Literature Survey

For Hand of Midas

By: Xing Du, Songhe Yu

CIS 660	Advanced Topics in Computer Graphics and Animation
Instructor	Dr.Stephen Lane

Introduction

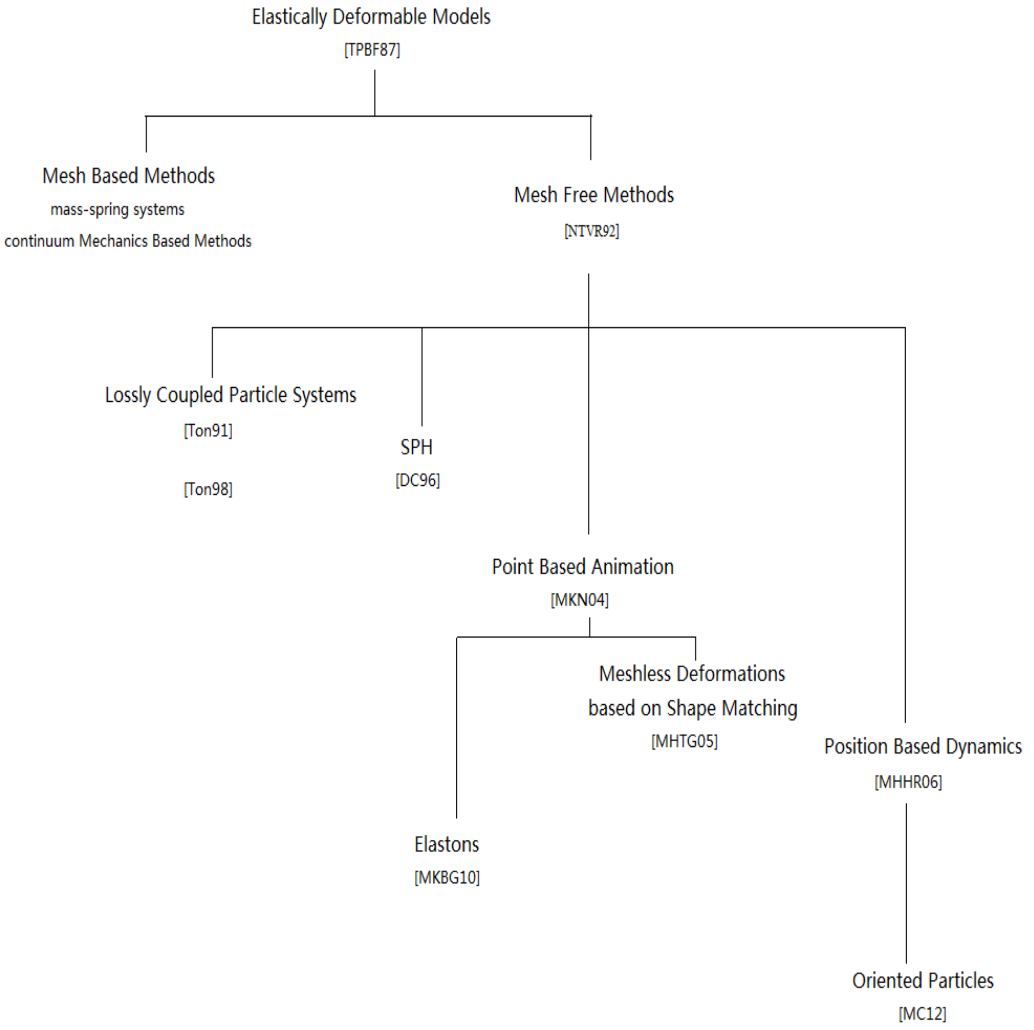
Physical simulation has been invested for more than two decades in computer graphics: since Terzopoulos et. al' s seminal paper on elastically deformable models[TPBF87], numerous researchers have partaken in the quest for the visually and physically plausible animation of deformable objects. This inherently interdisciplinary field elegantly combines Newtonian dynamics, continuum mechanics, numerical computation, differential geometry, vector calculus, approximation theory and Computer Graphics into a vast and powerful toolkit, which is being further explored and extended. The field is inconstant flux, active and fruitful.[NMK05]

Our authoring tool, Hand of Midas, is based on a new fast and robust method to simulate various types of solid, proposed by Muller et. al [MC12]. This approach adopts oriented particles to solve the singularity problem of degenerate cases and takes shape matching [MHTG05] into the framework of position based dynamics [MHHR06], which allows us to create complex dynamic objects with only a small number of simulation particles and makes turning a visual mesh into a physical object a simple task.

