Introductory Physics Based Visual Simulation

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ABSTRACT

This paper provides a succinct review of physics based visual simulations methods. It is aimed at newcomers in visual simulation in an advanced IT simulation course, including flexible learning mode. It is also intended as an inspiration for research into physically truthful visual simulation. The emphasis is on how to approach presenting visualizations of the processes modeled, which are physically correct and consistent, with minimal error. While this paper does not intend to provide a "Physics in a Nutshell" course, it merely invokes physics in a few instances where a quick reminder is appropriate. Simulation methods are grouped into static and dynamic simulations, and modeling solids, liquids and gases. For example: Clouds (dust, water) for gas/static; and fire, clouds, turbulences for gas/dynamic. A selection of specific cases and visual examples are discussed in the paper.

Keywords

Visual Simulation, Scientific Visualization, Computer Graphics, Education, Modelling

1. INTRODUCTION

This paper provides a succinct review of physics based visual simulations methods. It is aimed at newcomers in visual simulation in an advanced IT simulation course, including flexible learning mode. It is also intended as an inspiration for research into physically truthful visual simulation. The emphasis is on how to approach presenting visualizations of the processes modeled.

Physics based modeling comprises the methods that use models from physics, for example the interaction of internal and external forces in their models, to mimic the behavior of objects displayed on the screen.

In many applications pseudorealistic visualizations are sufficient, as the eye and the brain can easily be tricked. However with the ever increasing demand for virtual reality and CAD systems physical truthfulness is required not only for the eye but also because they are accompanied by scientific data processing in another stratum of the software, as for example, but not exclusively, in Scientific Visualization systems [Nie97].

Scientific Visualization systems are software systems, with the purpose to facilitate visual images of the ongoing data processing. The weight of interest and skills of the user is in the interpretation and evaluation of the data, and not necessarily in the production or rendering of images. Scientific visualization software is typically written in object oriented programming, such as C#, where the objects are either entities or tools. The entities represent the data for the phenomena under analysis, and the tools comprise the methods to model the processes applied to data either for processing or visualization purposes [Har97].

Visual simulation plays an important role as an aid for understanding physical or chemical behavior that is used in engineering, architecture, or complex molecular simulations. When processes are simulated their resulting effect can be represented by mimicking physical behavior (this includes static mechanic), or as abstract concepts and color-coded quantities.

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Despite increasing computational power and speed, we are still far away from real time dynamics or rendering. Computations required for a visual simulation can take several hours requiring two phases: (a) calculations, and (b) production of animated postvisualizations (a movie) using the results of the calculations.

For a visualization on a 2D computer screen, it is often not necessary to know the details of ongoing physical details. With the increase of CAD visualizations for industrial product development, a range of shortcuts has emerged for fast approximations of the visible details, for example surfaces. However, more research is needed to fill the demand for shortcuts for faster physically truthful visualizations.

The field of physics based visual simulation is as vast as nature itself. We approach the problem from two sides: from the modeling aspect where simulation methods are grouped into static and dynamic simulations; and from the object's physical state, as solids, liquids and gases. Examples of it are given in table 1.

	Static	*Dynamic*
Gas	Cloud (dust and water)	Fire, clouds, turbulences, wind
Liquid	Lake (reflections), container (jug, dam)	Running/pouring (tap, coffee), waves
Solid	Equilibrium of a body (center of gravity) Fragility	Mechanics, elasticity and plasticity Body movement (human) Hair, cloth movement Unsynchronized motion dynamics control

Table 1 Examples of visual simulations grouped into static and dynamic simulations, and modeling solids, liquids and gases

At current state of the art, not all the physically possible states can be modeled and rendered into meaningful visualizations. Conversely, not all the currently applied rendering is physically truthful. Much of the wealth of visualization techniques is proprietary to the movie or game industry, and thus not published. As a consequence, what is taught at Universities is not necessary at the forefront of the graphics industry.

