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Technical Section

Adaptive cloth simulation using corotational finite elements ☆

Jan Bender *, Crispin Deul

Graduate School CE, TU Darmstadt, Germany

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A B S T R A C T

In this article we introduce an efficient adaptive cloth simulation method which is based on a reversible $\sqrt{3}-$refinement of corotational finite elements. Our novel approach can handle arbitrary triangle meshes and is not restricted to regular grid meshes which are required by other adaptive methods. Most previous works in the area of adaptive cloth simulation use discrete cloth models like mass-spring systems in combination with a specific subdivision scheme. However, if discrete models are used, the simulation does not converge to the correct solution as the mesh is refined. Therefore, we introduce a cloth model which is based on continuum mechanics since continuous models do not have this problem. We use a linear elasticity model in combination with a corotational formulation to achieve a high performance. Furthermore, we present an efficient method to update the sparse matrix structure after a refinement or coarsening step.

The advantage of the $\sqrt{3}-$subdivision scheme is that it generates high quality meshes while the number of triangles increases only by a factor of 3 in each refinement step. However, the original scheme was not intended for the use in an interactive simulation and only defines a mesh refinement. In this article we introduce a combination of the original refinement scheme with a novel coarsening method to realize an adaptive cloth simulation with high quality meshes. The proposed approach allows an efficient mesh adaption and therefore does not cause much overhead. We demonstrate the significant performance gain which can be achieved with our adaptive simulation method in several experiments including a complex garment simulation.

1. Introduction

Interactive cloth simulation has a long history in computer graphics. In this area the resolution of the simulation mesh plays an important role. On one hand the resolution must be high enough to get realistic wrinkles during the simulation, on the other hand simulations with high detailed meshes cost much computation time and often do not run at interactive frame rates. In this article we present a cloth simulation method which changes the resolution of the cloth model adaptively. In regions of the model with fine wrinkles small triangles are used for the simulation while a low resolution is used in areas without fine details. The advantage of such an adaptive model is that the performance can be increased significantly without loosing much details.

The idea of using an adaptive mesh as cloth model is not new. There exist different works which focus on this topic. Most of the previous approaches use adaptive mass-spring systems for the simulation. In general such systems are not convergent, i.e. the simulation does not converge to the correct solution as the mesh is refined [1]. To solve this problem we introduce an adaptive cloth model based on continuum mechanics. We use a linear finite element method (FEM) in combination with a corotational formulation to perform the simulation efficiently. This method works on triangular elements which are defined by the adaptive triangle mesh of our cloth model. The resolution of this mesh is adapted during the simulation by using a $\sqrt{3}-$subdivision scheme [2]. This scheme defines how a triangle mesh can be refined adaptively while maintaining a high mesh quality. In this article we present an extension which allows us to coarsen the mesh in areas where a fine resolution is not required anymore.

In contrast to other adaptive simulation methods, our approach can handle arbitrary triangle meshes and is not restricted to meshes based on regular grids. Our refinement criterion is based on the mean curvature. Therefore, we get a high resolution for fine wrinkles and a low resolution in flat regions. The proposed method can speed up the simulation significantly at the cost of accuracy. The performance gain and therefore also the accuracy loss can be controlled indirectly by the user-defined parameters of the refinement criterion. The mesh adaption with our method can be performed very efficiently. Hence, the computational overhead caused by the adaption is low.

This article is an extended version of our earlier paper [3]. In comparison to our earlier paper we added the description of

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* Corresponding author.
E-mail address: bender@gsc.tu-darmstadt.de (J. Bender).

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a hybrid method to determine the area in the triangle model which is represented by a single particle. These particle areas are required for a consistent mass distribution and to compute the mean curvature of the model. The mean curvature is needed by the refinement criterion in our adaptive remeshing process. We also added more details about the refinement process as well as the computation of the bending matrix and the damping matrix. Furthermore, we developed a fast matrix assembly strategy. Since we use an adaptive cloth model, the matrix structure changes after each refinement and coarsening step. The presented matrix assembly allows us to update the structure efficiently. As a final extension we present new experiments to demonstrate the contribution of our simulation method in a complex garment simulation.

2. Related work

In this section we want to give an overview over important works in the area of cloth simulation and adaptive deformable models.

