Graphical Simulation of Deformable Models

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Preface

This book is on dynamics simulation of deformable objects. We are especially interested in the simulation of deformable models with anisotropic materials, which is less exploited in existing research. To do this, it is essential to improve the physical realism of simulation, since many real-world objects have complex mechanical rather than isotropic properties. An in-depth survey is conducted on the relevant research topics. Both physically-based and geometrically-based approaches are studied, and our contributions are made in modeling and controlling of anisotropic dynamics deformations.

To prepare the ground for dynamics simulation with the finite element method, we first introduce a previously developed mesh representation algorithm, *isosurface stuffing*, which fills an object domain with a uniformly sized tetrahedral mesh. This algorithm is numerically robust. It generates tetrahedra from a small set of precomputed stencils. A variant of the algorithm creates a mesh with internal grading. That is, on the boundary where high resolution is desired, the tetrahedral elements are fine and uniformly sized; and in the interior, the tetrahedra may be coarser and vary in size. This combination of features makes isosurface stuffing a suitable tool for large-deformation mechanics.

We then investigate transversely isotropic materials for the simulation of deformable objects with fibrous structures. In previous work, direction-dependent behaviors of transversely isotropic materials can only be achieved with an additional energy function which incorporates the material preferred direction. Such an additional energy term increases the computational complexity. We introduce a *fiber-field incorporated corotational finite element model* (CLFEM) that works directly with a constitutive model of transversely isotropic material. A smooth *fiber-field* is used to establish the local frames for each element. The orientation information of each element is incorporated into the CLFEM model by adding local transformations onto each element of the stiffness matrix.

We further introduce deformation simulation for orthotropic materials. An orthotropic deformation controlling *frame-field* is conceptualized and a frame construction tool is developed for users to define the desired material properties. A quaternion Laplacian smoothing algorithm is designed for propagating the user-defined sparsely distributed frames into the entire object. The orthotropic frame-field is coupled with the CLFEM model to complete an orthotropic deformable model.

And finally, we present an integrated real-time system for animation of skeletal characters with anisotropic tissues. Existing geometrically-based skinning techniques suffer from obvious volume distortion artifact, and they cannot produce secondary dynamic motions, such as *jiggling* effects. *Physically-based skinning* with FEM models has high computational cost that restricts its practical applications. To solve these problems, we introduce a strain-based *Position based Dynamics* (PBD) framework for skeletal animation. It bridges the gap between geometric models and physically-based models, and achieves both efficient and physically-plausible performance. Natural secondary motion of soft tissues is produced. Anisotropic deformations are made possible with separately defined stretch and shear properties of the material, using the user-designed *frame-field*. Owing to the efficiency and stability of our proposed layered constraint solving scheme, we can achieve real-time performance, and the system is robust with large deformations and degenerate cases.

The monograph is written for researchers who would like to develop their own algorithms. The important mathematical and computational concepts are presented together with illustrations and working examples. It can also be used as a reference book for graduate students and senior undergraduates in the area of computer graphics, computer animation, and virtual reality. Academics, researchers, etc. will find this to be an exceptional resource.

Enjoy the read.

Singapore
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Notational Conventions

Most symbols in this work are denoted according to the notational conventions as follows:

Notations

Scalar: a (*Italic* lowercase)
Vector: $\boldsymbol{a}$ (*Italic* and bold lowercase)
Matrix and Tensor: A (Italic and uppercase)
Space of n dimensional real numbers: $\mathbb{R}^n$
Space of $m \times n$ real matrices: $\mathbb{R}^{m \times n}$
Identity matrix: I

Operations

Dot product: “$\cdot$”such as $\boldsymbol{a} \bullet \boldsymbol{b}$;
Cross product of vector: “$\times$”, such as $\boldsymbol{a} \times \boldsymbol{b}$;
Tensor product of two vectors: “$\otimes$”, such as $\boldsymbol{a} \otimes \boldsymbol{b}$
Double product or double contraction of two matrices: “:”, such as $A{:}B$

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