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Author(s):
Mazzone, Andrea; Kunz, Andreas

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Sketching the Future of the SmartMesh Wide Area Haptic Feedback Device by Introducing the Controlling Concept for such a Deformable Multi-Loop Mechanism

Andrea Mazzone* Andreas Kunz*
(*) *Swiss Federal Institute of Technology Zurich, Switzerland*
E-mail: mazzone@imes.mavt.ethz.ch, kunz@imes.mavt.ethz.ch

Abstract

Lately, we have been proposing a novel concept for a wide area haptic feedback device. It is based on a deformable mechanical structure capable of morphing its shape in order to imitate a desired object. Due to the physical presence of the resulting shape, the latter can intuitively be touched and explored with the whole hand. The prototype has been called SmartMesh [1].

After a short review of the SmartMesh mechanism, this paper focuses on the controllability issue of such a multi-degrees of freedom structure and introduces the concept and the implementation of the control algorithm responsible for providing the required parameters for the actuation of the mechanical structure. The results emphasize the amazing deformation capability and expressiveness of a future haptic feedback enabled user interface device based on the SmartMesh concept.

1. Introduction

The exploration of more effective user interfaces, especially in the way of how to use the human innate spatial and tactile abilities, is one of the most intriguing challenges of current human computer interaction (HCI) research. The enormous success of the humble mouse can hint at the still concealed potential that the research of advanced user interfaces might reveal. For example, computers still lack interfaces that can imitate the ease of building castles in sand, sculpturing with clay, manipulating, assembling or disassembling physical objects such as Lego^{TM} blocks, activities that humans can perform intuitively from a very early age.

The amazing human dexterity also strongly relies on his sophisticated haptic sense that allows him to explore and better understand his environment. In many circumstances and activities, haptic feedback is of primal importance, especially when no direct visual contact is possible. Consequently, it is not astonishingly that there is a strong research community focusing on the investigation and understanding of the haptic perception and on the development of haptic feedback devices. The advances in these research efforts are eagerly awaited and will generally benefit human computer interaction by facilitating daily interaction with machines and computers. An increasing demand for haptic feedback devices for various applications is palpable. The existing devices (PHANTOM, Haptic Master, DELTA Device, CyberGrasp, etc.) provide an astonishing feedback sensation and can be employed for various dedicated tasks, where a punctuated haptic feedback to one or several fingertips is sufficient.

However, literature shows, that if the contact force (or feedback) is not spatially distributed, then pressure sensitivity, orientation detection, spatial acuity and detection of a lump by palpation are all markedly impaired (e.g. Ledermann and Klatzky [2]). The conclusion is that in order to provide a realistic feedback, a larger surface of the human skin has to be accurately stimulated. We call that a wide area haptic feedback.

We believe that one way to successfully realize such a wide area haptic feedback device is the development of deformable structure capable of physically imitating the objects or at least the section of interest. A haptic feedback device based on the SmartMesh concept [1], a mechanical deformable structure we have been proposing, physically reproduces the desired object. Due to resulting physical presence, the latter can intuitively and naturally be touched and explored with the whole hand. This paper introduces the latest advances concerning the control algorithm for a future SmartMesh haptic feedback device and presents the highly expressiveness of the deformable structure.

2. SmartMesh

The SmartMesh mechanism [1] is based on a double-layer square grid of extendable links (see also Figure 1(a)).

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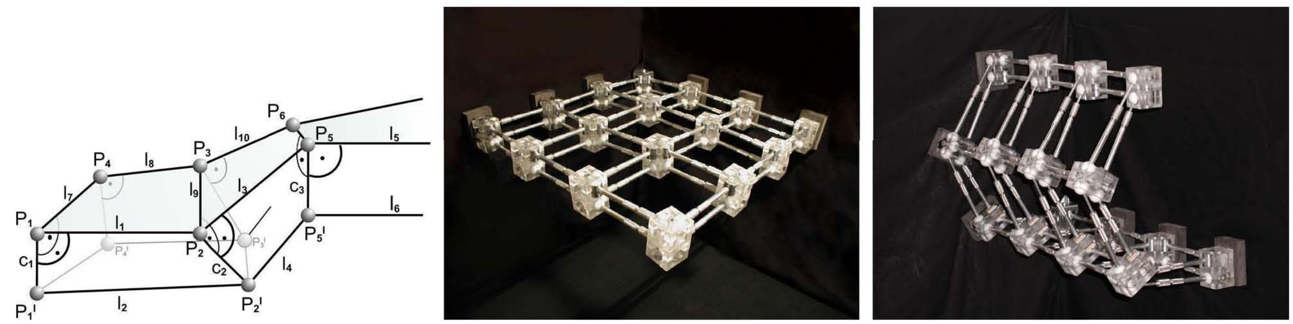

(a) Conceptual structure of the SmartMesh (b) SmartMesh prototype reproducing a plane (c) SmartMesh prototype imitating a wave

Figure 1: 4x4 SmartMesh Prototype.