In this literature survey, we trace from the seminal work [TPBF87], mainly through mesh free methods of particle systems, including coupled particle systems, SPH, point-based animation, to the novel idea of shape matching, position based dynamics and finally solid simulation with oriented particles, which we plan to implement.

Content

The research evolution is shown in the following graph:



Research Evolution Graph

[TPBF87] In this seminal paper, Terzopoulos and his co-workers compute the dynamics of deformable models from the potential energy stored in the elastically deformed body. For volumetric objects, they define the deformation energy as the weighted matrix norm of the difference between the metric tensors of the deformed and original shape, integrated over the entire continuum. The continuous variational derivative of this energy functional is discretized using the Method of Finite Differences, and the simulation is moved forward through time by semi-implicit integration. This work is further evolved in [TF88] and [TW88] where the model is extended to cover plasticity and fracture. A hybrid mesh/particle method for heating and melting deformable models is given in [TPF89].

However, the contribution of [TPBF97] is not only to the FD method, but also the whole field of physically-based animation. Before the elastically deformable model, most methods for computer graphics modeling are kinematic; that is. The shapes are compositions of geometrically or algebraically defined primitives. Kinematic models are passive because they do not interact with each other or with external forces. The models are either stationary or are subjected to motion according to prescribed trajectories. Expertise is required to create natural and pleasing dynamics with passive models. Terzopoulos proposed models based on elasticity theory which describes the shape and motion of deformable materials. Elastically deformable models are active, they respond in a natural way to applied forces, constraints, ambient media, and impenetrable obstacles. The models are fundamentally dynamic and realistic animation is created by numerically solving their underlying differential equations. Thus, the description of shape and the description of motion are unified.

Since Terzopoulous' pioneering work on simulating deformable objects in the context of computer graphics, many deformable models have been proposed. A large number of mesh based methods for both off-line and interactive simulation of deformable objects have been proposed. Examples are mass-spring systems, the Boundary Element Method(BEM) and the Finite Element Method(FEM).

[NTVR92] This paper gives rise to mesh-free methods for the solution of partial differential equations. It describes the new "diffuse approximation" method, which may be presented as a generalization of the widely used "finite element approximation" method. It removes some of the limitations of the finite element approximation related to the regularity of approximations functions, and to mesh generation requirements. The diffuse approximation method may be used for generating smooth approximations of functions known at given sets of points and for accurately estimating (DEM), which presents several advantages compared to the "finite element method" (FEM), specially for evaluating the derivatives of the unknown functions.

[Ton91] [Ton98] Particle systems were first defined in computer graphics as sets of moving points, without interaction between them[Ree83]. Later on particle systems have been widely used for simulating inelastic deformations, using attraction-repulsion force, which derives from the Lennard-Jones potential, proposed for modeling pairwise microscopic interactions between atoms in a liquid. Tonnesen proposed that particles which interact with each other depending on their spatial relationship are referred to as spatially coupled particle systems. The interactions between particles evolve dynamically over time, thus, complex geometry and topological changes can be easily modeled using this approach. Tonnesen presented a framework for physically based animation of solids and liquids based on dynamically coupled particles which represent the volume of an object [Ton91] [Ton98]. In [Ton91], an iso-surface of some "implicit function" controlled by the particles is used to compute a smooth surface, essential for interfacing particles with other models. In [Ton98], Tonnesen introduced oriented particles for deformable surface modeling, where each particle represents a small surface element (called surfel). Each surfel has a local coordinate frame, given by the position of the particle, a normal vector and a local tangent plane to the surface. To arrange the particles into surface-like arrangements, interaction potentials are defined which favor locally plannar or locally spherical arrangements.

