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Physically-based modelling techniques for movement synthesis and animation

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Among the many physically-based modelling techniques, various have been designed in computer graphics for movement synthesis and animation. In the following, we present the main of them based more on the types of principles and techniques than on the type of objects: particle-based methods (particles systems, particle modelling, mass-interaction generic formalism, smooth particles), numerical resolution of mathematical continuous equations, solid-based methods (finite elements method, solid physics).

Particles systems

It exists several different approaches within the framework of particle modelling. A first type of approaches has been introduced in computer graphics by Reeves [Reeves, 83] in order to render behaviours of fuzzy geometrical objects. Reeves's particles are actually non physical particles, that evolve by following a path defined by global fields such as uniform fields, velocity fields etc. and various lifetime rules. They do not interact physically. Only since recently, such particle systems have acquired a physical behaviour by adding inertia and gravity. This scheme is today implemented in many computer graphics software, and is widely used for various peculiar models, e.g. explosions, fires, fireworks, etc. Basically, particles are independent from each-others, and the technique is not adequate for the modelling of interactions.

Particle modelling

[Greenspan, 73] introduced the term of particle modelling to simulate physical phenomena within a totally discrete formalism, by opposition to the classical continuous expressions usually used in Physics. Greenspan's particles are physical punctual masses that physically interact with each other through a generic family of interactions functions based on the attractive-repulsive Van der Waals function.

Mass-interaction generic formalism

The Greenspan's formalism has been generalized by the mass-interaction formalism [Luciani et al., 91], by extending the interaction functions with dissipative interactions and with a generic modelling of their non-linearity, with the aim of modelling a larger variety of dynamic phenomena, visual or not. Being very generic, the mass-interaction framework is indeed adequate to model any type of dynamic object and phenomena: natural phenomena such as deformable and plastic objects, pasts, fluids and other phenomena such as crowd behaviours, etc. It is also an efficient way to simulate multisensory object including acoustical deformations and force feedbacks. It is hence discussed with more detail in the item [→ Physically-based modelling techniques for multisensory simulation].

Smooth Particles

To improve the limitation inherent to the two first point-based approaches (particle systems and particle modelling), [Desbrun & Gascuel, 96] has introduced in the domain of computer graphics the principle of Smooth Particles proposed in hydrodynamics. The technique starts from a discretization of an object whose macroscopic behaviour equations are known, in a sum of particles, each of them representing a piece of the matter. Each particle possesses a core that represents the matter distribution around it, and its action area on others particles. A force field is added to spatially extend the particle determined by the macroscopic behaviour equations.

Numerical resolution of mathematical continuous physical model

This approach is based on continuous formulation of a specific physical phenomena. In computer graphics, these equations are digitalized to become computable. The most typical example of the use of this approach is the modelling of fluid behaviours by solving the Navier-Stokes equations of the fluid mechanics [Kass & Miller, 90]. Generally, the technique used is a discretization of the space in Voxel (volume elements) to locally solve the equations at hand.

Finite elements method

The finite element method is dedicated to the computation of deformable solid objects, when the continuous equation is not directly computable. In finite elements method, deformable solid objects are decomposed in a mesh of geometric discrete regions (the finite elements) [Gascuel et al., 89] of which the physical behaviours are computable. It is then a geometrically mesh-based physical model. The core of the method is to guaranty the continuity between elements. A common use of the finite elements method is determining stresses and displacements in mechanical objects. This technique has also been used in computer graphics to deform bodies, skins, organs. However this method is often considered as too much time-consuming for animation goals and for real-time purposes.

Solid physics

This technique is based on the simulation of solid primitives on which forces and torques are applied. The primitives can be independent or linked through solid-solid interactions Solid physics is often linked with collision detection (geometrical determination of inter-penetrations, see [Teschner et al., 05] and collision rendering algorithms (forces are applied to prevent inter-penetration) [→ Collision detection algorithm].

Solids physics and collision detection are widely used and implement in most of computer graphics software and in video games' physical engine. It is efficient enough to render the dynamic of geometrically complex solids and articulated solids. However, when considering living articulated bodies like characters, animators face with control problems: finding the appropriate control forces to apply on solids to obtain a desired global movement is very difficult. This problem is generally solved by inverse dynamic methods [Barzel & Barr, 88]. The animator defines in terms of constraints and geometrical paths the way he wants the object to behave, and an algorithm pre-computes the forces and the torques to apply.

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