Modeling Deformable Objects as Compliant Mechanisms

Daniele F. Silva and Anderson Maciel
Instituto de Informática (INF)
Universidade Federal do Rio Grande do Sul (UFRGS)
Porto Alegre, Brazil
Email: {dfsilva, amaciel}@inf.ufrgs.br

***Abstract*—Several applications require high computation power due to the presence of complex geometry and physical principles applied to the virtual environment. One of these principles is the geometry deformation, occurring when forces are applied on a deformable body. This work proposes a study towards the introduction of compliant mechanisms models as an approach to simulate deformation. We believe that such technique can be used to reduce computational complexity for simulations that require both great accuracy and high performance.**

***Keywords*-physically based animation; rigid body; deformable body; elasticity; compliant mechanisms;**

I. Introduction

Physically based deformable models are applied in many fields of computer graphics, e.g. cloth and hair animation, organs behavior in surgery simulation, haptic feedback rendering for deformable objects. It occurs when external forces are applied on the deformable object and it deforms under the complex mechanical properties of the materials that compose it. In order to create virtual representations of deformable objects realistically, it is necessary that these objects behave with a high degree of similarity to the real world.

In computer graphics literature we highlight the occurrence of two classical deformable models: mass-spring damper (MSD) and finite element method (FEM). The MSD is used in applications that do not require great accuracy, such as games, due to its simplicity to implement and its relatively low computational cost. Then, when accuracy is required, FEM is more often used e.g. medical and engineering applications. The drawback of FEM is the complexity to implement and the very high computational cost.

Objectives: In this paper we propose a study upon an alternative solid deformation approach. We highlight the concept of compliant mechanisms (CM) to model highly deformable objects under the hypothesis that they are sufficiently accurate to produce better realism than MSD with better performance than FEM. The only assumption is that the materials deform homogeneously.

II. Background

In computer graphics, physics-based and non-physics-based approaches are discussed for solid modeling. Due the importance of realism for many applications, we overview articulated and physics-based models here.

A. Rigid bodies

A rigid body is an idealized solid which the size and shape are fixed and remain unaltered when forces are applied, i.e. the deformation is unconsidered. The distance between any two given points of a rigid body remains constant in time regardless of external forces exerted on it.

Notice that it is possible to simulate non-rigid motion using articulated rigid bodies.

1) Denavit-Hartenberg notation: The Denavit-Hartenberg (DH) notation describes articulated structures as a set of attached links connected by joints. Each joint has a coordinate system organized in a hierarchical structure. Transformation matrices are created between those coordinate systems and are associated to the respective articulations.

The DH notation represent structures with joints presenting only 1 degree of freedom (DOF) each. For kinematic modeling this notation provides simplicity of implementation and the formulation of the problem. Joint structures with more than 1 DOF are represented as a set of 1 DOF joints, making the structure more complex to manipulate and consequently using more computational resources [1].

B. Deformable bodies

1) Mass-Spring Damper: In this method, a discretized object is used. To simulate the deformation behavior motion equations are applied on nodal points which are called masses. They store position, velocity and acceleration values. The connections between masses neighboring nodes are called springs. They are defined by their Hooke's constant of elasticity and a nominal distance.

The MSD is a physics-based model that guarantees a certain realism with low computational resources. Their mathematical simplicity facilitates the implementation of the algorithm and allows real-time execution up to hundreds of nodes. On the other hand, the simplicity of the model shows great instability. To circumvent this problem, implicit or explicit numerical approximation are used in combination with treatments for the configuration parameters of the model [2], [3], [4].

Despite these limitations, physics and game engines implement this model effectively circumventing many problems that cause instability. Examples are PhysX, Bullet and SOFA.

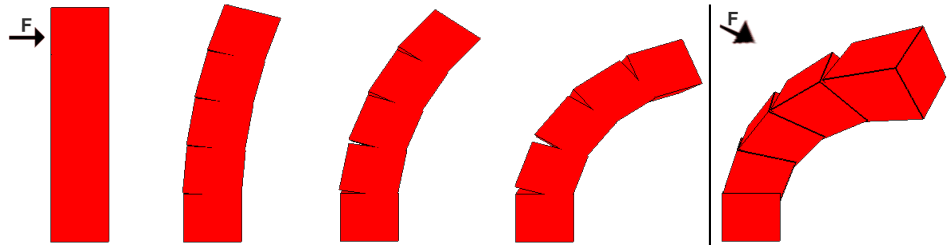

Fig. 1. Visualization of deformation behavior with linked rigid bodies a horizontal force is applied.