A selection of specific cases and visual examples are discussed throughout this paper, assessing their applicability (or the lack of it) of physical truthfulness. The paper is organized in the following way. We look first at gases and clouds, followed in section 3 by flow modeling. In section 4 we look at elasticity and plasticity in particular in engineering and CAD, textiles and medicine. We analyze motion dynamics in section 5. Finally, section 6 summarizes and concludes the paper. The paper does not include basic concepts of visualization and virtual reality such as object representations, trees for structuring 2D and 3D databases, etc. although they should be included in a physics based visual modeling course.

2. PARTICLE MODELS OF MATTER

All materials are made of particles (atoms, molecules). Particle interaction is best described by the Lennard-Jones (LJ) potential model, described in molecular dynamics. For graphic visualizations we do not necessarily have to go down to the level of atoms. Our objects of interest can be composed of macroscopic particles, but interacting in similar ways like atoms.

In this model, depending on the materials involved, and depending on how close the particles are next to each other, they either attract or repel each other.

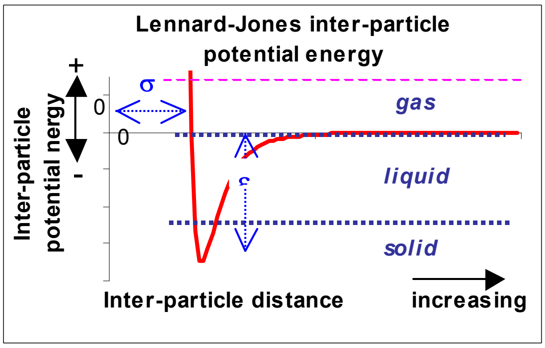

Figure 1 Lennard-Jones potential modeling attraction or repulsion between two particles of an arbitrary material

The particle model works in the following way. The equation for the Lennard-Jones potential is

$$V_{LJ} = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \qquad (1)$$

where σ and ε depend on the material, and *r* is the distance between the centres of the two particles. Figure 1 shows the LJ-potential (red line) as a function of the distance between to particles of an arbitrary material.

Imagine particles, floating around freely, with a certain energy (e.g. pink dashed line). The energy of any particle is in part kinetic energy (above the red line) and in part potential energy (below the red line). Consider two neighboring particles, one of them at distance 0, the other sufficiently distant (flat part of the red line). At this distance, they are not interacting much. However, when this particle comes closer to the other, for example, into the region where the red line dips down, its kinetic energy increases, at the expense of the potential energy, and the particle is attracted towards the other particle (like “rolling down the hill”). As soon as it passes the minimum, it is repelled by the other particle (“rolling back down” away from it). When a particle with high energy comes too close, both particles collide and behave like billiard balls.

We can think of the different states of materials by grouping in zones them according to their characteristic energy at a given temperature.

For the purpose of modelling, the term containing $\frac{1}{r^{12}}$ in equation (1) is the dominant term to model the short range repulsive potential, while the term containing the $\frac{1}{r^{6}}$ controls the tail modelling.

The derivative of the LJ-potential, expressed in equation 2.

$$F_{LJ} = -24\varepsilon\left[2\left(\frac{\sigma^{12}}{r^{13}}\right)-\left(\frac{\sigma^{6}}{r^{7}}\right)\right] \qquad \textbf{(2)}$$

This is used to model the attracting/repelling force between the particles. However, by staying in the potential domain instead of the force domain, physical approximations can be made, simplifying complex and lengthy calculations.

In the Lennard-Jones model, the particles are molecules or atoms. However, this is a resolution detail far too small for the purpose of virtual reality visualizations. In equation 1, the value for σ is the size of the particle as it is represented on the screen. This reduces the number of particles that need to be simulated to a controllable number that is suitable to the desired level of detail.

