Morphing the SmartMesh: Proposing a Novel Control Architecture

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Abstract. In this paper we propose a novel control algorithm for the SmartMesh [1] based on clothes simulation modelled with masses and springs. The SmartMesh is modelled as a tissue or as a blanket which is attracted by the object, that has to be represented, enveloping it. Applying the sampled data (the lengths of the springs) to the actuators of the SmartMesh will result in a deformation of the structure.
The SmartMesh has been recently proposed as a novel type of haptic display affording the output of 3D shapes with the purpose to give a wide area haptic feedback. The SmartMesh is based on a mechanical structure, more precisely, on a double layer grid of nodes linked by prismatic joints. By elongating the linkages, the structure can be deformed to represent the desired object.

1 Introduction

Compared to the development of computational speed or the increase in the amount of memory over the last decades, the development of more powerful man machine interfaces is lagging behind. The keyboard or the mouse for instance are practically the same as in the seventies, even though they have been technically improved. This is even more amazing as the need for more advanced interface devices has not only been growing strongly in some dedicated and specialized work environments, but also for daily applications. The rising number of human machine interfaces incorporating haptic feedback capabilities, such as some of the commercially available mice or similar devices and more advanced haptic feedback devices, such as the Phantom [4], the CyberGrasp [6] or the the Haptic Master [5] for instance, reflect the growing need for these more intuitive and powerful interfaces. Simultaneously to that growing need, the requirements on quality and working space have been evolving. Wide area haptic feedback for instance, is mandatory for many applications, such as the simulation of palpation, or such as the simulation of objects and prototypes in the first phases of the product development.

After many studies and basic research we believe that one way to successfully realize such a wide area feedback device is the development of so-called smart structures (according to Spillman's group, a smart structure is "a non-biological physical structure that has: (1) a definite purpose, (2) means and imperative to achieve that purpose, (3) a biological pattern of functioning." [7]), capable of simulating the objects themselves or at least the sections of interest. The SmartMesh was a first attempt to develop an active deformable structure offering output and input capabilities.

2 The SmartMesh

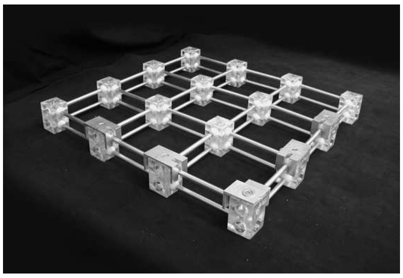
The SmartMesh [2], a double-layered grid of nodes linked by prismatic joints, can be deformed by simply altering the lengths of the linkages. The second layer ensures a controlled movement into the third dimension and provides a support for a better distribution of the arising forces and torques. The linkages are connected to the nodes via spherical or revolute joints. The analysis of the degrees of freedom using the Kutzbach criterion [12], [13], has shown, that for each degree of freedom of the structure a linkage with one prismatic joint is present. Thus, the structure is statically determined.

By integrating linear actuators into the linkages the SmartMesh can actively be deformed and controlled by a computer. The technical requirements on these actuators are quite challenging. To achieve a high resolution the actuators have to be very small. In addition, they should reach an elongation rate of 80% and have to be lightweight. The pushing and pulling force has to be adequate to give them the ability to deform the structure, to hold their own weight and to bear the forces applied by the user touching the system.

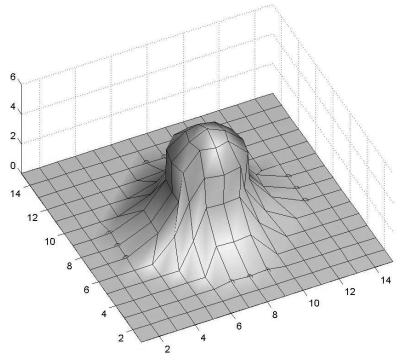
A prototype with 4x4 nodes and 48 linkages was built (see Figure 1(a)). The linkages can manually be altered in their lengths and fixed at any position with integrated screws. Even though the resolution is very small, the structure already shows its inherent capabilities of reproducing surfaces, including overhanging shapes (Figure 1(b) shows its capabilities during a simulation). Research is still ongoing with great effort to develop an actuator that suits the above mentioned requirements. Smart materials will probably be used due to their high energy density, which makes them ideal for this kind of application. First promising results were achieved with electro active polymers, which seem to suit the requirements very well [3].

