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A Haptic Feedback Device based on an Active Mesh

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ABSTRACT

This paper introduces the SmartMesh, a novel type of active structure capable of deforming actively its shape and thus being able to form objects. It is a new approach to find a solution to the difficulties that are encountered in the field of haptic interaction in virtual environments. The SmartMesh creates in real time the virtual objects as seen through head mounted displays or on projection screens at the according position in space. Thus, the virtual objects are not virtual anymore. The SmartMesh can be embedded into a table, into walls, ceilings and floors. The SmartMesh is actuated by a large number of linear actuators and its resolution depends on the amount of nodes and the length of the actuators.

Keywords

Haptic displays, active mesh, active structures, free hand haptic feedback devices, actuators, linear actuators, smart materials

1. INTRODUCTION

While the visual and auditory components in virtual environments have reached a quite satisfying quality, the haptic components are still in the fledgling stages. In fact, today's state of the art haptic interfaces show some constraints and disadvantages. This is due to several factors, though they are crystallisable firstly into the complexity of the human anatomy and its dexterity of the tactile sense and secondly into the inappropriate properties of the state of the art actuators.

Basically, two types of haptic interfaces can be distinguished. The grounded devices and the portable ones [1]. The former types mostly consist of robot arms, which work in a reverse mode, such as the PHANToM [2] or The Haptic Master [3] for instance. Many prototypes based on this principle have been developed. They can be grounded on a desk, a floor or a ceiling. The user usually holds or touches the tip of them and haptic feedback is provided in the desired direction and strength. Other types of grounded devices are the pin array based ones for texture simulation, such as the Haptic Texture Display [8] or the Array Force Display [9].

The portable devices mostly consist of exoskeletons, that transfer mechanically the feedback signal from it source to the desired location on the body. They are always grounded on the body itself. Different types can be found also in this category, such as the CyberGrasp [4], the Rutgers Master Glove [5] or studies, such as a haptic display based on a particle mechanical constraint working principle [6] for instance.

These devices were developed for dedicated tasks and fulfill their requirements quite well. Thus, some of the existing devices can be used with a quite satisfying quality for some specific simulations, such as minimal invasive surgery simulations for instance, where high precision and dexterity is needed [7]. The PHANToM or the CyberGrasp for example, both commercially available devices, can be well used for dedicated tasks, where dexterity and applied forces are in well known and defined ranges.

However, the human perception does not only concentrate on a few points of the extremities. For many tasks, haptic feedback to the whole palm, the whole hand or even to the whole body is needed. A good example can be given in relation to surgery interventions. Investigations made during different surgery interventions [11] have shown, that the surgeons use their hands directly as surgery instruments (pull, push, palpate, hold, etc.) during up to 20% of an intervention time. Thus, if a virtual reality simulator for open surgery has to be developed, then an overall haptic feedback is not only needed but mandatory.

The new approach presented in this paper takes into account the above mentioned problems. The SmartMesh is an active structure, which simulates the object itself, its shape and also its physical, structural behavior. The surfaces and structures created by the SmartMesh can be touched practically as real objects. By controlling also the stiffness of the

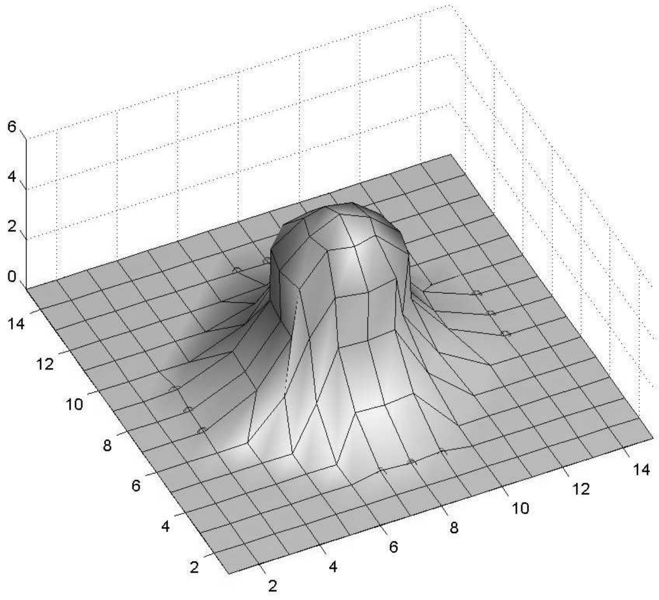


Figure 1: A model of a mesh representing a knob

actuators, thus of the whole mesh, different types of materials can be simulated, enhancing dramatically the haptic experience. In figure 1 the SmartMesh with 15*15 nodes represents a knob. This figure was the result of a simulation made with Matlab [10] (more details can be found in section 2).