[DC96] Descrun and Cani were among the first to use mesh free models in computer graphics. In [DC95], soft , inelastic substances that can split and merge are animated by combining particle systems with simple inter-particle forces and implicit surfaces for collision detection and rendering. The Smoothed Particle Hydrodynamics (SPH) method [Mon92] is applied in [DC96].The smoothed particles defined in this paper can be viewed either as matter elements, or sample points scattered in a soft substance. Each of them represents a small volume of inelastic material that moves over time. In practice, smoothed particles are used to approximate the values and derivatives of continuous physical quantities, such as local mass density or pressure, that need to be computed during the simulation. Smoothed particles ensure valid and stable simulation of a state equation describing the physical behavior of the material. They also use them for defining the surface of the substance in a coherent way using the level sets of the mass density function. Furthermore, as a particle based Lagrangian approach, it has the advantage that mass is trivially conserved and convection is dispensable. This reduces both the programming and computational complexity and is therefore suitable for interactive applications.

[MKN04] Muller et al. introduced to the graphics community a mesh-free continuum mechanics-based framework for modeling and animating a wide spectrum of volumetric objects, with material properties anywhere in the range from stiff elastic to highly plastic. Both the volume and the surface representation are point based, which allows arbitrarily large deviations from the original shape. In each step, the spatial derivatives of the discrete displacement field using a Moving Least Squares (MLS) procedure is computed, from where strains, stresses and elastic forces at each simulated point can be obtained. And finally, based on these forces, the equations of motions can be solved. In addition, this paper proposes techniques for modeling and animating a point-sampled surface that dynamically adapts to deformations of the underlying volumetric model.

The material properties ranging from stiff elastic to highly plastic are extended to viscous materials such as fluids by merging the solid mechanics equation with the Navier-Stokes equations in [KAG 05] and the framework is extended in [PKA 05] to cope with fracturing.

[MHTG05] related to modal analysis approaches, this paper proposes geometrically motivated approach for simulating deformable objects. The main idea is to replace energies in point based animation by geometric constraints and forces by distances of current positions to goal positions. These goal positions are determined via a generalized shape matching of an undeformed rest state with the current deformed state of the point cloud. Since points are always drawn towards well-defined locations, the overshooting problem of explicit integration schemes is eliminated. The versatility of the approach in terms of object representations that can be handled, the efficiency in terms of memory and computational complexity, and the unconditional stability of the dynamic simulation make the approach particularly interesting for games.

[MHHR06] This paper introduced the Position Based Dynamics approach, which omits the velocity layer and immediately works on the positions. It generalizes and extends the method proposed by [Jak01]. A Verlet-based integrator is used which bypasses the force and velocity layers and directly modifies the positions of particles or vertices of a mesh. The main advantage of a position based approach is its controllability. Overshooting problems of explicit integration schemes in force based systems can be avoided. In addition, collision constraints can be handled easily and penetrations can be resolved completely by projecting to valid locations.

The simplicity of the method is due to the fact that the solver processes the constraints one by one in a Gauss-Seidel type manner. In contrast to global Newton-Raphson solvers, the local solver can easily handle non-linear constrains as well as constrains based on inequalities. Unfortunately, this advantage comes at the price of much slower convergence. [M07]propose a multi-grid based process to speed up the convergence of PBD significantly while keeping the power of the method to process general non-linear constraints.

[MKBG10] In[MKN04], MLS is only stable if local particle neighborhoods are in non-degenerate configurations. This problem was fixed by Marin et al. who introduced the concept of elastons. In addition to the deformation field, the elaston approach also stores derivatives. This way, particles in zero, one, two and three-dimensional configurations can be simulated robustly using generalized MLS (GMLS).

