Physics-based Modeling for Animation and Medical Applications

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Abstract

In this paper we present two instances of our physics-based modeling methodology that we have been developing for over 10 years. The first method deals with modeling liquids for computer animation and is based on the solution of the Navier-Stokes equations on coarse grids using finite differences. The second method models the motion of the heart from MRI data based on finite element theory. The method is capable of analyzing the heart's motion in a clinically useful way.

1. Introduction

The development and use of Physics-Based Modeling (PBM) methods and techniques by many researchers has made it possible to address successfully, difficult problems in computer animation (e.g., modeling of visco-elastic materials and fluid phenomena) and medical imaging (e.g., visualization and analysis of heart motion), that were not possible with purely geometric and kinematic techniques. PBM methods utilize geometry, kinematics, dynamics and material properties in order to model physical objects and their interactions with the physical world. Therefore, as opposed to purely geometric models, physics-based models incorporate additional constraints (e.g., material properties) that are very useful in both modeling and estimation applications. A unique feature of PBM is that it provides a unified methodology for the modeling and estimation of rigid, articulated, and deformable models, and their motions.

In this paper we will demonstrate two instances of our physics-based modeling methodology that has allowed us to model fluid phenomena for computer animation and analyze the motion of the heart for medical applications.

2. Modeling Fluids for Computer Animation

Some of the most breathtaking animations in recent years have been generated by modeling the interaction between light and water. Effects such as caustic shading, reflection, refraction, and internal scattering have been addressed in some detail, with realistic results. One characteristic of that work however, has been that the motion of the water surface is approximated by a non physics-based function. Such approximations cannot easily incorporate dynamic objects or buoyant effects into the model, because the velocity of the fluid is known only on the surface, and internal pressure is not calculated at all. Chen and Lobo go further towards a physics-based fluid methodology by solving a simplified form of the Navier-Stokes equations in two dimensions [2]. However, they assume that the fluid has zero depth, and calculate the elevation of the surface solely from the instantaneous pressure. This allows them to perform some interaction between moving objects and the flow field, but restricts the class of problems that can be solved using the method. Although the surface height is varied for animation, they treat the fluid as being completely flat during the calculation. Therefore, convective wave effects, mass transport, and submerged obstacles are not covered by their technique.

Comprehensive models of fluid motion do exist, and there are a variety of tools for solving them in the field of Computational Fluid Dynamics (CFD). These methods generally involve direct simulation techniques to get accurate fluid motion. Unfortunately, in any direct simulation technique the temporal resolution is strongly coupled to the spatial resolution. Thus, if the spatial resolution doubles, the temporal resolution must also be doubled so that the solution does not move more than one spatial sample per time step. This gives running times proportional to the fourth power of the resolution, so most of these techniques will scale poorly. Furthermore, an animator needs a fairly clear understanding of the system of equations being solved so that he or she can set initial and boundary conditions to get the desired results. An ideal fluid simulator for graphics applications would apply the correct conditions automatically based on the underlying geometry. CFD methods also resist external control, making it difficult to force a particular motion from a fluid, unless it is a natural consequence of the system. These restrictions are an inherent part of the fluid modeling problem. The question arises whether it is possible to accurately model realistic fluid motion while keeping within acceptable efficiency bounds for Computer Graphics.

In our research [5, 4, 3] we have devised a solution to the Navier-Stokes equations for modeling liquid motion, that satisfies many of an animator's needs. Realism is provided through a finite difference approximation to the incompressible Navier-Stokes equations. This gives rise to a complete pressure and velocity profile of the simulated environment. This profile is then used to determine the behavior of free surfaces, and is loosely coupled to the Lagrange equations of motion to include buoyant rigid objects into a scene. The range of behaviors accounted for include wave effects such as refraction, reflection and diffraction, together with rotational motion such as eddies and vorticity. Furthermore, velocity and pressure are strongly coupled within the model. This means that even the simplest animation exhibits subtle realistic behavior not available using previous computer-graphics fluid models.

Usability has also been a strong motivation for this work. The Navier-Stokes equations are solved over a coarse, rectangular mesh containing an arbitrary distribution of submerged or semi-submerged obstacles. Boundary conditions for the mesh are generated automatically by constraining the free variables at an obstacle-fluid or air-fluid boundary. This low resolution calculation together with homogeneous boundary conditions leads to a relatively efficient determination of fluid velocity and internal pressure. Detail is achieved by using the velocity field to concentrate attention on regions of interest, i.e., the fluid surface. The surface is represented as either a chain of massless marker particles, or a height field. The markers are carried around the mesh by convection, and can have arbitrary connectivity, accounting for multiple colliding surfaces in a scene.

Consideration is also given to controlling the overall behavior of the fluid. Liquid sources or sinks (known as inflow and outflow boundaries) can be included anywhere in the environment. They allow liquid to flow (or be forced) into a scene, or flow out at a natural rate. A time dependent pressure field may also be applied to the fluid surface. Thus, the effects of a strong wind can be simulated and initial waves be driven realistically. The output from the system is a polygonal surface or height field, both of which can be rendered using many of the techniques presented by researchers in recent years. [7, 9, 10, 12].