Due to its particular topology and specific mechanical constraints (internal and on its boundaries), it becomes statically determined and consequently controllable. The mechanism can be deformed by activating the prismatic joints of the links.

In order to validate the concept, a low resolution prototype has been developed. It consists of 4x4 surface nodes and 48 links with integrating a prismatic joint each. These links can be lengthened manually and blocked by the adapter bushing. Despite its low resolution, it already shows its inherent capability of reproducing arbitrary surfaces, including shapes with overhanging regions. Figures 1(b) and 1(c) show the SmartMesh prototype imitating a plane and a wave-like surface.

3. Controlling the SmartMesh

The SmartMesh mechanism is a complex multi degrees of freedom multi-loop mechanism. A structure with 30 x 30 surface nodes framed on all four sides sides already exhibits 3'248 degrees of freedom which are dependent from each other due to the multi-loop topology of the structure itself.

N	$Links$	DoF
30	3'248	3'248
10'000	399'880'008	399'880'008

Table 1: NxN SmartMesh

Provided an actuated mechanism with thousands or millions of nodes and links, the question arises of how such an actuated mechanism will be controlled in order to achieve a desired deformation. In fact, there is a striking difference between the actuated SmartMesh and the state of the art robots. While the latter practically have only one end-effector that has to be moved to a desired position in space, introducing the typical inverse positioning problem in robotics, the SmartMesh mechanism exhibits as many end-effectors as moveable nodes. In order to deform the structure to represent the desired object, every node has to be moved to the desired end position. This leads to questions such as: Can the desired shape be reproduced by the mechanically constrained SmartMesh structure? How much have the links to be shortened or lengthened? Will they have to be altered sequentially or simultaneously (dependent degrees of freedom!), or will some of the links of a specific region have to be moved first followed then by others in other regions?

By summarizing all these questions, two main issues emerge to be fundamental for the SmartMesh structure and will be analyzed in the following sections.

1. The existence of a desired final state/shape.
2. The existence of an actuation plan to reach the desired final shape, often also called *the inverse positioning problem.*

3.1 Existence of the Desired Shape

The object, which is supposed to be imitated and represented by the SmartMesh, is generally computed by a simulation or another tool, providing the position, the shape and the material parameters.

Assuming that in a first step we are only interested in the shape of the simulated object, then the main question becomes quite simple: Can this shape be imitated by the SmartMesh? The geometrical constraints and the fixed topology of the SmartMesh automatically limit the possible imitations. Objects with holes, such as a torus for instance (therefore with different topology), will not be imitable by the SmartMesh. Consequently, the desired shape firstly must be representable by a mesh with the SmartMesh topology. Secondly it must be reproducible by the mechanically constrained structure (due to the constrained joints, such as the rectangular angle, min and max lengths and angles) and the consequently maximal reproducible area. For example, if the local gradient of the surface is larger than the maximal possible curvature of the SmartMesh, than an inaccurate imitation will result. Further, if the surface area of the desired object is larger than

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the reproducible one, then only a section may be representable (see also Figure 2 for a better understanding).

In robotics, the term *workspace of a machine* is often employed, defining the set of all attainable positions (joint configurations). If a position is not attainable, then it is said to be outside of the machine's workspace. The SmartMesh's workspace is clearly defined due to the mechanical/geometircal properties and multi-dimensional, as every re-positioning of one SmartMesh node automatically leads to a new configuration of the remaining workspace. The consequence is that most shapes will not be perfectly imitated, but only approximated.