Particles must be randomly generated, others need to be randomly deleted and they move around. The initial conditions of the particles such as the position, velocity and direction, size, shape, and transparency are also required, together with the particle’s lifetime. All this information needs to be part of the data. Data management is slow, in particular for 3D objects, and new ways of organizing and managing the data are required [Wat92]. The LJ-model is not necessarily the fastest and most efficient way for modeling, but it serves as foundation to derive several other models from it.

Particle interaction dynamics is obtained by solving Newtonian mechanics. The mathematical tool is solving the Lagrangian equations.

3. GASES AND CLOUDS

Gases or clouds can be modeled at different levels of resolution, depending on the purpose of the visualization. There are several ways of modeling clouds. The advantage of modeling as particles is the physical and visual realism obtained, where regions with higher or lower density of particles can be expressed in a fuzzy shaped form. In a gas or cloud, particles are fairly distant from each other, they have high energy, and their kinetic energy is much higher than the potential energy, therefore the particles can move away. For a cloud, the dashed pink line representing the total energy of the particle shown in figure 1 would be much higher up than it is now. This means that the lower part with the potential dip is negligible. The part that is relevant for a cloud is then somewhere above the dashed line separating gases from liquids. As we can see on figure 1, the LJ-potential for the gas zone is practically an abrupt vertical line, where the two particles just collide. This simplifies modelling to just the billiard ball model. When the two particles collide, the colliding particle passes its kinetic energy to the other particle and this hit particle shoots off with the gained energy. Its speed and direction are calculated in the traditional way using the laws of energy and momentum conservation, as described in physics textbooks.

Dynamic Gases and Clouds

To this category, also belongs the modeling of the cloud as a coherent, and moving mass that is constantly changing in shape. It is more dense at some places, and less at others, in particular at the edges. We can use the particle model even for larger particles. For example a dust storm over a desert can be modeled with clusters of large bubbles (e.g. the size of children’s globes) drifting and colliding subject to external forces, i.e. wind, as long as the bubbles have the correct mass as they would in a real sandstorm. The model becomes manageable when it is reduced to some thousands of dust bubbles instead of zillions of particles, as they would occur in nature.

Depending on the case it may be necessary to model the internal, cohesive forces that hold the cloud together, and the external forces that shape it.

The cohesive forces can be modeled as a network of springs pulling together, acting between two adjoining particles, and limited by collision detection between them. With the force of the spring holding together the particles, together with the external forces such as wind, gravity, or an obstacle, we can calculate the dynamics of the cloud as a whole [Gar97]. For a cloud the forces holding the particles together must be comparable to the wind force, such that they can be overcome by the wind, breaking them up.

For vortex realism, Adabala and Manohar propose particle maps using a gridless Lagrange formulation. They apply vortex elements methods [Ada00] to model the dynamics. Calculations are complex and often require approximations that in turn, reduce their physical accuracy. The advantage of particle maps is its un-boundedness, and the vortex element method for modeling the velocity of curly flows. Both are suitable and required, for example, in visualizations of smoke, or the bulging shapes of clouds.

4. FLOW MODELLING

While visualizations of still liquids do not pose a major modeling problem other than the usual rendering issues such as reflections, dynamic visualizations of fluids are challenging. Fluid flow has vast applications ranging from large ocean currents, melted metals, to the minute quantities fluids in Micro Electromechanical Systems.

It is possible to use a particle approach to model fluidic flow, however in most of the cases a continuous model is more appropriate. Fluidic flow is best modeled with a grid and Navier Stokes (NS) equations when considered as non-compressible fluid. It is calculated at the gridpoints (finite differences) or their grid-cell centers, i.e. the finite element method (FEM) [Nie97]. It is not the purpose of this paper to go into the details of the physical details of the well-documented NS-models. What is important for visual modeling, is that situation dependant, specific constraints need to be considered to get correct results when using NS-modeling.