The SmartMesh differs drastically from devices based on needles by its ability to create overhanging surfaces as shown in figure 2. This augments by factors the amount of possible simulated objects. The SmartMesh can be integrated in several places, such as tables, walls, ceilings and floors. It is scalable, which means, that structures with a low number of nodes can be developed as well as such with a high resolution.

2. PRELIMINARY WORK

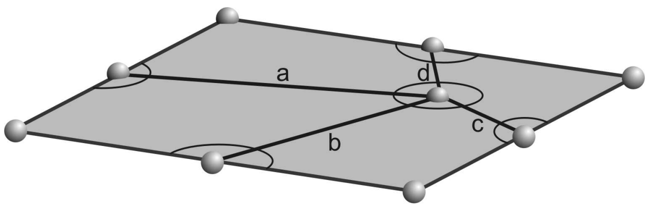


Figure 3: Moving a node, while keeping the lengths and the angles in a defined range

Basic research has been done to understand, if such a structure can work out mechanically. Simulations in Matlab were done first with a one-layer mesh. Figures 1 and 2 show some of the results achieved with it. In both figures the one-layer mesh, one grid with 15*15 nodes and quadrilateral polygons, is clearly visible. The structures were created by elongating and shortening dedicated linkages (in figure 3 that would be linkages a,b,c,d), while keeping the lengths as well as the angles between the adjacent linkages in a defined range (for example lengths between 1 and 1.8 units and angles between 30° and 150°). These constraints were used with an outlook on a mechanical structure that comes up with mechanical constraints, such as for example joints with a maximum angle exertion or linear actuator, that usually have a limited elongation rate.

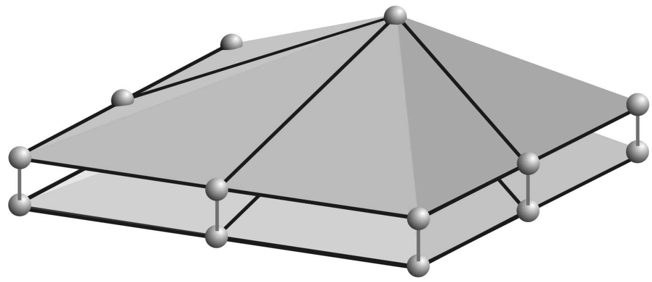


Figure 4: The model of a double-layer mesh

To be able to move a particular node out of the plane it was necessary to add a second grid. A detailed explanation about the principle and the developed solution for the connection can be found in section 3. In this vein, a double-layer mesh was generated. Figure 4 shows the model. With this double-layer model, simulations were done considering possible mechanical constraints. Equivalent to the one-layer model, all angles between adjacent linkages, including the connections between the two grids, and the lengths of the linkages were controlled by the simulation. The simulation would not allow movements outside the given ranges.

