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Simulating a Deformable Object using a Surface Mass Spring System

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Abstract

This paper introduces volume springs that provide the volume effect to a surface model when it is deformed. The estimation of the properties of the model takes the real material properties into consideration, where each spring stiffness is derived based on the elasticity, rigidity and compressibility modulus. The proposed model can be adopted to simulate soft objects such as a deformable human breast, and it can be further extended to address other material properties.

Keywords: Deformable Model, Mass Spring Systems, Volume Preservation

1. Introduction

Soft volume simulation has been employed in computer animation, product design as well as medical training. For instance, in medical simulation, the organs are geometrically modelled into 3 dimensional volumes based on medical data such as the CT/MRI scans. This volume data can then be rendered in a virtual environment based on the organ's material and mechanical properties.

However, due to the issue of computational as well as geometrical complexities, there is a significant interest in utilising surface data as an alternative to its volume counterpart. The main issue is the non-existence of volume information for the surface model. Furthermore volume simulation requires constant volume preservation as well as correct volume behaviour during simulation. Generally, a surface model would collapse under gravity and without the internal volume, determining the correct deformation effect would be a challenge.

2. Related Works

The most common method in achieving a volume model using surface data is by re-meshing the surface model in order to create internal volume. However, this creates computational overhead during simulation imposed by a more complex volume network. The addition of new artificial springs [1] to the existing volume mesh produces an object that is stiffer than it should be [2]. There are also attempts that employ surface data which addressed shape preservation but not volume [3][4]. [2] introduced weighted constraints that control the deformation distribution of the muscle instead of using additional springs. However, this

method is fundamentally focusing on the local radius of influence of the interaction and is not influenced by the orientation of the interaction force.

A more effective shape preserving method has been embedded into the Mass Spring Systems (MSS) where the springs are placed at the mesh nodes. They are also known as the Local Shape Memory [5]. These springs have been employed to simulate non-linear skin behaviour of a virtual thigh [6][7]. [8] administered these springs to preserve object shape during simulation. However, the stiffness of the springs was either statistically fine-tuned based on predefined properties [9] or regularly distributed. [10] extended this method by extracting the properties of the springs based on radial links [11][12].

Volume behaviour is influenced by the properties estimated for the model. Regular properties distribution is very common where the regular node concentration is assumed [1][13][14][15]. In the case of irregular node concentrations, the mesh topology is modified to be as regular as possible [16][17]. However, when a portion of the surface model is refined, the regular topology becomes irregular. Consequently, the properties require re-estimation within the refined area. [8] attempted properties re-estimation after surface refinement based on the topology but the behaviour patterns between the coarse and the refined area do not coincide. The behaviour is improved by our method discussed in [10] where these patterns achieve a higher level of co-incidence.
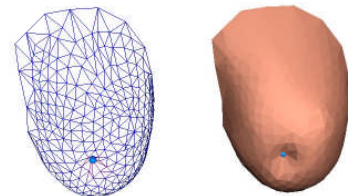
3. The Proposed Deformable Model

Figure 1 Interacting with a Deformable Breast Model

The scope of dynamic behaviour in this research is within a constrained space, such as a human breast fixed on a static body (Figure 1). The model is constructed from the surface mesh and the dynamic behaviour is achieved by employing the surface MSS with volume

preserving springs. The assumption is that the initial shape of object is convex with known centre of mass.

To address the issue of properties estimation as well as the non-existence of inner volume for the proposed surface model, the object's internal volume represented by the surface elements has to be considered. This framework extended the scheme described in [10], where a surface mass spring systems with additional shape preserving springs are employed.

3.1. The Mass Spring Model

The model is made up of nodes and edges as illustrated by the wireframe breast model in figure 1. This geometrical topology represents the topology of the mass spring systems. The proposed model is made up of the surface springs and the volume springs.