[MC12] Based on [MHHR06] and [MHTG05], this paper proposes a new fast and robust method to simulate various types of solid including rigid, plastic and soft bodies as well as one, two and three dimensional structures such as ropes, cloth and volumetric objects. The underlying idea is to use oriented particles that store rotation and spin, along with the usual linear attributes, i.e. position and velocity. This additional information adds substantially to traditional particle methods. First, particles can be represented by anisotropic shapes such as ellipsoids, which approximate surfaces more accurately than spheres. Second, shape matching becomes robust for sparse structures such as chains of particles or even single particles because the undefined degrees of freedom are captured in the rotational states of the particles. Third, the full transformation stored in the particles, including translation and rotation, can be used for robust skinning of graphical meshes and for transforming plastic deformations back into the rest state.

References

[DC95] DESBRUN M., CANI M., -P.: Animating soft substances with implicit surfaces. In Computer Graphics Proceedings(1995), ACM SIGGRAPH, pp. 287-290.

[DC96] DESBRUN M., CANI M., -P: Smoothed particles: A new paradigm for animating highly deformable bodies. In 6th Eurographics Workshop on Computer Animation and Simulation '96(1996), pp. 61-76.

[KAG 05] KEISER R., ADAMS B., GASSER D., BAZZI P., DUTRE P., GROSS M.: A unified lagrangian approach to solid-fluid animation. In Proceedings of the Eurographics Symposium on Point-Based Graphics(2005).

[MC12] MULLER M., CHENTANEZ N.: Solid simulation with oriented particles. Trans. on Graphics (Proc: SIGGRAPH) 30, 4, 92:1-92:10

[MHHR06] MULLER M., HEIDELBERGER B., HENNIX M., RATCLIFF J.: Position based dynamics. 3rd Workshop in Virtual Reality Interactions and Physical Simulation" VRIPHYS" (2006).

[MHTG05] MULLER M., HEIDELBERGER B., TESCHER M., GROSS M.,: Meshless deformations based on shape matching. Proceedings of ACM Siggraph(2005), 471-478

[MKBG10] MARTIN S., KAUFMANN P., BOTSCH M., GRINSPUN E.: Unified simulation of elastic rods, shells, and solids. ACM Trans. on Graphics (Proc: SIGGRAPH)29, 3. 39: 1-39:10.

[MKN04] MULLER M., KEISER R., NEALEN A., PAULY M., GROSS M., ALEXA M.: Point based animation of elastic, plastic and melting objects. In Proceedings of 2004 ACM SIGGRAPHI/Eurographics symposium on Computer animation(2004), pp. 141-151

[NMK05] NEALEN A., MULLER M., KEISER R., BOXERMAN E., CARLSON M.: Physically based deformable models in computer graphics. Eurographics 2005 state of the art report(2005).

[NTVR92] NAYOLES B., TOUZOT G., VILLON P., RICARD A.: Generalizing the finite element method: diffuse approximation and diffuse elements.

Computational Mechanics 10, 5(1992), 307-318.

[PKA 05] PAULY M., KEISER R., ADAMS B., DUTRE P., GROSS M., GUIBAS L. J.: Meshless animation of fracturing solids. In Proceedings of ACM Siggraph(2005),

[Ree83] REEVES W.T.: Particle systems- a technique for modeling a class of fuzzy objects. ACM Trans. Graph. 2, 2(1983),91-108.

[TF88] TERZOPOULOS D., FLEISCHER K.: Modeling inelastic deformation: viscolelasticity, plasticity, fracture. In SIGGRAPH '88(1988), pp. 269-278.

[Ton91] TONNESEN D.: Modeling liquids and solids using thermal particles. In Graphics Interface(June 1991), pp. 255-262.

[Ton98] TONNESEN D.: Dynamically Coupled Particle Systems for Geometric Modeling, Reconstruction, and Animation. PhD. Thesis, University of Toronto, November 1998.

[TPBF87] TERZOPOULOS D., PLATT J., BARR A., FLEISCHER K.: Elastically deformable models. In SIGGRAPH '87(1987), pp. 205-214.

[TPF89] TERZOPOULOS D., PLATT J., FLEISCHER K.: Heating and melting deformable models (from goop to glop). In Graphics Interface' 89(1989), pp. 219-226.

[TW88] TERZOPOULOS D., WITKIN A.: Physically based models with rigid and deformable components. IEEE Computer Graphics and Applications 8, 6(1988), 41-51.