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Pre-computation Approach to Nonlinear Simulations of Deformable Objects

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Link Foundation Fellowship Final Report

Description of the work completed while on the scholarship

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Introduction

My research area involves building real-time interactive simulations of solid deformable objects. For example, liver tissue should deform realistically during a virtual surgery simulation. A virtual assembly simulation can catch airplane construction design flaws early on during the manufacturing process. Deformable objects are also useful in computer games, for example to model the motion of trees in the wind.

Researchers in computational physics, mechanics, and applied mathematics have been developing algorithms for simulations of deformable objects for the past 40 years. However, the partial differential equations of solid continuum mechanics that govern deformations of physical objects are very involved and as such computationally demanding. Even on a modern computer, long computation times are necessary to simulate such systems. This effectively prohibits interactive simulations of objects with detailed geometry, because such simulations require the state of the system to be updated at very fast rates: for example, 30 times per second for quality visual feedback and 1000 times per second for quality force-feedback. It can easily take several seconds for traditional methods to compute one timestep of a simulation of a large model, such as a liver model with 15,000 elements. The goal of my research is to develop methods that require substantially less computation time, while at the same time sacrificing as little accuracy as possible in the solution. An interesting question is the following: Given a fixed amount of computation time, what deformable object algorithm achieves the highest simulation accuracy (for a large class of deformable models)?

Results

During the scholarship year, I completed the majority of the work on the project which was accepted into the papers program at the annual computer graphics conference (SIGGRAPH 2005) in Los Angeles (August 2005). Together with my professor Doug James, we developed a new method for fast simulations of deformable objects, suitable for interactive applications in computer graphics and haptics. The method can simulate nonlinear deformations of complex deformable objects at very modest simulation costs. For example, a 3D volumetric mesh model of the human heart consisting of 15,000 elements can be simulated with a computation time of about 1 milisecond per timestep on a 3.0 Ghz Pentium processor with 2 Gb of memory.

The central idea of this project is dimensional model reduction. When complex objects deform, different parts of the model deform coherently. Think of a large bridge swaying in the wind. It usually doesn't just deform arbitrary - it has certain typical shapes that it tends to deforms into. We designed an automatic process that can identify such typical shapes directly from the principles of continuum mechanics. Note that this problem has already been addressed in literature for the case of small deformations, where linear physics is sufficient for simulation. We presented an approach to extract a space of typical deformations for the more general case where deformations are allowed to be large, and where the nonlinear terms in the equations of motion are significant. By restricting the motion to the vector space spanned by such typical shapes, one obtains a reduced nonlinear deformation model. This results in a significant reduction in the complexity of the simulation, with a modest loss of simulation accuracy. The compromise is that the non-typical nonlinear shapes can't be simulated since they are not included in the deformation shape vector space.

In addition, we make use of the observation that model reduction on large deformation models with linear materials (as commonly used in deformable object mechanics and computer graphics) results in internal force models that are simply cubic polynomials in reduced coordinates. Coefficients of these polynomials can be precomputed, for efficient runtime evaluation. This allows for a fast runtime evaluation of internal elastic forces and their gradients. We can then simulate the system with a standard reduced implicit Newmark integrator, which results in fast simulations of nonlinear dynamics. Simulation costs depend on the dimensionality of the shape vector space and are as such independent of model geometric complexity.

A key question is how to select the vector space of shapes that best captures typical nonlinear deformation response of a system. This is in general a hard open problem in solid mechanics. To this end, we present two useful approaches: modal derivatives and an interactive sketching technique. Also, we suggest mass-scaled principal component analysis (mass-PCA) for dimensionality reduction. We presented several examples from computer animation to illustrate high performance, including a force-feedback haptic rendering of a complicated bridge model (about 6000 brick elements) undergoing large deformations. Simulation costs were 65 microseconds per timestep, compared to several seconds per timestep when the same model is simulated using a standard approach.

Significance and impact

This project is the first system to demonstrate haptic rendering of a detailed deformable object undergoing large deformations. If compared to existing systems where only visual feedback is necessary, our system is faster than other approaches in several important cases. I hope the project will inspire other applications of model reduction (such as fluid simulations in computer graphics). Also, this project raises the important scientific question: How much computation is ultimately necessary to solve the partial differential equations of solid mechanics? While we cannot guarantee that this algorithm is optimal for a given amount of computation time (such a claim would be very difficult to prove), we believe it to form a good trade-off between simulation speed and accuracy.

Where might this lead?

The ultimate goal of this kind of research is to build extremely fast simulators that can simulate very complex deformable objects extremely accurately and with negligible CPU costs. For example, build a detailed model of the human body consisting of millions and millions of elements. Model the different tissue properties and connectivity. Then, simulate any kind of a surgical operation with perfect accuracy and extremely high update rates. Or build a very detailed model of a spacecraft, and then be able to simulate the response to various force loads and conditions with negligible CPU costs. If design turns out to be insufficient, one should be able to change the geometry and material properties interactively, without having to execute large jobs that take several hours (as often the case today). Such capabilities would also be useful in computer animation industry.

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List of journal/conference papers (acknowledging Link Foundation support)

Jernej Barbič, Doug L. James: Real-Time Subspace Integration for St.Venant-Kirchhoff Deformable Models, ACM Transactions on Graphics (SIGGRAPH 2005), Los Angeles, CA, August 2005

How the discretionary funds were spent

The funds were spent to support the work on the project: 3D models (meshes), computer resources, attending conferences (which is the standard way of disseminating research results in computer graphics), books, computer software.

How the fellowship made a difference

The fellowship was a great personal encouragement. Winning this scholarship made a very positive impression with my colleagues and professors, and it will help in the future when going on the job market. It also finalized my decision to solve computer simulation problems as a part of my PhD thesis. I was also able to network with previous winners of this scholarship when we met at conferences. The fellowship helped my professor fund my research. In addition, following the general policies of the computer science department at CMU, I received a $250 fellowship bonus per month (during the fellowship year) on top of my standard stipend, as a reward for having won the fellowship. This extra money was very welcome for a tight grad student budget.