Such kind of actively deformable structures need smart control algorithms. The actual deformation state has to be detected as well as the end position after the deformation. Out of this information, the sequence of actuation of the elements has to be computed. At this point questions arise such as: do the linkages need to be moved sequentially or all in parallel, or should the deformation start from one single node and expand through its neighbors? In this work we introduce one possible way to achieve the deformation, from now on called "morphing".

We represent the SmartMesh in our dynamic simulations as a tissue or a cloth with its specific mechanical constraints and let it fall over the desired object. Additionally, the cloth is attracted by the object minimizing the volume between itself and the object. The deformation of each linkage during each time step is



(a) Developed prototype



(b) Possible deformation of the SmartMesh

Fig. 1. The SmartMesh

stored and can be used to deform the real mechanical structure by applying the changes to the actuators.

3 Surface Metamorphosis

The word "metamorphosis" has Greek origins and is composed of two words: Meta, meaning between or after, and Morphosis, the way a shape or a structure changes. The term "surface metamorphosis" describes the continuous evolution of a surface from an initial surface through intermediate states into the designated surface. This technique is widely employed in computer graphics in the field of computer games as well as in the movie industry and is generally called morphing. The term is derived from "image metamorphosis". A lot of research has been done in this field to improve the quality and speed of the algorithms. Thus, different types of morphing algorithms can be found, some concentrating on 2D, others on 3D morphing.

However, there are different reasons, why the morphing techniques used in computer graphics can not directly be employed for the mechanical morphing. Using some of them would even have considerable consequences on the deformation of the SmartMesh. In the following, a few of them will be discussed.

First of all, many techniques do not support a controlled transformation, in other words, the intermediate states are unknown or not precisely defined. Thus, details such as the self-intersections of the polyhedra of the mesh or the length of the edges between different vertices and the angles between them are not always well defined and no guarantee can be given that the constraints given by the mechanical structure can be kept. In fact, during the deformation of the SmartMesh every state is determined and has to be well known. Another problem is that some of the algorithms need some anchor points in both the original and the designated objects, which have to be set manually and which is not desired for the activation of the SmartMesh. A further problem is that many techniques do alter the topology of the mesh, which is impossible with the SmartMesh. Due to these reasons we have opted for a novel way to achieve the morphing as described in the following section.

4 The Falling of a Blanket

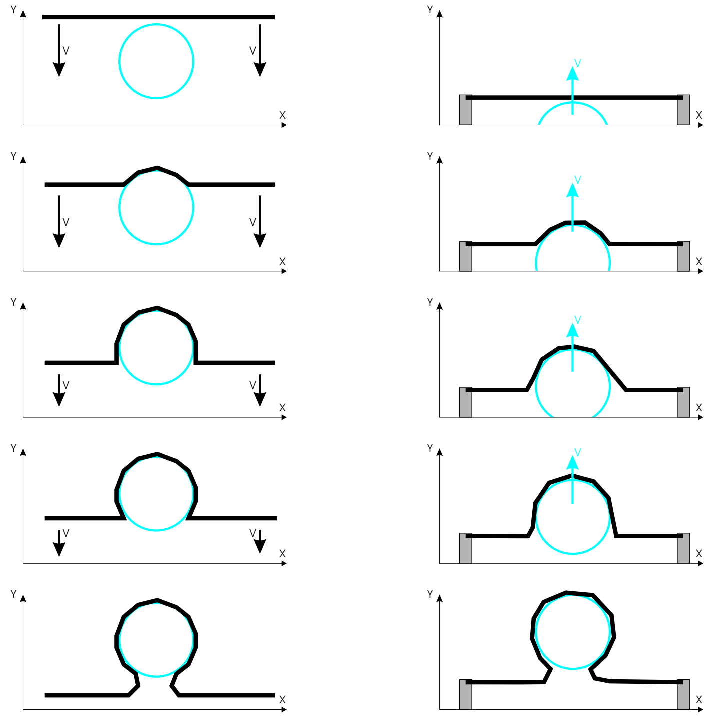
Another strong field of research in computer graphics addresses the simulation of tissues or clothes. Deep investigations have been done in the last decades and by now the results have reached an astonishing quality. The virtual fashion show for example is not a vision anymore [8]. Virtual mannequins wearing virtual clothes slowly begin to replace extras in a growing number of movies and advertisement sketches. The simulations of tissues in surgery interventions [9] have reached a satisfying quality allowing even realistic cutting [10].

For the simulations of tissues or clothes, different models are employed. Mass spring models, finite element models or particle models are used to approach at best the physical properties of the objects. In addition, collision detection and response are used in the dynamic simulations to reproduce realistic collision conditions.