Research in cloth simulation has been done for more than 20 years in the field of computer graphics (for surveys see [4,5]). Often the assumption is made that cloth is an elastic material in order to perform an efficient simulation using spring forces. The problem is that many real textiles cannot be stretched significantly. Different techniques have been presented to solve this problem. Provot [6] used a mass-spring system for cloth simulation in combination with an explicit time integration. Instead of using stiff springs which can cause instabilities, Provot proposed to displace particle positions after each simulation step as an alternative way for strain reduction. Baraff and Witkin [7] used an implicit Euler integration in order to perform a stable simulation for stiff systems. This approach supports the simulation of arbitrary triangle meshes whereas other approaches require regular grid structures, e.g. [6,8]. A semi-implicit method was used by Choi and Ko [8] for a stable simulation with stiff springs. They also solved the problem with instabilities of the post-buckling response which are not caused by stiff equations. In order to limit the strain, Bridson et al. [9] applied corrective impulses to the velocities of the particles. Goldenthal et al. [10] presented an approach based on Lagrangian mechanics in combination with a fast projection method in order to simulate inextensible cloth. English and Bridson [11] performed cloth simulations using triangle meshes with a hard constraint on each edge. In order to solve the consequential locking problem, they used a nonconforming mesh for the simulation which has more degrees of freedom than the original one. Bender et al. [12] combined this technique with an impulse-based approach [13] to simulate models with hard constraints more efficiently. A continuum-based strain limiting method was introduced by Thomaszewski et al. [14].

In the last years different authors proposed to use continuous models to simulate cloth. In contrast to discrete models like mass-spring systems, a model based on continuum mechanics has the advantage that it is independent of the mesh resolution. Etzmuss et al. [15] used a finite difference discretization of the model in order to solve the differential equations. Due to this discretization only quadrilateral meshes can be handled. In a second work they presented an efficient approach based on the finite element method (FEM) with a corotational formulation which can also handle arbitrary triangle meshes [16]. Thomaszewski et al. [17] also use a corotational formulation for their finite element simulation. In their work they show how membrane and bending energies can be modeled consistently for thin, flexible objects. Volino et al. [18] present a cloth simulation system based on continuum mechanics which is able to simulate nonlinear anisotropic materials.

There exist different approaches to improve the performance of cloth simulations by using an adaptive refinement of the simulation model. Hutchinson et al. [19] presented an adaptive mass-spring model for cloth simulation. This model has a regular grid structure which is refined when the angle between two neighboring springs exceeds a certain tolerance value. A similar approach which also uses regular quad meshes in combination with a mass-spring model was introduced in [20]. Li and Volkov [21] presented an adaptive version of Baraff's cloth simulation method [7] which is able to handle arbitrary triangle meshes. They use a modified $\sqrt{3}-$refinement rule without explicit edge flip which forces a subdivision of adjacent triangles. Hence, the number of triangles increases faster compared to our method. Lee et al. [22] use a mass-spring system in combination with a Loop subdivision scheme for refining a triangle model. The subdivision steps are precomputed in order to get a multi-resolution hierarchy. This is used to adaptively reduce the dimension of the linear system which must be solved for an implicit integration step. In contrast to these previous works that use mass-spring systems which are not convergent, our model is based on continuum mechanics. Brochu et al. [23] use the continuous cloth model proposed by Etzmuss et al. [15] and perform simple edge splitting, flipping and collapsing in order to demonstrate that their continuous collision detection is able to handle adaptive meshes. Grinspun et al. [24] use a continuous model for the adaptive simulation of thin shells and volumetric deformable models. But instead of refining the elements, they introduce a refinement of the basis functions to reduce the computation time of a simulation step. Further adaptive methods for volumetric deformable models are presented in [25,26].

3. Simulation step

This section gives a short overview over the time integration of the adaptive cloth simulation method. In the following sections each step will be explained in detail.

For the simulation we use a triangular mesh of particles as cloth model. Each particle has a mass m, a position $\mathbf{x}$ and a velocity $\mathbf{v}$. A single simulation step is performed as follows:

1. Determine all external forces which are acting on the model.
2. Perform a simulation step with the continuous model to get new positions $\mathbf{x}^{n+1}$ (see Section 4).
3. Determine average velocities $\mathbf{v}^{n+1/2} = (\mathbf{x}^{n+1} - \mathbf{x}^n)/\Delta t$.
4. Detect proximities for $\mathbf{x}^n$ and resolve them with friction by modifying the average velocities $\mathbf{v}^{n+1/2}$ with impulses (see Section 6).
5. Perform a continuous collision detection step for the linear trajectory from $\mathbf{x}^n$ to $\mathbf{x}^n + \Delta t \mathbf{v}^{n+1/2}$ and adapt the average velocities $\mathbf{v}^{n+1/2}$ by applying impulses to resolve collisions with friction (see Section 6).
6. Compute final positions and velocities (see Section 6).
7. Adapt the resolution of the mesh (see Section 5).

4. Cloth simulation

In this section we first introduce our cloth simulation model. Then we introduce the corotational formulation for linear elasticity in order to simulate stretching and shearing. Furthermore, we show how the simulation of bending and damping is realized. In the end of this section we briefly introduce an implicit time