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Technical Section

MSRS: A fast linear solver for the real-time simulation of deformable objects

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Abstract

Nowadays many interactive computer graphics applications deal with soft-bodies. These applications are always demanding higher and higher levels of realism, increasing the complexity of the animated scenarios. Therefore, the techniques used to animate the objects should be very efficient to grant interactivity. Most often, an accurate answer is not needed and a visually plausible one is enough. One of the most important issues in physically based simulations is to keep the model stable under all simulation conditions. In this paper we present a technique called matrix system reduction solver (MSRS) to highly accelerate the real-time simulation of a finite element-based technique. Our method is fast, visually plausible and robust. In the first stage of the algorithm an initial solution is estimated. Then, only those equations showing a large error are solved using a more precise technique. In the final stage the linear and angular momenta are corrected. Experimental results show the feasibility of this new approach from the point of view of performance compared to the results provided by the stiffness warping method.

Keywords: Real-time simulation; Deformable objects; Robust linear FEM

1. Introduction

A lot of effort has been devoted to the task of achieving a higher level of realism in physically based animation of deformable objects during the last two decades. The technological improvements introduced both in graphics hardware and general purpose processors have allowed to tackle challenges like the real-time simulation of deformable entities such as cloth and hair for characters in games and animation, soft tissue in surgical simulators, etc. These applications constantly demand higher degrees of accuracy and visual realism, which affect the interactivity of the simulations. In such applications, only a small percentage of the computation time is devoted to physical simulation, since most of the available time has to be spent in other tasks like rendering, character's behaviors, etc. Therefore, the computations associated to physical simulations suffer from strong time restrictions, demanding the development of efficient solutions.

To keep the interaction realistic between the users and the virtual worlds created for these applications, two main objectives must be pursued:

- To grant the simulation stability.
- To reach near real-time responses (around 30 frames per second) [1].

For the first objective, robust environments must be designed to provide the user with complete freedom to perform any action compatible with the applications. This requires developing physical models that are always stable, independently of external events. Implicit integration has proven its value for keeping the simulations stable [2–6]. For the second objective, a compromise between accuracy

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and speed has to be reached. The final objective then becomes to produce plausible responses rather than the exact one as long as that approach allows getting close to real time.

This work deals with deformable models using a finite element method (FEM) approach. FEM is physically more accurate than most methods, although solving its governing equations is computationally expensive and its use in real-time simulations has been limited. Nevertheless, due to the performance of the latest computers and the availability of simplified approaches, FEM is experiencing a growing use in real-time applications where visually plausible results are considered to be good enough.

This paper presents matrix system reduction solver (MSRS), a new technique to accelerate the solution of the warped stiffness finite element approach [7] using the global rotation of the mesh while granting the simulation robustness. An initial solution is first computed combining a precalculated solver and the global mesh rotation. Then, the nodes that show large errors are solved separately using a matrix smaller than the whole system matrix. Finally, the linear and angular momenta are corrected to grant their conservation. Summarizing, the main contribution of this work is a technique to accelerate the real-time simulation of deformable objects using a stable finite element method. The initial solution given by the system would be good enough when the object is under small deformations. When the object is highly deformed extra time is needed to give a more plausible answer. This extra time depends on the magnitude of the deformation.

Even though in this paper the proposed technique has been applied to accelerate the finite element stiffness warping method, it can also be easily modified in order to accelerate other finite element methods.

The paper is structured as follows. First, a brief overview of previous works is given in Section 2. Section 3 presents a summary of the stiffness warping finite element formulation, since it was chosen as the starting point for the method presented here, given its advantages in terms of speed and stability. Section 4 describes the technique proposed in this paper and how it can speed up simulations. Section 5 presents the experimental results, comparing the proposed technique with previous methods both in terms of velocity and accuracy. Also, this section analyzes the results achieved while modifying several of the method's parameters. Last, Section 6 is devoted to conclusions and ongoing work.

2. Previous work

Nowadays there is a wide variety of physical models that can be used to simulate deformable objects, but few of them are able to deal with real-time simulations. For example, the following techniques can be pointed out: mass-spring systems [2,8–13]; mesh free methods [14–16]; finite elements [17–19]; finite differences [20]; finite volumes [21,22]; boundary element methods [23]; and finally, position-based methods [24–26]. None of them can be considered the best, since they depend on specific features of both the applications and the deformable objects. For example, a system like ArtiSynth that simulates the vocal tract and upper airway combines in a open-source library support for particle–spring systems, splines, finite element models and PCA driven point clouds [27]. Extensive surveys for deformable models can be found in [28], and more recently, in [29].

Many approaches for the real-time simulation of deformable objects use simplified and/or precomputed models of the finite element method. An excellent and complete treatment of the FEM theory can be found in [30]. We will discuss some recent papers that propose simulating deformable objects in real time using finite elements techniques.

Bro-Nielsen and Cotin were among the first researchers to present detailed work to simulate real-time deformations of a volumetric linear elastic object using finite elements [31]. They reduced the computation time required by the volumetric model preprocessing the responses and using only the surface nodes of the mesh. However, it was not possible to simulate dynamic behaviors due to the quasi-static nature of their model (a succession of static pose solutions). Modal analysis [32] is another option to reduce the computational load precomputing a set of deformation modes. Choi and Ko apply this technique to propose a real-time simulation technique to constrained deformable objects attached to rigid supports [33]. Huang et al. [34] propose a similar technique to the modal approach. They manually decompose the object into several sub-domains to apply a linear elastic model. A better accuracy is achieved in this case because only local rotation estimation is computed in each sub-domain. Complex objects make the manual task of decomposing the objects difficult, although they propose to run a cluster principal component analysis to obtain a good decomposition without user interaction. Huang et al. reduce the matrix system dimension in the frequency domain and perform an adaptive computation of the rotations in the spatial domain [35], but the preservation of the angular momenta is not granted in their simulation technique.

Further reduction of the computation time can be obtained introducing a general multiresolution adaptive approach to produce "conforming, hierarchical, adaptive refinement methods (CHARMS)" based on the refinement of base functions [36]. Unfortunately, the improvement achieved by this method is limited because it must still deal with the inherent problems resulting from the nonlinearities. Multigrid has also been used to accelerate the animation of deformable models. Wu and Tendick apply a multigrid integration scheme to simulate deformable models in surgical training systems [37], improving stability and convergence over one single level explicit integrator. Georgii and Westermann integrate linear, corotational linear and nonlinear Green strain into a multigrid-based