Unfortunately, no analytical solution has been found capable of providing the means for finding the best approximation of the desired shape. In fact, the analytical analysis of this multi-dimensional space is, understandably, very complex. Nevertheless, we have found a numerical approximation of the desired shape to be an elegant, powerful and straight forward solution to the problem. The approach relies on modelling the SmartMesh and the desired shape in virtual space while trying to minimize the volume inbetween. The minimization can be achieved by computing and minimizing the potential energy between the nodes of the SmartMesh model and the surface of the object. Obviously, the geometrical and topological characteristics of the SmartMesh need to be kept at all times during the approximation. For better understanding, please refer again to Figure 2, which shows the concept including also one typical approximation error due to the small resolution of the SmartMesh model compared to the object's curvature. In this specific case, no better approximation will be possible.

Our implementation of this approach relies on a physically-based modelling technique and will be detailed in Section 4 and 5. The SmartMesh is modelled according to its topology and geometry and energy functions force the model to comply with the SmartMesh specific and environmental constraints at all times during the simulation.

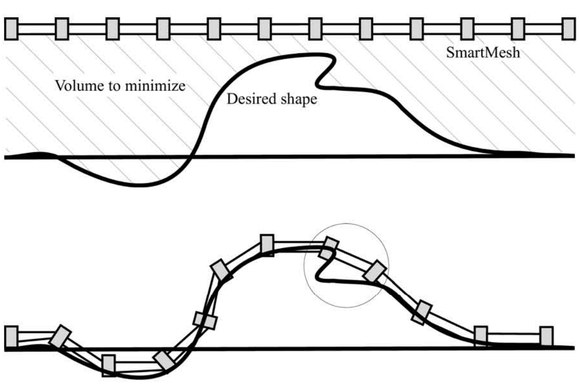

Figure 2: Approximation of an arbitrary surface with the SmartMesh structure with a typical error due to its low resolution (marked with a circle).

The object that needs to be imitated, such as a sphere for instance, is also loaded into the simulation environment, where both the models can interact, following the rules in the virtual environment. One of the latter is a force emanated by the desired object attracting the SmartMesh model, which tries to envelope it as good as possible, minimizing the volume in between.

This approach guarantees a valid solution, as the topological and geometrical characteristics of the SmartMesh structure are kept correctly during the complete deformation. In other words, the model stays within its workspace. However, the resulting final shape may differ from the desired one, while being a good approximation of it. Is the space between the two surfaces minimal, then the mechanical best approximation of the desired shape has been reached. If the resulting minimal potential energy is equal zero, then a perfect imitation of the desired shape has been achieved.

3.2 The Inverse Positioning Problem

Assuming that a desired valid (topological and geometrical correct) final shape is given, the second question introduced in Section 3 becomes important. How is the SmartMesh deformed or morphed from its initial state to the desired final one? How much need the links to be shortened or lengthened in order to achieve the desired deformation? Which speed and order is required? These questions need to be answered because there may be some specific intermediate states, which are not within the workspace of the SmartMesh. These particular intermediate state have to be avoided in order to succeed in deforming the SmartMesh. Figure 3 shows the conceptual problem.

In order to find a solution to this problem, different techniques have been investigated: 3D morphing techniques, inverse kinematics and physically-based modelling techniques.

3D morphing techniques are inappropriate for the SmartMesh problem, as the morphs, or in other words the intermediate states, are unpredictable. In order to deform the SmartMesh every intermediate shape has to be known.

Inverse kinematics techniques, widely employed in robotics, allow to compute the joint coordinates of the SmartMesh. The equation system describing the multiloop SmartMesh structure can numerically be computed providing the required lengths of all links. However, it does not provide any information about the sequence (intermediate steps) and speed of actuation. As already men-

Figure 3: Finding a actuation plan in order to deform the SmartMesh from an initial state to the desired final one.

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tioned, just driving the links according to those results may lead to singularities.

Physically-based modelling techniques resulted to be the most appropriate. They are widely employed in many fields for simulating events, where the physical accuracy plays an important role. By modelling the SmartMesh accordingly, its behaviour can be simulated and its geometrical and physical correct deformation due to internal and external influences can be computed. Depending on the complexity and on the computing power, this can even be done at a reasonable speed. Furthermore, these techniques address both issues mentioned in Section 3. In fact, they can be employed to approximate the geometrically constrained SmartMesh to the desired surface, but simultaneously can also be deployed to deform the model of the SmartMesh while keeping the geometric properties legally at all times. The more accurate the model is, the better the parameters correspond to reality. In the sense of a quasi-static process, these parameters can directly be used to control the deformation of the physical SmartMesh (by providing to the actuators the lengths of the links).