3. THE SMARTMESH

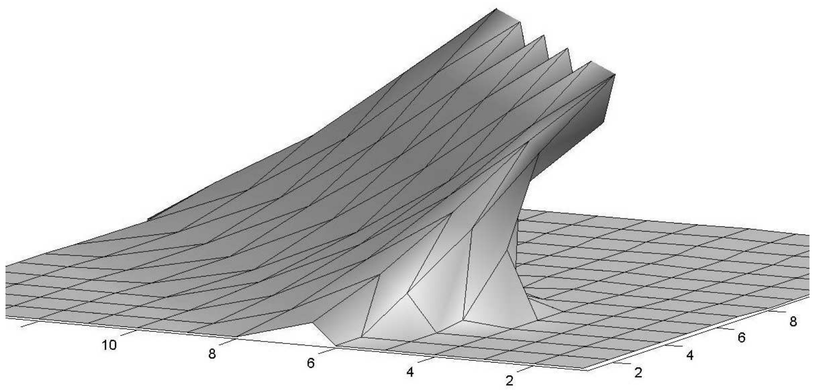


Figure 2: A wave generated with a one-layer model

The SmartMesh consists of two grids connected together forming a multi layer structure. These grids consist of nodes connected by linkages. The linkages can be shortened or elongated and their actual length can be measured. By elongating these linkages, the shape of the whole structure can be altered in any dimension to form the surface of an object. By controlling the stiffness of the actuators, the physical behavior of the structure can be altered to simulate different types of materials. The resolution of the whole structure is determined by the total amount of nodes and by the length of the linkages. The Mesh can have a rectangular or a quadratic shape. However, for the following analysis, a n*n nodes SmartMesh (thus quadratic) has been chosen.

3.1 The double-layer

A particular node can be moved within the plane by changing the length of the adjoining linkages respectively (see figure 3). But to be able to move a particular node in the third dimension a second grid is needed. The principle can be explained with a cross section through the structure as follows (see figure 5): Node P_1 of the upper grid is connected to the

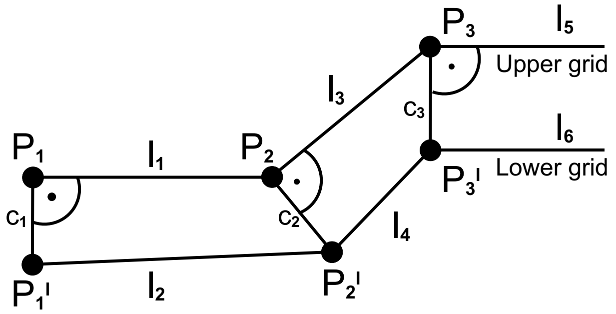


Figure 5: cross section for the movement in the third dimension

equivalent node P_1^l of the lower grid perpendicularly to the linkage l_1. These perpendiculars c_n have a constant length. It is assumed now, that the nodes P_1 and P_1^l are grounded. By elongating or shortening the lower linkage l_2, linkage l_3 is forced to move, thus rotating node P_3 around node P_2. The length of linkage l_4 determines the position of P_3^l, thus

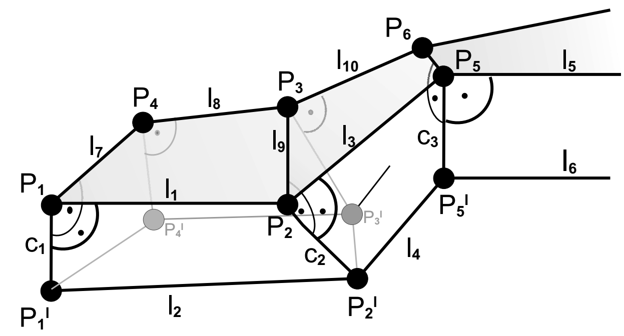


Figure 6: Principle for the complete mesh

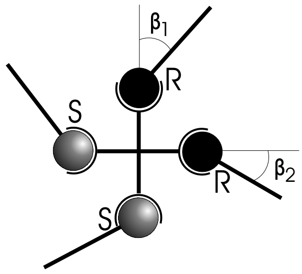
the direction of l_5.

The same principle can be extended to the whole structure, by connecting all upper nodes to the equivalent lower nodes perpendicular to two of the linkages of the upper grid (See figure 6). In this example c_1 would always be perpendicular to l_1 and l_7. Using this technique, the positioning of a node in the z-direction can be accomplished. However, this is not the only advantage. A second layer ensures also a better stability during manipulation, due to its better distribution of the forces on both grids. As a result, the torque on one single node will be smaller when a force is applied.

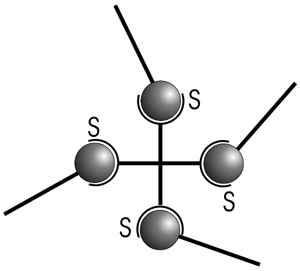
3.2 Nodes

The SmartMesh consists of $2n^2$ nodes (two grids with n^2 nodes each) and each node connects four linkages and one perpendicular. An ideal node would have all four joints embedded in one single point and would have no dimension at all. However, in reality this is not possible, which leads automatically to a node with a specific size. The size depends on the architecture of the joints and their position.