2) Finite Element Method: Different of discrete algorithms for objects such as used in the MSD, this model works on the continuous domain. The FEM belongs to continuous mechanical, in which the object is divided into finite elements comprising a set of nodes. This model is used to find approximate interpolation functions. For each element the function that satisfies a balance equation is computed.

The advantage of FEM is that complex geometry, general boundary conditions and variable or non-linear material properties can be handled relatively easily. The disadvantage is the high computational cost, making the use of this method unviable for most interactive applications.

This model became very popular, being used in non-real-time applications or in those where real-time animation is displayed after simulation preprocessing [5], [6], [7], [8].

III. Compliant Mechanisms

The CM are flexible mechanisms that transfer an input force or displacement to another point through elastic body deformation. Traditional rigid body mechanisms consist of rigid links connected at movable joints.

A CM, in turn, transfers or transforms motion, force, or energy. Unlike rigid link mechanisms, CM gain at least some of their mobility from the deflection of flexible members rather than from movable joints only [9], [10], [11].

In a simple case as shown in Figure 2, a set of rigid links bends homogeneously under a force application. Such simple motion is almost impossible to achieve with MSD because springs eventually allow some elasticity to stretch the links. Some objects, like strings, are flexible and inextensible at the same time.

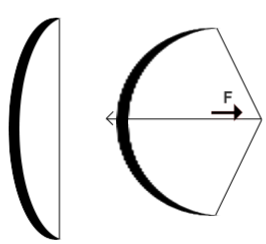

Fig. 2. CM bow in the rest shape (left) and when applied a force (right).

IV. Current results and future work

In this paper we have overviewed two mechanical models for physics-based animation, rigid and deformable solid. We highlight a new approach for the deformation behavior. Figure 1 shows a similar behavior of CM, using rigid bodies organized hierarchically by joint structures to simulate deformation. To present this approach we applied the Newton's law and rotational motion on the flexible object. The object is composed by a set of rigid bodies, where the bottom is attached to the ground. A force vector is applied parallel to x axis on the top of the object.

However, hierarchy is not applicable to complex geometries as in some cases it is impossible to define the root. For this reason the problem will be modeled so that we can combine the rigid body and CM theory.

As the future work, we propose the implementation of CM in order to obtain greater accuracy over classical methods. We expect to obtain interactive refresh rates even when haptic feedback is required. The hypothesis of this work is that the use of this mechanism can be very fast and accurate in structures that show homogeneous deformation.

References

[1] A. Maciel, *Biomechanics-based Articulation Models for Medical Applications: A computer graphics approach to bring a new dynamic into image based medical applications*. VDM Verlag Dr. Müller, 2010.

[2] J. Georgii and R. Westermann, "Mass-spring systems on the gpu," *Simulation Modelling Practice and Theory*, vol. 13, pp. 693–702, 2005.

[3] A. Selle, M. Lentine, and R. Fedkiw, "A mass spring model for hair simulation," *ACM Trans. Graph.*, vol. 27, no. 3, pp. 64:1–64:11, Aug. 2008.

[4] J. Mesit, R. Guha, and W. Furlong, "Simulation of lung respiration function using soft body model," in *Computer Modeling and Simulation (EMS), 2010 Fourth UKSim European Symposium on*, nov. 2010, pp. 102 –107.

[5] T. Kim and D. L. James, "Skipping steps in deformable simulation with online model reduction," *ACM Trans. Graph.*, vol. 28, no. 5, pp. 123:1–123:9, Dec. 2009.

[6] P. Kaufmann, S. Martin, M. Botsch, E. Grinspun, and M. Gross, "Enrichment textures for detailed cutting of shells," *ACM Trans. Graph.*, vol. 28, no. 3, pp. 50:1–50:10, Jul. 2009.

[7] P. Kaufmann, S. Martin, M. Botsch, and M. Gross, "Flexible simulation of deformable models using discontinuous galerkin fem," *Graph. Models*, vol. 71, no. 4, pp. 153–167, Jul. 2009.

[8] M. Becker, M. Ihmsen, and M. Teschner, "Corotated sph for deformable solids," 2009.

[9] K. jia Lu and S. Kota, "Design of compliant mechanisms for morphing structural shapes," *Journal of Intelligent Material Systems and Structures*, 2003.

[10] S. Kota, K.-J. Lu, Z. Kreiner, B. P. Trease, J. Arenas, and J. Geiger, "Design and application of compliant mechanisms for surgical tools," *Journal of Biomechanical Engineering*, vol. 127, pp. 981–989, 2005.

[11] S. Wilding, L. Howell, and S. Magleby, "Introduction of planar compliant joints designed for combined bending and axial loading conditions in lamina emergent mechanisms," *Journal of Mechanism and Machine Theory*, vol. 56, pp. 1–15, 2012.