4 Solving the Inverse Positioning Problem Employing Physically-Based Modelling Techniques

Physically-based modelling techniques provide the means for simulating a geometrical and physical correct deformation of the SmartMesh as explained in the following (please refer also to Figure 4 for a better understanding): Let a physically correct model of the SmartMesh be in an initial flat state (in the morphing nomenclature that would be the source object S) and let a model of the the designated object, in this case a sphere (target object T), be beneath the SmartMesh model. If the sphere is raised, it will touch the SmartMesh model and will, due to collision detection and response, force the latter to deform and bend around it, much like a cloth would do at the borders of a table. Further, if the SmartMesh model is attracted by the sphere it will also try to envelope or entangle it as much as possible (shown in the last figure of the sequence). By eliminating the originated wrinkles a quite satisfiable deformation from the object S to the object T' can be achieved. T' is just slightly bigger than T given by the thickness of the blanket. The thinner it is compared to the size of object T and the higher resolution it has, the better the approximation will be.

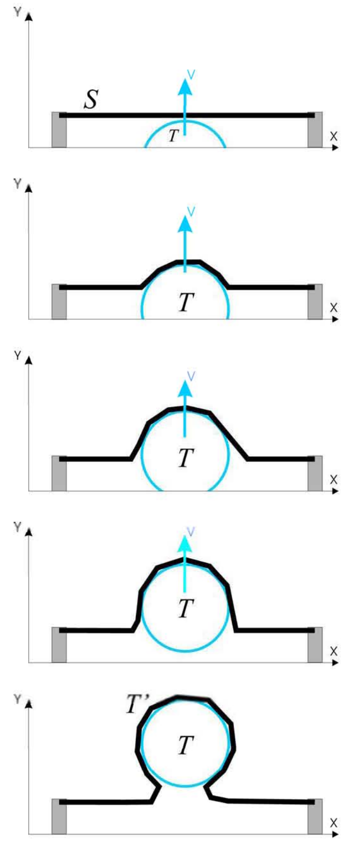

Figure 4: The SmartMesh model is being deformed by a sphere, while remaining geometrically correct at all times.

5. Implementation of the Controlling System

As the SmartMesh presents a fixed topology of nodes and links, it has been implemented with its closest digital counterpart: a mass-spring system with the same topology, where the masses represent the nodes and the springs the links and the perpendiculars. Furthermore, energy functions were introduced in order to keep the mechanical constraints fulfilled. These SmartMesh specific implementations were integrated into an existing versatile and robust model for geometrically complex deformable solids [3], called the DefCol-Model.

A way to express and solve the mechanical constraints in the digital domain is the formulation of so-called energy functions [4]. Energy functions are non-negative functions with zeroes at points where the constraints are satisfied. They are being widely employed to solve the constraints of various objects in almost any field of computer graphics animations, but also in chemistry and molecular biology research in order to realistically simulate the structures of molecules.

A force due to a scalar function is minus the energy gradient and therefore, the force on particle x_i due to C is (1).

$$f_i = \frac{-\partial E}{\partial x_i} = -k_s C \frac{\partial C}{\partial x_i} \quad (1)$$

The last fraction in equation 1, denotes the transpose of the *Jacobian* matrix. The forces f_i can be though of as generalized spring forces that attract the system to a state

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where $C = 0$ is satisfied. The last definition of f_i may be modified in order to suppress oscillations by adding $-k_d \dot{C} \partial C / \partial x_i$, where k_d is a generalized damping constant and $\dot{C}$ is the time derivative of C. The technique of using extra energy terms to impose constraints is also known as the *penalty method*.

The implementation for some of the specific constraints are exposed in the following:

Fixed perpendicular length: In order to keep all the springs that model the perpendicular to a fixed length, the behaviour function $C = |u| - r$ has been chosen, where u is the vector between the two end nodes x_1 and x_2 of the spring ($u = x_1 - x_2$) and r is the length of the perpendicular.

Minimal and maximal link lengths: Both constraints are handled as explained above, when the maximum and minimum lengths are outrun.

The right angle constraint: Two behaviour functions can be deduced for each angle separately, as both constraints have to be fulfilled simultaneously and independently from each other: $C_1 = v_1 \cdot v_2$ and $C_2 = v_3 \cdot v_4$ where "$\cdot$" is the Dot Product of the adjoining vectors respectively. The Dot Product is equal 0 only if the corresponding vectors are perpendicular to each others.