For this prototype the nodes have been designed as follows: Each node of the upper grid has two standard revolute joints and two standard spherical ones, while each node of the lower grid has only standard spherical joints. Figure 7(a) and 7(b) show the models of the nodes of the lower, respectively the upper grid. The revolute joints ensure that the two linkages attached to them are always perpendicular to the node's centerline.



(a) Upper node with two spherical and two revolute joints



(b) Lower node with four spherical joints

Figure 7: Modelling of the nodes

As the nodes have a defined size, the joints show some constraints in their rotation angle. A revolute joint for example has ideally a rotation angle of 360°. For the chosen design this is not possible, thus a working range of -90° to +90° is aimed at. The same applies to the spherical joints. Here the working range aimed at, is from -60° to +60°. In section 5 the achieved results will be discussed.

3.3 Actuators

The SmartMesh consists of $4n(n-1)$ linkages, which have one degree of freedom each (prismatic joint) and thus can be elongated or respectively shortened. Their size defines practically the overall size of an n*n SmartMesh.

However, these linkages will be driven by linear actuators to be able to activate the structure. The amount of actuators needed corresponds to the total number of linkages (see section 4 for the analysis of the degrees of freedom). The type of linear actuator, thus its technical specification, affects the physical behavior of the complete structure.

4. DEGREES OF FREEDOM AND COMPLEXITY

The basic element of the SmartMesh is a 2x2 nodes structure as illustrated in figure 8. It contains 8 nodes (4 in the upper, 4 in the lower grid), 8 linkages and 4 perpendiculars, which connect both grids together.

To be able to understand, if the structure is controllable, the degrees of freedom have to be determined. The analysis of

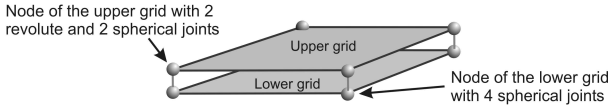


Figure 8: The basic element of the SmartMesh

the degrees of freedom can be done by using the Kutzbach [12], [13] criterion: An arbitrary spatial kinematic chain with n_B bodies (without the grounded ones), n_J joints, f_{Gi} degrees of freedom per joint and $n_L = n_J - n_B$ loops, has

$$f = \sum_{i=1}^{n_J} f_{Gi} - 6n_L$$

degrees of freedom. Mechanical systems may also have some passive degrees of freedom. Passive (or isolated) degrees of freedom are unconstrained degrees of freedom, which do not affect the transmission of motion in a mechanism. A linkage with two spherical joints for example, has one passive degree of freedom - the rotation around its own axis. The Kutzbach criterion detects them properly.

Figure 9 shows the chain structure of the basic element for the modelling. It has to be noted, that a linkage consists of tow bodies connected by one prismatic joint. This model has $n_B = 19$ bodies (3 nodes (=3 bodies) and 8 linkages with 2 bodies each; the grounded nodes are not counted), $n_J = 24$ joints (12 spherical, 4 revolute and 8 prismatic joints). The amount of loops can be calculated according to $n_L = n_J - n_B$, which is $n_L = 5$. Notice, that a spherical joint has 3, the revolute and prismatic joints have 1 degrees of freedom respectively. Using now the formula by Kutzbach, the number of degrees of freedom would be equal 18. It is important now to remind, that the passive degrees of freedom should not be counted. The basic element has exact 4 isolated (passive) degrees of freedom, thus the whole system exactly 14 of them.

The whole structure of the prototype, which is being build up, has two grids connected through perpendiculars as above explained and one grid has exactly n^2 nodes and $2n(n-1)$ linkages. Thus the overall structure consists of $4n(n-1)$ linkages, $2n^2$ nodes and n^2 perpendiculars and the complexity of the system rises quadratically. Nevertheless, a 4x4 nodes double-layer mesh is statically determinate. The structure has 48 linkages and exactly 48 independent degrees of freedom. By replacing all the linkages with linear actuators, which have 1 degree of freedom each, the mechanism can be completely controlled.

5. EXPERIMENTAL RESULTS

5.1 Nodes

The nodes of the prototype were realized by combining the equivalent nodes of the upper and lower grid to one single node, called from now on a 'node-double'. The node-double is made up of six spherical and two revolute joints. In figure 10(a) the node-double and in figure 10(b) the actuation range is shown.

