Visualizing "Fuzzy" Construction Materials Using VITASCOPE's ParticleWorks Add-On

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Abstract

The presented work extends the state-of-the-art in scientific simulation-driven 3D construction process visualization. We present a tool, ParticleWorks that engineers can use to visualize construction processes involving "fuzzy", unstructured, materials that are generally capable of flowing. Common processes that involve such fuzzy materials include placing concrete, dumping dirt, shotcreting, sandblasting, dewatering, water distribution, and inserting slurry. We capitalize on a classical computer graphics concept called particle systems to design simple, parametric text methods to represent arbitrary dynamic volumes of fuzzy construction materials in 3D virtual construction environments. Engineers can use these methods to instrument external authoring interfaces (e.g. simulation models) to automatically generate dynamic visualizations of any modeled operations that handle and process such fuzzy materials.

Keywords: Construction Operations, 3D Visualization, Virtual Reality, Vitascope, Particle Systems.

Introduction

Ongoing visualization research efforts at Virginia Tech focus on designing automated, process simulation-driven methods to visualize construction products and the processes involved in building them. In addition to visualizing what components are built where and when, the efforts are concerned with visualizing who builds what and how by depicting the interaction between involved machines, resources, and materials. The tangible outcome of this ongoing research is the VITASCOPE visualization system. VITASCOPE is an acronym for VIsualizaTion of Simulated Construction OPErations. VITASCOPE is a user-extensible 3D animation language designed specifically for visualizing modeled construction operations in smooth, continuous, dynamic 3D virtual worlds. A limited subset of the VITASCOPE language and the corresponding prototype implementation were referred to as the Dynamic Construction Visualizer (DCV) in some prior publications (Kamat and Martinez 2001, 2002).

In this paper, we describe an extension to the VITASCOPE visualization system. We present a tool, ParticleWorks that engineers can use to visualize construction processes involving "fuzzy", unstructured, materials that are generally capable of flowing. Common processes that involve such fuzzy materials include placing concrete, dumping dirt, shotcreting, sandblasting, dewatering, water distribution, and inserting slurry. We capitalize on a classical 3D computer graphics concept called particle systems to design simple, parametric text methods to represent arbitrary dynamic volumes of fuzzy materials in virtual construction environments. External authoring processes such as discrete-event simulation models can be instrumented to use these methods to automatically generate dynamic 3D visualizations of modeled construction operations that commonly handle and process such materials.

Initiative

We address three intertwined issues in this work. First, we investigate feasible procedures to accurately describe the motion and dynamics of arbitrary volumes of fuzzy construction materials (i.e. the physical model). Volumes of fuzzy construction materials such as concrete, dirt, gravel, mortar, sand, slurry, and water naturally do not have fixed or deterministic shapes and forms. Such materials flow under the influence of prevailing natural (e.g. gravity) and imparted (e.g. pump pressure) forces until physical equilibrium is established. Second, we design simple methods to encapsulate such physical descriptions in a finite number of parametric statements of text (i.e. the interface model). These methods must be simple so that their syntax and the values sought by their parameters are both within authoring capabilities of external processes (e.g. simulation models). Finally, we explore techniques to represent the descriptions in dynamic 3D virtual construction worlds such that the results looks visually convincing, move realistically, and can be animated in real-time (i.e. the implementation model). Surfaces of fuzzy material volumes are irregular, complex, and ill defined and cannot generally be represented with smooth polygonal, surface-based models inside virtual worlds.

In attempting to address these issues, we found most promise in a technology based on the concept of particle systems. Particle systems are a classical technique of describing fuzzy objects in interactive virtual environments. William T. Reeves (1983) coined the term "Particle System". He used it to describe a method that uses an arbitrary number of geometric primitives (called particles) in virtual space to visually represent certain objects or effects that can not be represented using conventional techniques. He called an object represented by such a particle system a "fuzzy object". Examples of physical phenomena and materials that can be called fuzzy objects include clouds, smoke, water, and fire. Reeves and his colleagues first applied this concept in creating the wall of fire element from the Genesis Demo sequence of the film "Star Trek II: The Wrath of Khan" (Paramount 1982). Their astonishing results have since pioneered several research works in computer graphics on realistic representation of fuzzy objects in virtual worlds.

A particle system is an abstraction for simultaneously operating on many similar objects that all move and change according to the same basic rules, no matter what the objects and rules are. A particle system is realized as a simple collection of many particles that together represent a fuzzy object. The important issue when describing a particle system is the overall appearance of the entire object it represents. Reeves (1983) describes the following three basic ways in which particle system representations differ from other techniques of describing physical objects:

- An object is represented as a cloud of primitive particles that define its volume, and not by a set of primitive surface elements, such as polygons or patches, that define its boundary.
- A particle system is not a static entity. Its particles change form and move with the passage of time. New particles are "born" and old particles "die."
- An object represented by a particle system is not deterministic, since its shape and form are not completely specified. Instead, stochastic processes specify parameters that are used to create and change an object's shape, appearance, and behavior.