FEM is also often used for simulations of complex fluid dynamics such as waves, turbulences, vortices and eddies. However, it is often difficult to produce the mesh for complex shapes. These are niches of specific interest where much research lays still ahead. An interesting way of modeling fluids is proposed by Gareau and Vandorpe [Gar97]. The authors model the surface of water by a network of interconnected vertical pipes or columns of water, whose flow dynamics are individually modeled with physical laws. In this way they are able to simulate waves, based on an initial set of waves. Dynamic fluidic flow images can also be generated using periodic functions to obtain convincing wave appearance [Akl01], but this method does not necessarily lead to physically correct results.

A special case occurs in Microtechnology. In Micro Electro Mechanical Systems (MEMS), also known as micromachinery, the dimensions of ducts and pipes are very small, in the order of one micrometer (µm) or less. In those structures gravity is no longer dominant as in larger systems, and capillarity is more dominant. Friction with the pipe walls is affected by electric friction. Charges present at the solid-liquid interface form the "electric double layer" (EDL). When a pressure-driven liquid travels through a microchannel, the movement of ions in the mobile part of the EDL creates an electrical field i.e. the streaming potential. This results in a backward ion flow, pulling the liquid molecules with them. The streaming potential produces a liquid flow in the opposite direction to the pressure-driven flow. While not everyone in visual modeling would be interested in the details of the EDL, this example serves to emphasize that, that physically truthful modeling requires good understanding of what is being modeled to ensure truthful results. Early stage hidden errors are often propagated for years or decades.

5. ELASTICITY AND PLASTICITY

Solids are in general modeled with the particle approach. The total energy of their particles is rather low, the particles do not move freely. On figure 1 we can see that for solids, their kinetic energy is confined to the hyperbolic shape of the potential energy. That is, particles do not move to far away from each other (to the right branch of the curve) because they are attracted to each other; but they do not move close to each other because they are repelled (right side of the branch).

The parabola shaped curve is an advantage, because modeling is drastically simplified, and allows for modeling the elasticity of the material.

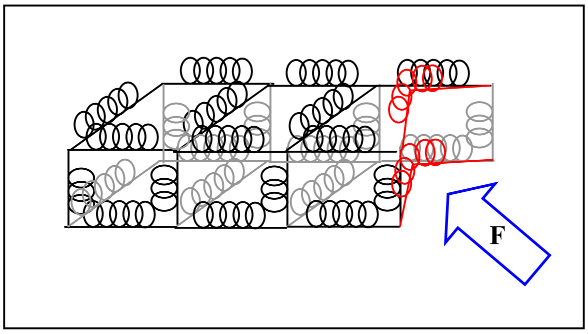

Figure 2 Mechanical springs network with deforming force

It depends on the material itself whether it changes shape temporarily (elastic) or permanently (plastic) after a force is being applied. Elasticity can be been modeled successfully as a set of springs as shown in figure 2. The familiar equation for the potential of a spring being stretched or compressed is also the equation of a parabola that fits closely to the lower part of the LJ-potential for solids. One still requires doing the complete static analysis of the forces, but this domain is much simpler and faster to model than FEM that is traditionally used to calculate deformations. Sophisticated software can be used for physical calculations with FEM [ANS01].

Engineering and CAD

For the purpose of Engineering and CAD design visualizations, the goal is to produce simulations of the devices and equipment being designed when functioning, with animated VR visualizations. The aim is to detect design flaws or timing issues of the components [Li01]. Virtual prototyping can reduce the time between design and delivery by 80% [Des02].

While flow, friction and timing are some of the key issues in industrial virtual prototyping, elasticity is an increasingly important issue, because it relates to deformations, desired or not, but also to wear and tear, fatigue and reliability of the product. Deformation modeling can become quite complex.