The nodes were realized with plexiglas due to its good handling properties for fabrication, its small weight and for its

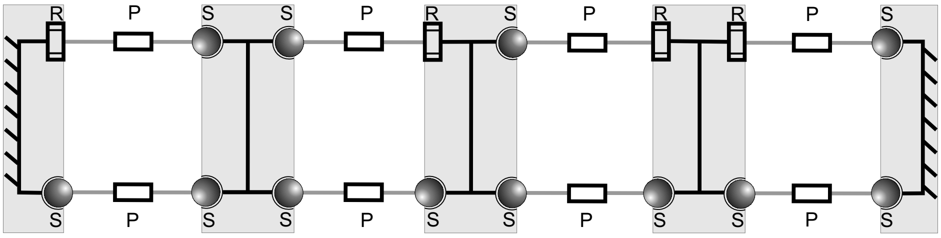
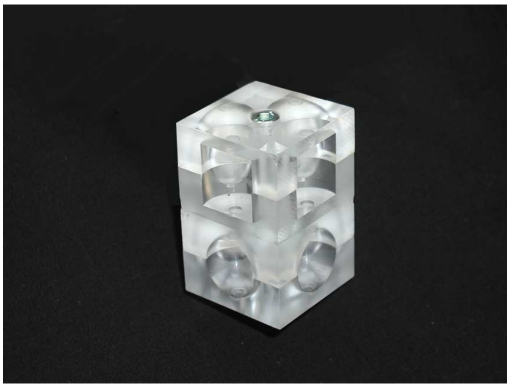
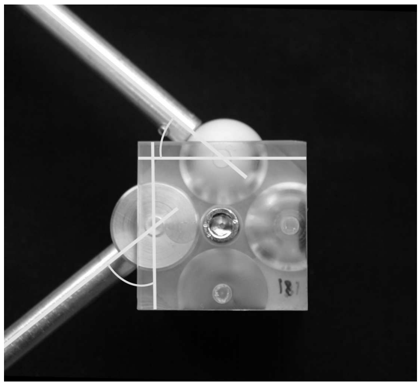


Figure 9: The model of the basic element for the analysis of the DOF



(a) Node-double



(b) Actuation range

Figure 10: Prototype of the node

transparency. A node-double with the overall dimensions of 37mm*37mm*57mm weights 56 grams. The rotation angle achieved for the revolute joint is 78° while with the spherical joint angles of 98° can be measured.

5.2 Linkages

The prototype here presented has no linear actuators build in yet. However, the linkages have a prismatic joint, which can be fixed at any position with a screw. The elongation rate is equal to 60%. The length in the retracted position is 120mm, in the extended 192mm and the diameter measures 8mm. The overall weight of a linkages with two spherical joints (figure 11(a)) is 26g, with one spherical and one revolute joint 36g (figure 11(b)). With these linkages different shapes can be created manually.

5.3 SmartMesh

The SmartMesh realized has 16 node-doubles and 48 linkages as introduced in former two sections. The corner node-double, that connects its two linkages via revolute joints is grounded. Its size with completely retracted linkages is 480mm*480mm while in the maximum extension it measures 690mm*690mm. Thus an overall extension of 43.7% can be realized. It has a total weight of 2750g. Despite its low resolution, it is already able to form many different surfaces, including also some overhanging ones. Figures 12-17 show some of these surfaces (in some cases two nodes were grounded).

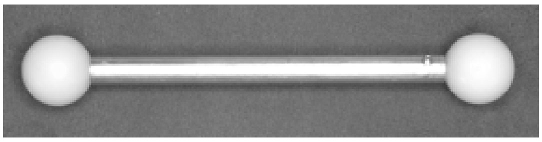
Measurements were done with this configuration as well to understand what forces the single actuators have to be able to exert and to hold. Thus, forces of at least $15N$ have to be achieved.

6. PROBLEMS AND FUTURE WORK

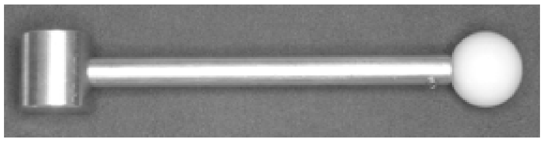
Although the prototype shows many promising features it still is in a very early development stage. It has not been actuated yet, which is a very important step to clarify if the concept works out as predicted. Thus, unknown problems will become visible as soon as all linkages will be replaced by the actuators.