The surface MSS is based on the surface mesh topology where the springs are represented by the edges of the triangular elements (Figure 2 (a)). For instance, the edge that connects the nodes with mass m_i and m_j is the spring with stiffness k_{ij}.
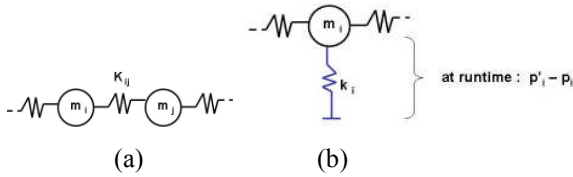

(a)   (b)

Figure 2 Surface MSS a) the surface spring b) the volume spring

For the spring link ij (Figure 2(a)) , the internal force F_{ij} is

$$F_{ij} = K_{ij}\left(\left\|p_j - p_i\right\| - l_{ij}\right)\frac{p_j - p_i}{\left\|p_j - p_i\right\|} \qquad (1)$$

, where $\|p_j - p_i\|$ is the magnitude of the displacement of the current state of the spring link ij, l_{ij} is the rest length of the spring link, and K_{ij} is the stiffness (spring) coefficient of the node pair.

The proposed volume spring (Figure 2 (b)) has been commonly utilised to preserve the shape of the model at equilibrium. They behave in a similar way as the surface spring but the rest length of each spring is zero. Therefore, based on Equation (1), the reaction force at inner spring will only affect mass at node i,

$$F_i + = K_i\left(\left\|p'_i - p_i\right\|\right)\frac{p'_i - p_i}{\left\|p'_i - p_i\right\|} \qquad (2)$$

,where K_i is the stiffness of the inner spring at node i, p'_i is the new position of node i at runtime and p_i is the anchored position of node i.

In order to not only preserve the object shape but also maintain a constant object volume during

simulation, the concept of these shape preserving springs has been extended.

3.2. Volume Relationship

The elasticity modulus of a material is extracted from the stress and strain relationship of the material, where a constant magnitude of force is imposed along the axis parallel to the normal of the surface. This relationship can be employed to discretise the surface model into tetrahedral volumes which guide the initial properties estimation at equilibrium.

In a MSS, the internal and external forces directly influence the dynamic behaviour of the nodes and not the triangular elements. Therefore, the volume under the triangular elements of the surface mesh should be discretised along the surface normal at the node.

The radial link method in [10] is extended, where the new distance vector with length L_i', relative to the object centre of mass, the initial length L_i and the surface normal at the node, are derived. The new volume (Figure 3) is based on node p_i relative to the new centre point c_i and the other nodes or vertices of the triangular element.

Therefore, the new centre point c_i, relative to the object *centre* and the new distance L'_i, has to be derived from the relationship. The new L'_i is the scalar projection of L_i along the normal unit vector at point p_i. Similar discretisation and volume calculation will be carried out for the other nodes relative to their respective normals and neighbouring triangles.

This explicit discretisation method is used to guide the estimation of mass and spring stiffness as the volume directly influences the amount of mass and the stiffness of the volume springs at the nodes.

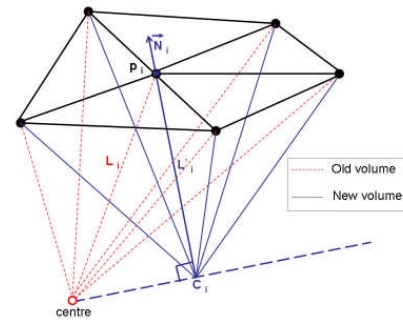**Figure 3 Explicit Discretisation based on the Normal at i**

This approach is more accurate compared to the radial link method [10]. For instance, for a rectangular prism with regular mesh topology, the properties for the inner stiffness and mass for the nodes (as illustrated in figure 4) should be the same. Radial links method (4(b)) produces irregular values based on the irregular volume discretisation.
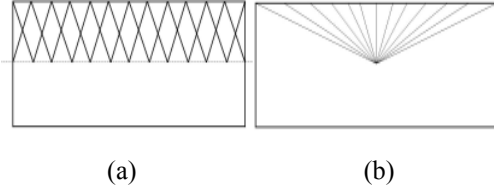
Figure 4 Explicit Discretisation – cross sectional view (a) proposed approach (b) radial approach

3.3. The Estimation of Mass and Spring Stiffness

The total mass of the model has to replicate the total mass of the real object. Therefore, the estimation method has to take mass preservation into account. This has to be true even when the mesh topology is modified. Therefore, the mass at node *i,* based on the discretisation in figure 3, is estimated as

$$m_i = \frac{\sum\limits_{i \in t} v_t}{\sum\limits_{j=0}^{n} v_j} M$$

, where the estimation ratio for each node is the total volume under the neighbouring triangular elements *t* (of which node *i* is a member) divided by the total volume for all **n** nodes, and **M** is the object mass.