Fig. 1 shows a snapshot from a 3D animation titled *Moonlight Cove*. A 50x15x40 mesh was used to finely resolve the effect of two large ocean waves crashing into a shallow cove. Submerged rocks, and an irregular sea bottom, focus the waves into the center of the cove, causing a number of interesting features on the water surface. The wave becomes steeper as the water depth decreases, and eddies and pressure waves appear to the left of, and behind the initial obstacle (Fig. 1(b)).

3. Heart Modeling for Clinical Applications

Estimating the volumetric shape, motion and deformations of the heart's left (LV) and right (RV) ventricles accurately and in a clinically useful way, is a very important yet open research problem. Conventional cardiac imaging methods (e.g., MRI) still have many limitations, such as no explicit data correspondence between frames, and insufficient resolution of the extracted data. In addition, most of the existing models for the analysis of the LV shape and motion are based on the use of parameters that are either too complex or too few to be used by a physician.

Recently, a new magnetic resonance imaging (MRI) technique based on *magnetic tagging* (MRI-SPAMM) has been developed at the University of Pennsylvania for imaging of regional heart wall motion (Axel and Dougherty [1]). This fast, non-invasive technique promises to be very useful in the analysis of heart wall motion because it provides temporal correspondence of material points within the heart wall. This correspondence, in conjunction with the use of the three-dimensional (3D) location of each tagged datum, can subsequently be used as input to a motion analysis technique to extract the three dimensional left ventricular motion parameters. The motion parameters can then be statistically analyzed to explore their correlation with the various types of LV disease.

In an effort to overcome the limited clinical usefulness of most existing models for analyzing the the heart we have developed a new class of deformable 3D *surface* models whose deformations can be described with a small number of intuitive parameters that are functions (Park *et al.* [11]) instead of constants. These parameter functions comprise an *intelligent* grouping into a small number of sets, of the many local parameters that are necessary to analyze the heart's wall motions. An example of a parameter function is longitudinal contraction, which is the set of parameters describing the contraction of the LV from the apex to the base. Based on this new model, we can analyze both locally and globally the shape and motion of the heart in a way that is readily understood by a physician. This initial method has been extended recently to model the combined motion of the LV and the RV [6].

Fig. 2 shows a color plot on the endocardial surface of the RV free wall of the minimum principal strains (E3) at each time phase during systole. The associated principal directions were plotted at the midwall with lengths normalized according to the maximum contraction at those points. These strains were fairly uniform at end-systole, with an extremum of about -0.3 occuring towards the apex. It can be seen that the RV exhibited greater contraction (more negative E3) in the free wall than in the septum. Also, the direction of the contraction was more oblique to the short-axis image planes in the free wall than in the septum.

(a)

(b)

Figure 1. Moonlight Cove. Two ocean waves crash into a shallow cove. Pressure and velocity effects throughout the water volume manifest themselves at the surface (a,b).

The tools we have developed allow the quantitative analysis of the heart's shape and motion and the visual representation of the analysis results in a clinically useful manner. Using these models we can quantitatively verify and visualize in 3D the knowledge about the heart that was qualitatively known to physicians.

4. Conclusions

We have presented two examples of PBM methods capable of modeling liquids and the motion of internal organs. These methods are a small subset of a variety of other PBM methods we have developed over the years for the solution of other problems in computer graphics, medical image analysis and computer vision [8].

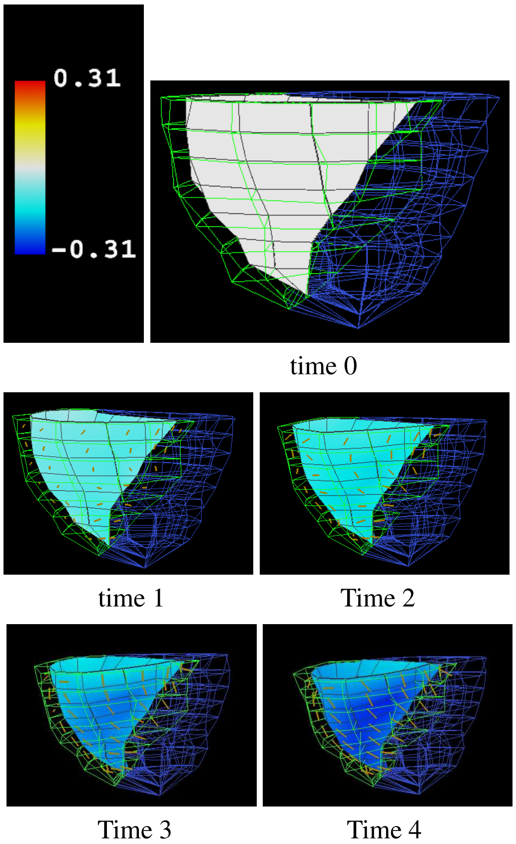

Figure 2. Normal heart deformation: color plot of minimum principal strain on the RV endocardium as biventricular model deforms from end-diastole to end systole (initial phase + 4 time intervals). Red lines are the minimum principal strain directions drawn at the centers of the elements, with lengths normalized by the strain magnitude

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