Abstracting, the simulation of a cloth falling over a table and bending around it can be interpreted as a morphing - from a flat state through intermediate ones to a bend one. But compared to the morphing algorithms mentioned in the section before, every intermediate state is well known and follows the rules of the mechanics of the model. Now - imagine a blanket - the SmartMesh - falling over a sphere - the designated object. And imagine now the blanket bending around the sphere and being attracted to it by a magic force. The blanket would envelope it and look alike it (see Figure 2(a)). Or imagine having an elastic blanket with its borders fixed into a frame and the sphere rising from beneath it, pulling it up and forcing it to bend around it as shown in Figure 2(b).

Thus, the control algorithm for the SmartMesh may be implemented based on this technique. Therefore, both the SmartMesh and the designated object have been modelled with masses and springs. The masses represent the nodes and the springs the linkages. In addition, the mechanical constraints of the SmartMesh were depicted: minimal and maximal length for the springs have been integrated as well as minimal and maximal angles between the linkages and the nodes to approximate the mechanical structure. Of course, the constraints of the rectangular angles of the SmartMesh were implemented as well. External forces can be applied to simulate gravity or other types of influences, such as the additional forces applied by a user touching the SmartMesh. While the topology of the model of the SmartMesh corresponds to the real structure, the designated objects are modelled with tetrahedrons. The objects do not need to be convex and may have overhanging surfaces.

The dynamic simulation of the deformation is made by using the Euler method with the leap frog technique to improve the accuracy. The forces, the accelerations an the velocities of each node are computed at every time step.



(a) The blanket falling over the sphere

(b) The sphere rising

Fig. 2. The idea of the mechanical 'morphing' in 2D

Collision detection plays an important role as the falling blanket touches the sphere and should not intersect it. The collision detection is implemented by using an optimized spacial hashing method [11].

A relatively good deformation can be achieved by using clothes simulation techniques. However, still some free volume may occur between the blanket and the object, resulting in folding and cavities. To achieve the best possible morphing, these volumes have to be minimized, which can be achieved by adding some centers of attraction and then moving them just beneath the cavities.

5 From the Simulation to the Deformation

The simulation technique introduced in the previous section samples the data of the length of each linkage at each time step. While Figure 2(a) shows the idea of the falling cloth enveloping the object, Figure 2(b) shows how in reality the SmartMesh will be deformed. Even though the SmartMesh has the capability of representing overhanging surfaces, there will always be some objects, whose reproduction won't be possible, due to different physical properties. The resolution of the grid (in other words, the amount of nodes), the minimal or maximal length of the linkages or their range in possible angular movement for instance, will limit its deformation capabilities. However, as the SmartMesh is modelled with all constraints, and as it is a dynamic morphing, it will try to approximate the designated surface as close as possible.

6 Results

First promising results were achieved with the dynamic simulations of the SmartMesh made in Matlab. Except gravity, no additional attracting forces have been implemented yet. Thus, the virtual SmartMesh falls straight and is not folded under the cube. It begins to fall at t=0, hits the object, in this case a cube, at t=32, and bends around it (see figures 3(a)-3(d)). However, the achievable adaptation of the SmartMesh to the cube is limited by the mechanical constraints and by the size of the linkages compared to the size of the cube. The lengths of the linkages are kept within the preset values as seen in Figure 3(e) for the spring between nodes 9 and 16. The movement of the linkage is well controlled and does not perform any abrupt movements. Figure 3(f) shows a cumulative image of the elongations of all linkages. The plot shows very well, that the movement of the different linkages are performed in parallel, allowing a fast and efficient morphing of the SmartMesh. This data will be used to deform the mechanical structure by feeding the actuators.

7 Problems and Future Work

A lot of effort has to be focused especially on the techniques for the minimization of the cavities (the volume between the blanket and the object) mentioned in section 4.

Additional tests will be done with many different objects in order to understand what kind of objects can or can't be represented to get some kind of technical specification for the SmartMesh.

Also the development of the structure itself including its peripheral hardware has to be carried on. We believe, that the overall bottle-neck in speed of the SmartMesh is not the morphing algorithm, which can be done in real time (the amount of nodes modelling the SmartMesh is little compared to the usual amount of nodes used in computer graphics), but the speed of the mechanical deformation. Thus, effort has to be put into the development of the actuator technology.