The surface spring stiffness is estimated based on a distribution algorithm which has been commonly employed to estimate the behaviour of a membrane with irregular mesh topology [10] [13] [18] [19].

The stiffness of the volume preserving springs describes the level of elasticity of the virtual space or volume represented by the node. Therefore, the value of the stiffness is influenced by the stress and strain relationship along the axis parallel to the normal at the node. The stiffness dimension based on the normal elasticity (Young's Modulus) and rigidity (Shear modulus) is initialised before the simulation. The dimension is defined as

$$\begin{bmatrix} K_E \\ K_G \end{bmatrix}_i = E \sum_{i \in t} \frac{V_t}{L'^2_i} \begin{bmatrix} 1 \\ 1/2(1-v) \end{bmatrix}$$

, where , K_E and K_G are the spring stiffness based on linear elasticity modulus and shear (rigidity) modulus respectively, **E** is the Young's Modulus and *v* is the Poisson Ratio of the material.

The behaviour of the spring stiffness at runtime depends on the orientation of the acting force along each spring. When force direction is parallel to the normal at *i,* the stiffness will be the perfect elastic stiffness. But when force direction is perpendicular to the normal at *i,* the stiffness refers to the shear stiffness. The stiffness K_i of the spring at each node *i* is derived at runtime:

$$K_i = \begin{bmatrix} \left\| \vec{N}_i \cdot \vec{F}_i \right\| & 1 - \left\| \vec{N}_i \cdot \vec{F}_i \right\| \end{bmatrix} \begin{bmatrix} K_E \\ K_G \end{bmatrix}_i$$

, where *N* and *F* are the normal and force at node *i.*

3.4. Volume Behaviour

In order to preserve volume during simulation, the spring dimension can be extended to address other properties such as bulk elasticity as a factor against volume variation during simulation. Bulk stiffness K_B at node *i* is

$$K_{Bi} = \frac{E}{3(1-2v)} \sum_{i \in t} \frac{V_t}{L'^2_i}$$

Volume displacement during simulation can be derived based on the volume calculation employed in [2]. This calculation will be correct even when the surface becomes concave during simulation. Therefore, force at node *i* along its normal unit vector at a time step without any external force interaction on the surface is

$$F_i \mathrel{+}= K_{Bi} \Delta V w_i \vec{N}_i \qquad (3)$$

, where **ΔV** is the volume displacement, and w_i is the weighted constraints that control the distribution of the volume penalty force. The constraint is generally set to 1, which means the volume change affects all nodes equally but constrained by their respective bulk stiffness.

Therefore, in order to correctly distribute the interaction force effect to the object surface, the weighted constraints have to be correctly distributed based on the interaction radius of influence where, the sum of the constraints is equal to the number of nodes.

The radius of influence [2] has been modified and the interaction force orientation is introduced as the correction factor. If the surface nodes are within the radius of influence *r,* weight at node *i* is

$$w_i = \left(\frac{p_i - p_f}{\left\| p_i - p_f \right\|} \bullet \vec{F}_f \right) \left(COS \left(\frac{\left\| p_i - p_f \right\|}{r * 2} * \Pi \right) \right) . \qquad (4)$$

, where p_i and p_f are the position vector of node *i* and the position of where force is imposed respectively.

Since the sum of weighted constraints is equal to the number of nodes [2], the constraint values have to be normalised. Upon interaction, the direction of the volume penalty force at node *i* depends on the position of node *i* relative to the point of interaction. Therefore, based on Equation (3) and (4), the penalty force at node *i* is

$$F_i \mathrel{+}= K_B \Delta V \; w_i \frac{p_i - p_f}{\left\| p_i - p_f \right\|} .$$

4. Empirical Evaluations

The framework for the empirical evaluations has been implemented on top of Microsoft Visual C++, OpenGL and OpenHaptics platforms. Phantom Desktop haptic device has been employed to provide the interaction and the desktop PC has the specification of Intel Pentium 4, 2.40 GHz and 1 G RAM. The object mass is 100 g, and each time step denotes 0.01 s. To evaluate the estimation method and the feasibility of having a 3 dimensional stiffness, 2 schemes have been compared:

- **Scheme A :** Single stiffness dimension

- **Scheme B :** The Proposed Deformable Model (3 stiffness dimensions)

Further comparisons are carried out against the Finite Element Model (FEM) and volume MSS (VMSS). The elasticity modulus is re-extracted from the model to evaluate if the proposed model emulates the same material behaviour.