An example of high modeling complexity and importance is can be found in switching devices in MEMS where electrostatic forces are capable of moving or deforming parts of the device, triggering the switch. In a specific design of a charged plate capacitor, one plate is rigid and the other is a flexible beam, that is pulled to the ground under electrostatic field, but jumps under a specific change of conditions [Kug02]. This system uses models of mechanical springs to approximate deformation. In-depth knowledge about the mechanisms of electrostatic loads is necessary for accurate deformation predictions.

Other examples where elasticity needs to be modeled and displayed in a physically truthful way are deformation applications in virtual prototyping, such as flexing membranes for pumps and rubbery structures used in tactile sensors.

For visualizations the use of systems of springs is a common practice. For the spring models one can use a network of springs in a similar way as for clouds. After simulating the forces acting on this system, splines can be fitted to the surface to model the deformation, and its rendering. Splines are families of polynomials with wide application in graphics. Splines are used to approximate surfaces or lines for a smooth, continuous appearance, instead of approximations with polygons and piecewise straight lines. There variety of splines and their utilization is extensive. A nice introduction to Splines and their use can be found in [Hea97] and [Vin01].

Textiles

Another industry where visual simulation is paramount is the textile industry. For thousands of years have the looks of design patterns and touch been the method of choice for sampling textiles. Computer simulated models can provide fast displays of an infinite range of patterns, but the haptic experience still needs to be translated into a visual experience. This is done by trying to mimic the physical behavior of the textile, providing an impression of what would be e.g. a silken, woolen, or hessian (yute) feel. This is achieved by attempts to mimic the natural fall and draping of the type of the fabric. It is modeled recursively, with the use of catenaries that are successively subdivided and re-positioned. A catenary is a function that models a chain or rope bending in its own weight when suspended at both ends. The process was originally described by Weil [Weil86]. This process is not trouble free and is not necessarily physically accurate.

A range of different attempts to model the draping effect of cloth has emerged. Meyer et a. have derived a model based on a spring system [Mey01]. This model was designed for interactive animation. Another proposed method uses iso-surfaces placed over limbs and body modeled by ellipsoidal structures. This allows several layers of fabric and includes collision detection between the layers. This method has the advantage of fast processing and physical realism, because in part it uses physically based models, i.e. spring models.

Medicine

Medicine is another area where physically accurate simulations are paramount. Many models in medicine can be implemented with deformable bodies, based on spring systems, but not all. Virtual surgery deals not only with temporary deformation, but also with cutting, removing and displacing organs. Meseure and Chaillou propose a hybrid model based on a deformable spring model and a rigid model to provide structure [Mes00]. Picinbono et a. have developed a simulator for laparoscopy, that features haptic feedback. Their simulator is based on FEM. It is capable to simulate anisotropic material, that is, different density and elasticity in different directions. An interesting application is presented by Godehardt et a. for virtually reconstructing a human heart based on computer tomographic and magnetic resonance measurements [God99]. The measures of the reconstructed heart are then used to fit a sleeve of elastic net around a ventricle. The dimensions of this net are sent directly to the manufacturer of the elastic net. A virtual elastic net is morphed, using splines, onto the heart and its effect simulated.

6. CONTROL OF UNSYNCHRONIZED MOTION DYNAMICS.

This topic deals with ways of filtering visual information, retaining physically truthful mapping. Problems arise in time scaled visualizations. In mechanic environments it is possible for one component to move at 500Hz while the others move at a rate of 100 times slower. To display simultaneously such components in action in a CAD VR environment is a challenge.

The trivial solution is downscaling in time to slow motion. This does not work when we have asynchronous events being displayed, e.g. one very fast, and one very slow, because the slow one would come to a stand-still or be distorted. To the observer the relative movements between the two bodies may no longer truthful [Li03].

The shape of the structure also influences the observability in VR. For example, a gear or rotor blades may be spinning very fast, so fast that they appear to our eyes as rotating in the opposite direction, but if the objects are for instance, a box, the effect appears only at higher speeds. While this effect is well known, and is no problem in games, it becomes a problem in a virtual prototyping environment, when mimicking the operation of equipment being designed.

