin again is always under tension, so besides the air, all materials only have to take tensile forces. This allows for an ultra-light weight structure. The cables connecting to the same pole were attached by a minimized eylet. Excentricity could thus be much better minimized. Further, structurally, this phenomenon does not pose a problem to a pure tensile net, as an equilibrum is found by the structure itself.
However, it is evident that such a formfinding structure is less predictible. These poor qualities of controllability are boosted by another inherent geometric inaccuracy: Only flexible balls can allow for a double-curved transformation process, if the spheres are arranged in a triangular pattern.
Due to the flexibility of the pneumatic elements, this construction becomes even less precise (Figure 5).
On the other hand, due to its light weight concept, it can be realized due to the well available materials, which are involved and it is easy to transport, assemble and to manipulate. Structures were build for three exhibitions and one commercial client. For economic reasons, they had to be operated manually.

5 Case Study III: Actuating A Tensile Structure

The Transformer 3 structure is currently advanced at Hyperbody, a sub-department of TU Delft´s Faculty of architecture, led by prof. Kas Oosterhuis. In the frame of a commission for a mobile interactive think lab, the structure shall be taken to be realized full scale and filly actuated.
The structure is simulated, using Virtools software development plattform, which has already been successfully applied to process data and control actuators of dynamic structures at Hyperbody.
To get closer to the goal of a more precise transformation process, the pneumatic spheres are distributed hexagonally on a cylindrical surface.
Virtools allows for programming behaviours. Thus, each sphere „knows" its neihbour and conects to it at a distance of their diameter. A cylindrical topology allows for a simpler control of the transformation process.
Yet, the hexagonal grid, structurally, is not stable. For the full scale construction, we will reintroduce some of the balls, which have been eliminated to obtain the hexagonal grid, deflating them locally when the transformation process is in progress, reinflating them, if a desired state is reached, again locally, as the structure should be able to transform permanently.
The Virtools model itself is manipulated by a technique, which is referred to as SpaceSeeds. These are points in space, which keep the elements of the structure at an arbitrary distance. This can lead to a „collapse" of the structure. Therefore also the Virtools model needs to be stabilized.
To stabilize the virtual model, the angles between neighbors are limited and all elements „memorize" there initial position, so an undesired shape can be undone by simply reducing the range of a SpaceSeed (Figure 6).
For an interactive design concept, this set-up offers many possibilities: to open or close, augment or reduce space. To pursue the idea of precise approximation and permanent adjustment to a given changing shape, a geometrical solution will have to be found. It is assumed by the author, that the performance of such a structure can be improved significantly by an equilateral hexagonal grid, which approximates to an arbitrary surface.
Conclusion
Three concepts for an actually transformable „real-world" construction have been introduced, one of them has been realized.
A tensile structure has clear structural advantages, as flexible joints are easier to design and to manipulate. Also lightness facilitates the feasibility of the transformation process.
„Precision", as proposed in this paper, will only be achieved after a proper geometrical analysis is accomplished.
To team up with experts in the field would greatly enhance the efforts of this investigation.

Acknowledgements
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