To keep the overall weight as low as possible, these actuators have to be small in size and weight. In addition, they have to show a good elongation rate (at least 60%). After an intensive study, it can be said, that smart materials seem to be more suited for such a kind of application, than any other state of the art actuator. This is mainly due to their high power density. In addition, they partly show also other very good characteristics, such as high frequency range, high expansion rates, a long durability, but also the capability to sense and measure their environment. Electroactive polymers for instance, are often compared to human muscles for their similar characteristics and thus are also called 'artificial muscles'. Thus, studies are already being made on how to integrate shape memory alloys [14] or electro active polymers [15] in such a linkage. Integrating smart materials has another advantage: the much more easier ability to scale down the whole mesh.

Further, the nodes will be downsized and other materials, such as carbon fibers for instance, will be used to reduce their weight and to improve their mechanical properties. By



(a) Spherical-Spherical linkage



(b) Spherical-Revolute linkage

Figure 11: Linkage with prismatic joint

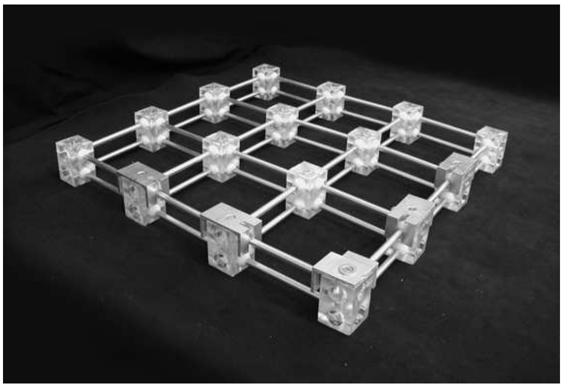


Figure 12: Flat SmartMesh

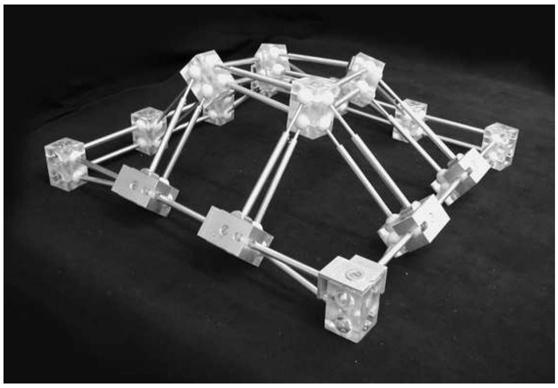


Figure 13: SmartMesh with raised nodes

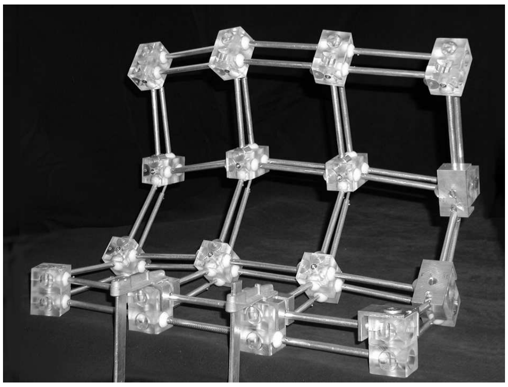


Figure 14: A wave

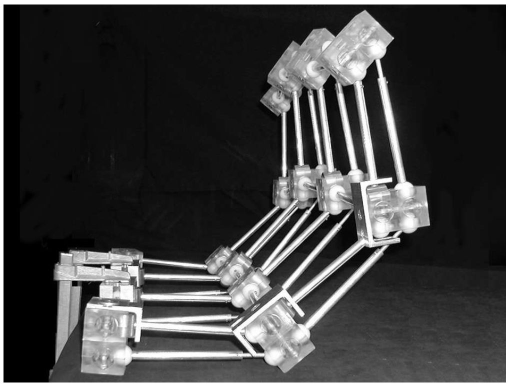


Figure 15: Side view of the wave

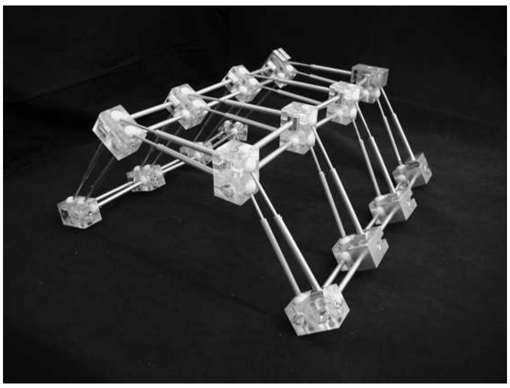


Figure 16: A bridge

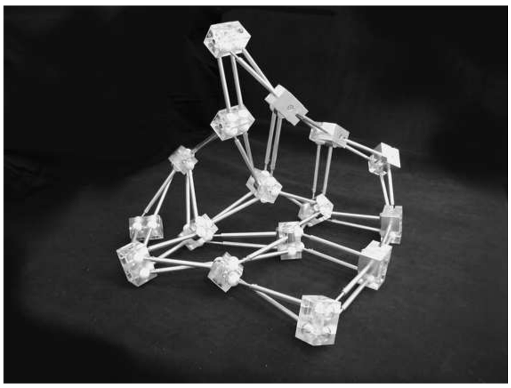


Figure 17: A random structure

scaling down their size also the inaccuracy of the whole system can be reduced: the rotation around their own axes (with all its implications). In addition, slackness has to be eliminated as much as possible. The joints themselves can be improved to allow a bigger range of rotation. However, extensive studies are being done here as well to find better solutions for the joints, such as joints without mechanical parts. This is also being done in view of a scaling down of the whole mesh.

The SmartMesh will be covered by a texture to hide and protect the complex mechanism. This texture has to be stretchable but also as stiff as possible.

Not only mechanical properties have to be improved. A concept for the quite complex control hardware has to be studied. It may be interesting for example, to have one node being responsible for its neighbors, integrating in it the actuation and sensory hardware. This would drastically reduce the connections to the controlling mainframe.