4.1. Properties Estimation

The stiffness of the springs is based on the real elasticity properties of the object material. Therefore, to evaluate the proposed properties estimation framework, the Young's modulus (E) can be derived from the strain and stress relationship of the proposed deformable model and compared to the original E. The same experiment is repeated for other surface mesh complexities. The values (table 1) demonstrate that the proposed model can closely emulate the volume material behaviour.

**Table 2 Young's Modulus (E) of the model compared to the original values (E = 67 pa and 100 pa)**

Model (nodes)	Cube (602)	Cube (1352)	Cube (2402)
E(67 pa)	67.8	66.8	67.0
E(100 pa)	100.07	98.7	98.7

To evaluate the re-estimation of properties, a local surface area is refined and the properties are then re-estimated. A constant force is imposed on a node and the displacement data is collected. The displacement patterns within the coarse and the refined area are compared [8] [10]. If the patterns are identical, the deformation behaviour is preserved despite the change in the mesh topology. The displacement behaviours are studied where 2 values are analysed:

- The standard deviation between the 2 patterns determines their level of co-incidence. The smaller the standard deviation, the more identical the patterns are
- The mean deviation of the 2 patterns represents the error in behaviour after refinement. The least value indicates the least deviation from the original behaviour

Figure 5 describes the findings based on a sphere model with irregular mesh topology to illustrate the concept. The standard deviations comparison in 5(a) shows that B produces high level of similarity or coincidence between the displacement patterns. Furthermore, scheme B maintains a minimal displacement deviation for any magnitude of force compared to scheme A where its deviation increases with force (5 (b)). Hence, the analysis concludes that the proposed scheme B preserves the properties and the local dynamic behaviour with minimal standard deviation when a local area is refined. Tests have been carried out

on models with various mesh complexities and they also draw similar conclusions.
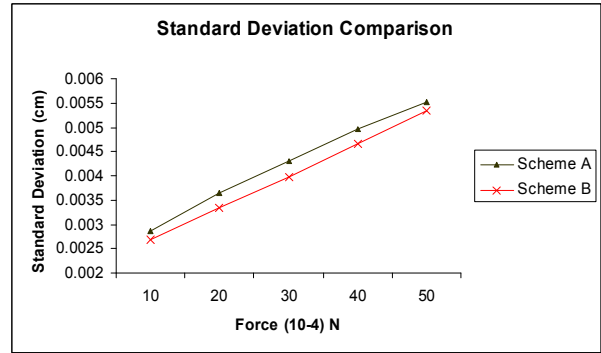
(a)
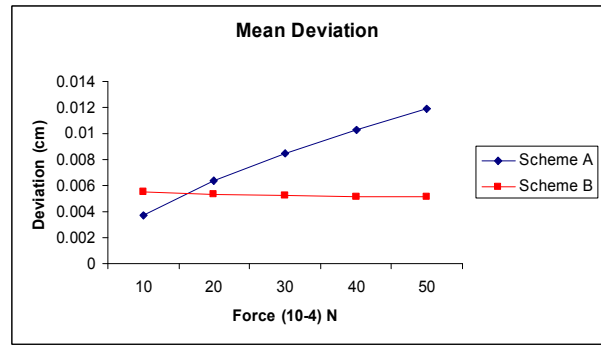
(b)

Figure 5 (a) B Denotes the most coincidence in the displacement patterns (c) B maintains the least error

4.2. Performance Evaluation

A simple performance test has been carried out to illustrate that the surface data reduces the computational cost. Table 2 shows that the average frame per second (FPS) achieved by the VMSS and the proposed surface model.