8 Conclusion

A control algorithm for the SmartMesh has been introduced. The structure and the desired objects are represented as mass spring systems, which undergo a dynamic simulation including gravity. Collision detection and response ensure that the objects are not penetrating each other. The modelled SmartMesh falls over the designated object and envelops it. First simulations show promising results for a successful control algorithm for the SmartMesh. Nevertheless, it already can be stated, that the quality of the morphing mostly depends on the mechanical properties of the real structure, especially on the amount of nodes and not on the technique introduced here.

Acknowledgements

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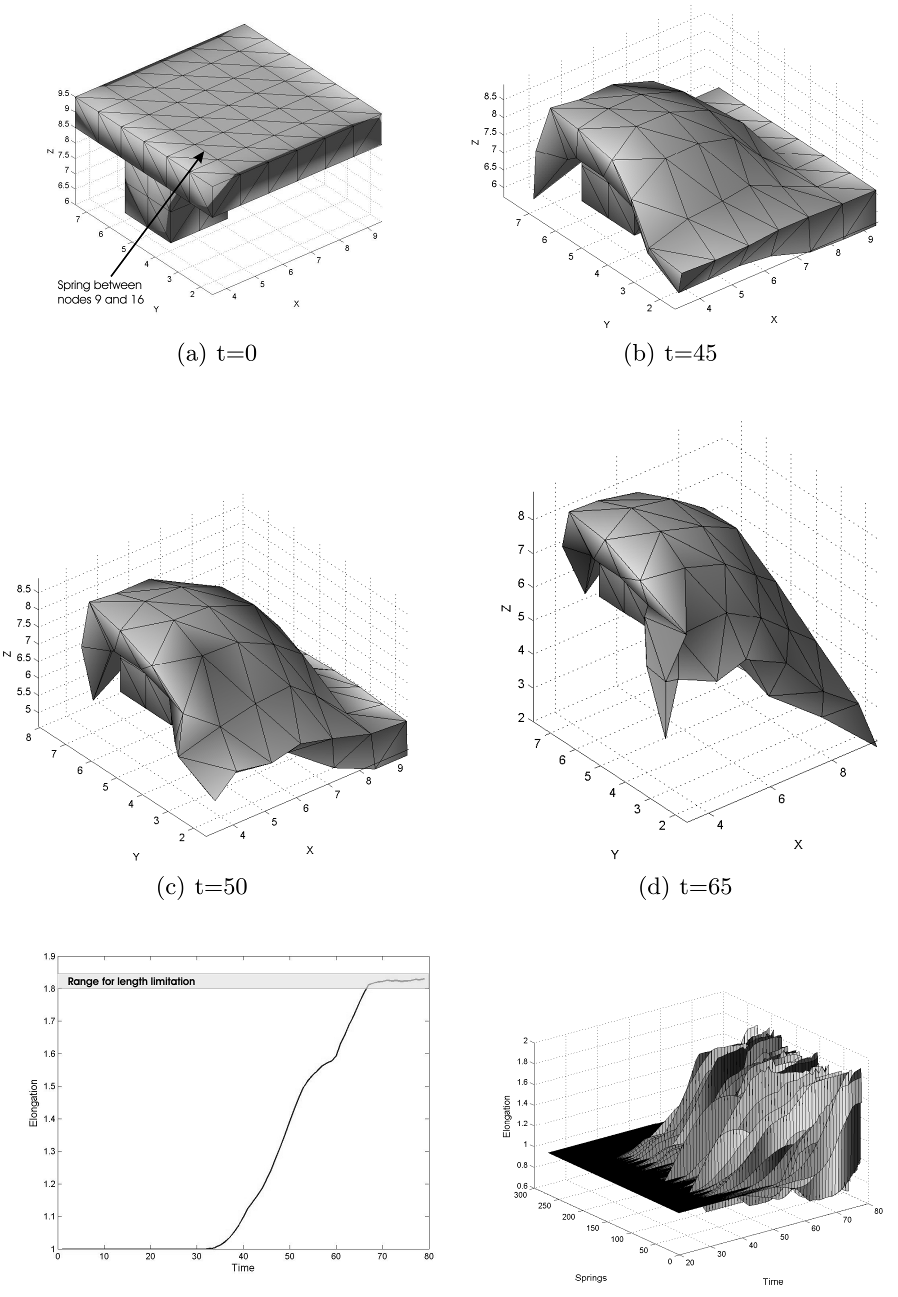

(a) t=0 (b) t=45

(c) t=50 (d) t=65

(e) (f)

Fig. 3. Simulation of the morphing: 3(a)-3(d), length of spring between node 9 and node 16: 3(e) and length of all springs: 3(f)