Much effort has also to be put into the modelling of the shapes. As the structure consists of loops, the position in space of any node-double depends on the positions of its neighbors and the lengths of the linkages to latter. To form a structure it will then be necessary to have some kind of sequence of actuation of the linkages during the shape forming. This sequence has to be calculated in real time. Thus, powerful algorithm have to be studied. The more nodes a structure contains, the more complex the forming will be. In addition, some interfaces to existing applications or even the applications themselves have to be written.

7. APPLICATIONS

The SmartMesh can be applied in many fields and perform also several functions. So it may have only output or only input functionalities or it may include both of them.

In the field of virtual reality its application is on the hand. It can generate objects, which can change their shape and which can be touched and grasped. Furthermore some material properties can be simulated, such as the stiffness for instance. The SmartMesh can create environments, like particular uneven surfaces on the ground, virtual clays or emerging and overhanging objects from walls and ceilings. The quality of the representation of the objects is related directly to the amount of nodes and the lengths of the linkages.

The SmartMesh can also be used as a novel type of input device for any kind of machine. It will be a device capable of changing its shape depending on the application or the actual task. For example CAD-input devices as well as navigation joysticks could be build up by such a mesh. Aligned to it, the software game industry, can integrate such input devices into their applications to enhance the feeling of immersion into a game.

Up to some extend the SmartMesh could also be used as a rapid prototyping tool or as a reusable mold, if the resolution is high enough.

In the world of design, such a SmartMesh can constitute a new type of furniture, which is able to change its shape. But it can also be just an instrument to create art objects.

8. CONCLUSION

The SmartMesh is still in a very early stage of development, but its principle and its structure allows the forming of overhanging surfaces. Compared to the amount of surfaces, which can be represented with pin array based devices, the SmartMesh raises by factors the number of structures that can be created. The haptic feedback provided by it is area-wide and not limited to some single points. The amount of nodes defines its resolution and thus the smoothness and texture of any surface. By miniaturizing the SmartMesh (with nano technology for example) the goal of a high quality reproduction of a texture can be achieved. In addition, the SmartMesh is not only able to reproduce static surfaces but also moving and vibrating structures up to a certain extend.

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