Table 2 Comparing Frame per Second (FPS)

Model (nodes)	Cube (602)	Cube (135)	Cube (2402)	Sphere (1000)
VMSS	77	37	20	47
Scheme B	80	44	25	77

4.3. Volume Behaviour

To produce a more realistic global deformation based on the interaction force radius and orientation of influence, the weighted constraints are manipulated at runtime. When the weighted constraints are set to 1, the global deformation as in figure 6 (a) is produced. Upon interaction, the weighted constraint at each node is changed during simulation in regards to the radius and

the interaction force orientation at runtime. Consequently, figure 6 (b) shows that at runtime, the automatic constraint derivation based on the force orientation and radius of influence produces a more realistic behaviour.
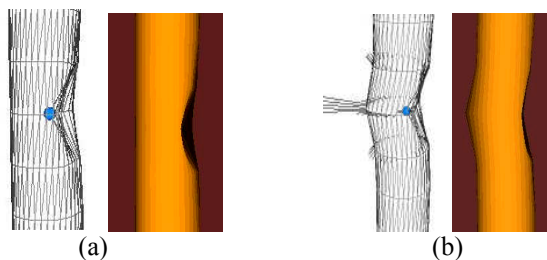

Figure 6 Shape Deformation Effect (a) uniform constraints (b) constraints extracted at runtime

Other models such as cubes with different surface mesh complexities have been compared with the FEM model as analysed by SolidWorks/Cosmos. A shear force is imposed on the top surface while the opposite surface is fixed. When compared with FEM, the shape produced is similar with minor deviation (Figure 7).
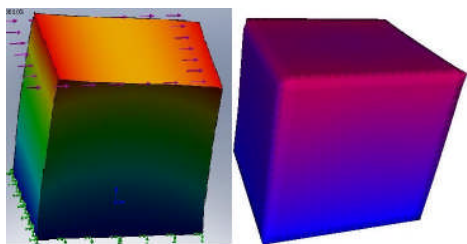

Figure 7 Shape Comparison (a) FEM (b) Scheme B

When a constant force is imposed on the surface, the object shape changes and deforms. The analysis concludes that the irregular framework preserves the object volume with the least volume deviation as illustrated by the average deviation percentage comparison in figure 8.
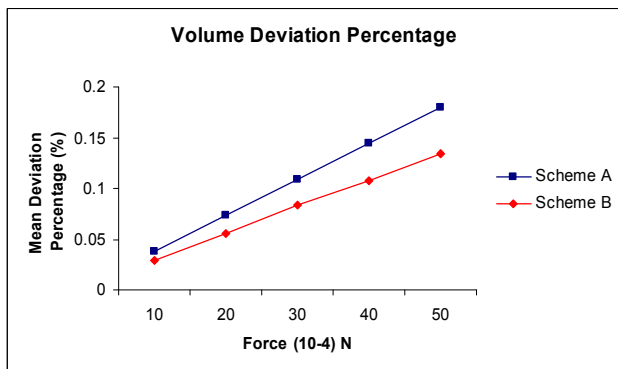

Figure 8 The Percentage of the Mean Volume Deviation from the Volume at Rest

5. Conclusions

This paper has illustrated the feasibility of employing a surface mass spring system that is able to emulate soft volume behaviour. The proposed model introduces volume springs which stiffness is extracted based on the explicit discretisation of the underlying surface mesh based on the node normal, the neighbouring triangular elements and the object centre.

The stiffness has 3 dimensions that represent the level of elasticity, rigidity (shear) and compressibility (bulk). The runtime extraction of the stiffness during the simulation is relative to force orientation as well as the weighted constraints to control the global deformation effect upon interaction. This addresses the anisotropic behaviour of the surface nodes.

Local deformation behaviour is preserved regardless of the mesh resolutions. The global deformation effect is achieved despite the non-existence of internal volume. It displays similar behaviour with the FEM model and produces minimal deviation from the original elasticity modulus. Furthermore, the computational performance is better than the volume counterpart. Even though the proposed method is based on materials that are linearly elastic, homogeneous and incompressible, it can also be extended to address other properties.

The framework is currently explored in the ongoing research in breast simulation. Further evaluations such as the perception test with the users will be carried out to verify the visual and haptic feedback experienced by the users

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