The rate for updating the position of the structures depends on the computer's frame rate and cannot exceed it. For example, if the frame rate of the computer is 25 times/sec, a rotation or flicking of 30 Hz must be scaled such that it maps the image truthfully. This alone does not solve the problem, because the fast movement would not be perceived by the human eye other than a flicker.

An acceptable compromise for this situation is to "illuminate" the moving structures with a stroboscopic light. This equates to extracting a subset of the pictures. The movement may no longer be smooth, but the relative movement of the objects is maintained. An example of this is shown in figure 3. The sequence of images shows two gears. The white stripe on the gears is for observation only. The left gear is moving at a rate of approximately 100 rps, faster than the right gear. We found that a stroboscopic illumination of about every 30 seconds seems to be a good frequency for this proportion of speeds and for the case of gears [Li03].

The number of teeth on the gear and the size of the radius have little effect on the observation, although fewer teeth allow for slightly faster movements, while still being comfortable for an observer. The exact proportion cannot be prescribed because it depends on the individual human perception. Research is still ongoing in this area.

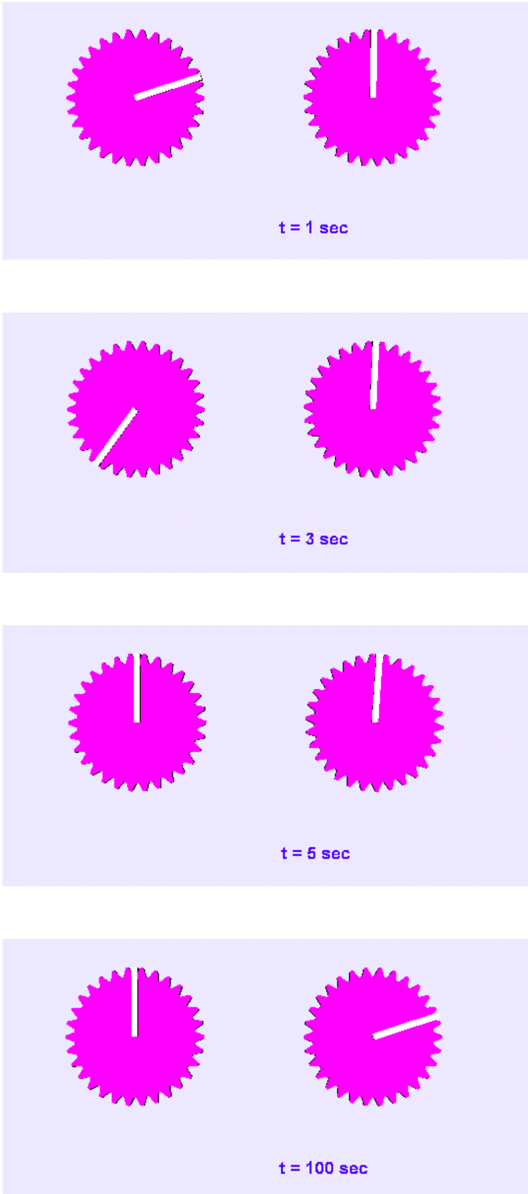

Figure 3 Two objects moving at very different speeds. The left gear is rotating at a rate approximately 100 times faster than the right gear.

7. CONCLUSIONS

This paper has provided an overview of the modeling and issues that are important in physics based visual simulations. It is aimed for a course in visual simulation. The paper tries to relate the physical models with the application to the individual cases. This is done with the aim, to provide an insight into how to interpret models, and what type of constraints can be expected. The cases presented here are not exhaustive, but they provide an overview of what an introductory course in physics based visual modeling involves. Things like the concentric ripples produced by an object e.g. a bird, a pebble, penetrating a virtual water surface; or hair or fur moving in the wind remain yet to be solved. This paper intends to encourage visual modeling practitioners in finding solutions to such challenges.

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