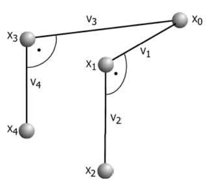

Figure 5: Rectangular angle constraint.

Minimal and maximal angles: Both constraints are handled by adding penalty forces as soon as the angles get too small or too large (v_0 and v_1 vectors of the links): $C = \alpha - \alpha_0 = \arccos((v_0 \cdot v_1)/(|v_0||v_1|)) - \alpha_0 = 0$.

6. Results

As exposed in the following, using the introduced physically-based modelling technique not only provides the answers to the two questions of Section 3 and consequently the means for computing the lengths of the links at all time steps of the deformation, but it also allows to observe the influences of different parameters (e.g. better elongation rate, different length of the perpendicular, etc.) to the deformation of the structure.

All simulations have been done either with a 15 x 15 SmartMesh or with a 30 x 30 nodes model using both, the two-sided and the four-sided frames. The 30 x 30 model handles 900 nodes and 15638 constraints. Using an AMD Athlon XP 3200+ with 2.2 GHz clock and 512 MB RAM an update rate of 11.5 Hz has been measured for a single computing step using the Verlet integration scheme (collision detection and handling are included, visualization is not). Hence, the morphing concept does not yet comply with the design specification for haptic feedback devices that require realtime deformation (update rates up to 1 KHz). Nevertheless, as computer power is increasing rapidly every year, the update rate will sooner or later approach the requirements and with high probability will not be the bottle-neck for small models (fast actuation technology may be much more challenging).

The actual modelling technique based on a mass-spring system does not describe exactly the mechanical structure. In fact, the model idealizes some elements of the mechanism. The nodes for example, are modelled as dimensionless mass points of a specific weight while connecting the five adjoining links in one single point (one perpendicular and 4 links for non border nodes). However, this does not correspond to the actual prototype, where the joints have a specific radial distance to the perpendiculars. Further, the links are represented by massless springs with no dimension except for the length. These simplifications lead to inaccurate computation of the dynamics of the deforming model. Neither the forces, nor the torques acting on the joints and nodes for instance are computed realistically. Friction is also neglected.

The inaccurate modelling has also some consequences on the deformation capabilities of the model itself. In order to compare both the prototype and the model, the springs of the latter have been modelled with the same lengthening rate of the mechanical links (60%). It can be shown that the model performs a maximal enlargement of the surface by a factor 2.56, whereas the mechanical surface undergoes only a maximal increase of 106%. The better performance of the model is due to the dimensionally nonexisting nodes. The more the surface can grow, the larger and more complex objects can be imitated.

Nevertheless, even though the model of the SmartMesh has been idealized for reasons of simplicity, it still represents a good approximation of the physical system.

In the following, the implication resulting from the different parameters are exposed (lengths and force specification have no units and no direct correlation the the physical values):

The mechanical constraints have all been implemented with energy functions. Their analysis at each time step shows that they are all handled physically correct. Nevertheless, a maximal deviation of 1% ($\epsilon < 1\%$) has been allowed for every constraint. The error does not further falsify the simulation results as the mechanical elements introduce slackness themselves, such as the revolute joints for instance.

The lengthening rate of the links can easily be changed by altering either the minimal, the maximal or both values of the link length. Figure 6 impressively shows the differ-

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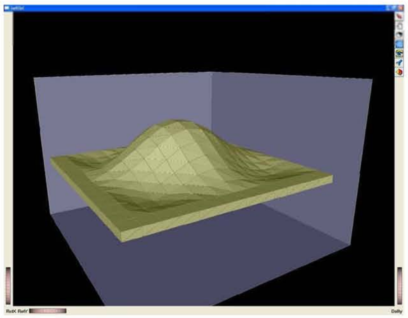
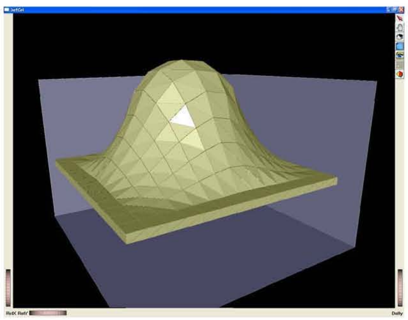
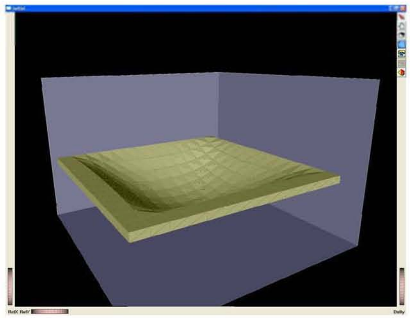


(a) Maximum link length = 1.2.

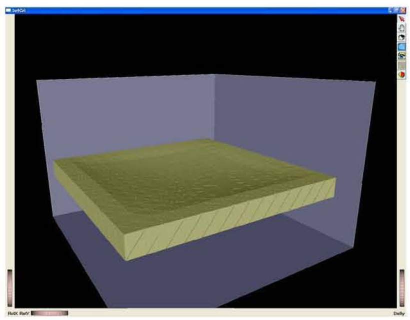


(b) Maximum link length = 1.60.

Figure 6: 15x15 SmartMesh framed on four sides; The SmartMesh with larger elongation rates exhibits much better deformation capabilities.

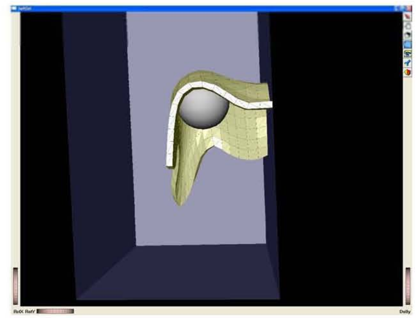


(a) Perpendicular length = 0.5.

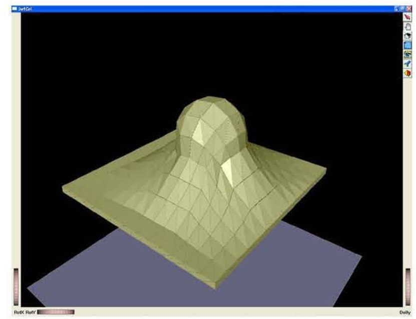


(b) Perpendicular length = 1.3.

Figure 7: 15x15 SmartMesh framed on four sides with shorter and longer perpendiculars. Longer perpendiculars inhibit a good deformation.



(a) The SmartMesh framed on two sides.



(b) The SmartMesh framed on four sides.

Figure 8: 15x15 SmartMesh; 2-side framed model with amazing deformation capabilities versus more stable 4-side framed one.

ence in expressiveness between lengthening rates of 20% and 60% respectively. The lengths of the perpendiculars can be altered by changing the corresponding values in the apposite energy function. By doing so, the influence of a longer perpendicular, or in other words, of a larger distance between the two planes of the SmartMesh, can be evaluated. Figure 7 shows an example of the same model being deformed by gravity only. The lengths of the perpendiculars are 0.5, and 1.3 respectively. It is clearly visible that longer perpendiculars inhibit a good deformation.

The frame can easily be chosen to be two-sided or four-sided - something that is more complicated to do physically. If a two-sided frame is chosen, amazing deformations are possible but in the same time the influence of the gravity can become a problem. The free ends of the mesh are strongly pulled downwards and the nodes close to the Corner-Node are exposed to higher forces and their joints to higher torques, than the equivalent nodes in a four-sided frame will ever be. In order to keep the resulting forces acting on each node in an allowed range, a maximum value can be determined. If this value is reached, all forces acting on the nodes are scaled respectively. In large models embedded in two-sided frames, this maximum value is more often reached than in their four-sides framed counterparts. In such a case, the mechanical constraints (especially the rectangular angle) can not be hold anymore and the model becomes physically incorrect. Furthermore, if that maximal force value corresponds to the maximal mechanical stress that the physical nodes or joints can support, than a fracture may be the result. Hence, the four-sided frame clearly shows some advantages. Even though the degrees of freedom are reduced, it offers a better distribution of the forces and therefore, the limit is seldom reached. In addition, it offers more stability and a more regular deformation. Generally, the deformation starts in the middle of the mesh. Figure 8 shows two examples of a the SmartMesh model framed on two sides with the gliding border nodes and framed on four sides having all border nodes fixed.

Material properties can be imitated as well by changing the spring constants and the values for the energy functions that control the surfaces and volumes of the tetrahedra. Stiffer materials obviously show less deformation capabilities than elastic materials.

Attracting and flattening forces have been implemented by using energy functions, which try to minimize the space in between both the objects and between the plane with $z = 0$ and the SmartMesh model. The concept has proven to be efficient only up to a certain extend, as Figures 9(a) and 9(b) show. The reason lays in the fact, that the functions do not take care of the distribution of the

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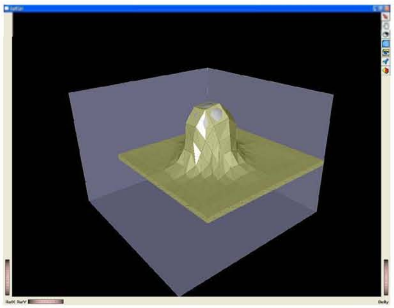
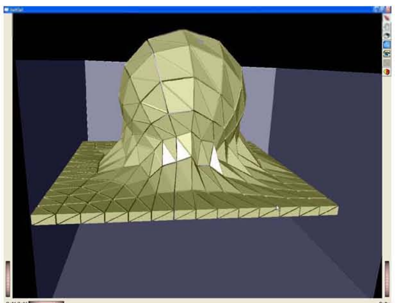


(a) Small sphere.



(b) Large sphere.

Figure 9: 15x15 SmartMesh with attracting and flattening forces applied in order to better approximate a small and a large sphere respectively. The results are only partially satisfactory and hard to improve.

nodes. The two figures show the deformed SmartMesh attracted by a smaller and a larger sphere respectively. Especially in Figure 9(a) it is clearly visible, that the nodes close to the borders are successfully kept onto the ground but do not significantly move away from their initial position. Ideally, "material" should be moved away from bottle-neck regions and distributed where enough place is available. Figure 9(b) presents the problem in the lower part of the sphere. The wrinkles emerge, because there is not enough place for all the nodes and links. There are practically two ways to solve this problem: A straightforward mechanical approach trying to reduce even more the length of the links and a second more theoretical one, which makes use of a more sophisticated optimization function, acting not only locally but also globally on the whole workspace. However, none of both has been implemented so far.

Figure 10 shows the amazing sequence of a 30x30 nodes SmartMesh deforming itself imitating a wave. The frame rate was 11.5 Hz and the complete sequence was computed in 44 seconds. The intermediate shapes of the structure are all geometrically correct and at all times valid. It clearly shows the highly expressiveness and the impressive capability of representing shapes with overhanging regions of a future haptic feedback device based on the the SmartMesh structure.

7. Conclusion

After a short review on the hardware realization of the SmartMesh the novel approach and implementation of a control algorithm is introduced. Due to the finite resolution and the mechanical constraints of the SmartMesh structure, arbitrary given shapes may not be imitated, but only approximated. The best approximation of the desired shape is reached by minimizing the volume in-between the shape and the mesh. The Jacobi matrix allows to validate the intermediate and final shapes of the SmartMesh, providing the required lengths of the links. However, it has been shown that it is inappropriate for controlling the deformation of the multi-loop mechanism (with dependent degrees of freedom). A physically-based modelling technique was chosen, as it turned out to be capable of simultaneously solving the approximation as well as the inverse positioning problems. The underlying idea is that the model of the SmartMesh is deformed by the designated object, much like a cloth does when bending at the borders of a table. Furthermore, attracting forces are responsible for the SmartMesh model to envelope the desired object leading to the best possible approximation. The algorithm was implemented and allows to simulate accurately the deformation of the SmartMesh structure, while keeping it physically and geometrically correct at all times. Consequently, the paper presents the first results, discusses the influences of different mechanical parameters, and concludes by proposing an amazing and highly expressive deformation sequence of the SmartMesh model imitating a wave.

8. Future Challenges

Although the prototype shows many promising features it is still in an early development stage. In order to implement a fully functional device several challenges have to be met.

Mechanics: 1) Actuation of the SmartMesh using smart materials based actuators, due to their high power density. Currently, the possible use of electroactive polymers is examined and has to be further investigated [5]. 2) Minimization of the complete structure. 3) Integration of strain gages in order to ascertain the pressure induced by the user interacting with the structure. 4) Application of a skin in order to cover the linkages.

Control system: 1) The accuracy of the physically-based model needs to be enhanced in order to better reflect the real physical system (no idealization of the nodes and the links for instance). This could be achieved by using finite element methods for instance. 2) The attraction and flattening forces have to be optimized in order to better and more efficiently distribute the nodes within the surface. By doing this, a better imitation of the desired objects can be achieved. 3) For real time applications, the efficiency of

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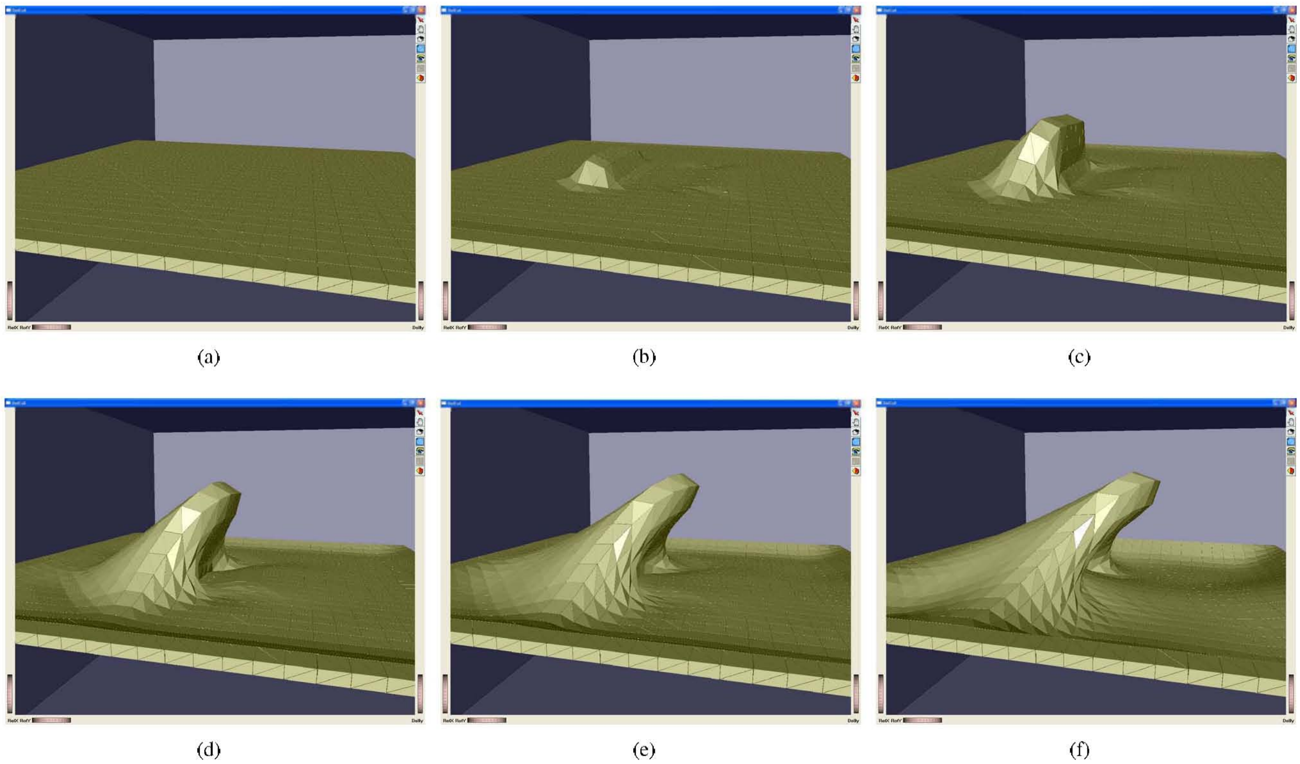

Figure 10: 30 x 30 surface nodes SmartMesh framed on four sides imitating a wave.

the physically-based modelling has to be increased, which automatically will result in higher update rates.

Psychological questions related to the way of interaction with such a device have to be answered, such as: 1) What form should a future digital clay device take in order to meet the users' expectation? Would a sphere, closely resembling a lump of clay, be more intuitive than a planar structure? 2) Is there the need to be able to cut the structure or to represent topologies with higher genus? What further benefits would construction-set like principles bring to the user? 3) Generally, deformable physical objects have a certain rigidity that must be overcome with a threshold force in order to deform them. Can this threshold be changed dynamically during the modelling? Would it make sense? 4) In physical world, devices generally do not move themselves (unless explicitly ask them to). It could be quite frustrating to attempt to mold a device that keeps changing shape or "fighting back". Therefore, should some restriction be implemented? 5) Can creativity be supported with load or save capabilities or with physical not necessarily linear undo functions? What are the advantages, if the users could for example by allowed to instantly save physical states along the interaction session and also to go back to any of these previous state?

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