Each particle contained in a particle system can be thought of as an entity with a set of attributes that ultimately dictate the particle's behavior and appearance. A particle's attributes typically include Mass, Color, Velocity, Size, and Age. A particle in this context is therefore not necessarily a very tiny speck but can represent many different things. Each particle within a particle system may be represented as a geometric primitive (e.g. point, line, triangle, quadrilateral etc.), a water droplet, a grain of dirt, or even a complex multi-polygon CAD model (e.g. bird, human, blade of grass etc.). Reeves' specification of a "particle" and how particle systems are generally computed prevail through most subsequent, including very recent related research in computer graphics (Foster and Fedkiv 2001, Dorsey et al. 1996).

Unstructured construction materials such as dirt, sand, mortar, concrete, and slurry may be appropriately termed fuzzy as they are not rigid objects and are typically capable of flowing until a stable physical equilibrium is established. The dynamics of such objects (e.g. concrete flowing from a bucket, dirt being emptied from a truck etc.) cannot be visually represented using simple geometric transformations commonly used in computer graphics. The concept of the particle system thus presents an ingenious technique to describe the dynamic and fluid changes in the shape and appearance of such material masses in virtual construction environments.

Approach

We represent fuzzy construction material volumes (e.g. concrete pouring out of a bucket, water spraying from a distributor etc.) as dynamic 3D particle systems. We treat each constituent particle in such a system as a point mass acted upon by prevalent natural and imparted physical forces. Abstraction of fluid material volumes as groups of individual point masses (i.e. particles) allows us to use Newtonian mechanics rather than fluid flow models (e.g. Navier-Stokes equations) to describe the physical behavior of our particle systems. In order to visually represent a dynamic fuzzy material volume, we 1) instantiate particles with appropriate initial attributes (color, mass, velocity etc.) at proper sources (e.g. latch of a virtual concrete bucket, nozzle of a virtual shotcrete applicator, discharge pipe of a virtual dewatering pump); and 2) monitor and modify the instantiated particles such that they together visually appear like the intended fuzzy material volume.

This is mathematically an initial value problem. Given each generated particle's initial position and velocity (interpreted as the force with which it is projected), we determine its evolution when subjected to virtual physical forces such as gravity and drag. The algorithm we designed to describe physical particle behavior uses numerical approximation techniques to solve a system of ordinary differential equations that describe the behavior of the Newtonian particles. Specifically, we integrate $\frac{dx}{dt} = \vec{v}$ at the same time we integrate $\frac{d\vec{v}}{dt} = \vec{c}$, alternating as we go. $\vec{c}$ is the net acceleration each particle is subjected to at a particular time instant and is a function of the prevailing forces (e.g. gravity) and particle attributes (e.g. mass) . We use a discrete time approximation when applying virtual forces to particles. This means that forces are applied to the particles at a particular instant in time as if the forces' effect accumulated over a small time interval *h.* The simulation clock is then ticked by the length of the interval and the forces are then reapplied with the particles having their updated values. We consider only the unary forces gravity and viscous drag in our analysis. These forces act independently on each particle, either exerting a constant force, or one that depends on particle velocity. Gravity is a constant force that is applied to all particles. The viscous drag (i.e. air resistance) that each particle is subjected to is taken to be a function of the particle's velocity.

The two coupled ODEs give us an iterative algorithm for computing particle positions resulting from any arbitrary resultant force on our particle systems. To satisfy this algorithm, then, all we must do is specify the initial position (x_0) and the initial velocity $\vec{v}_0$ of each particle in our system. We then use $\vec{v}_0$, the velocity at time t_0, to calculate the value of $\vec{c}_0$, the net acceleration at time t_0. We then use these values, along with x_0, to calculate the position and velocity at time $t_1 = t_0 + h$. These values along with the net acceleration at time t_1 are then used to calculate the values at t_2 and so on. We now present our implementation of particle systems to visualize fuzzy construction materials. The implementation, called ParticleWorks, is a powerful tool that allows simple, parametric text descriptions of dynamic volumes of fuzzy objects in 3D construction process visualizations.

ParticleWorks

ParticleWorks is implemented as an extension (add-on) to the VITASCOPE visualization system. ParticleWorks extends the VITASCOPE animation language and defines statements that allow instantiation and interactive manipulation of dynamic particle systems. The parametric text statements can be used together in interesting ways to describe dynamic, realistic-looking, volumes of several common construction materials such as dirt, concrete, slurry, and water in 3D process visualizations.

ParticleWorks provides statements that allow engineers to specify the static (e.g. mass, color, size) and dynamic (e.g. initial position, initial velocity) properties of the particles in an instantiated particle system. In addition, the add-on implements several statements that help define properties that influence the behavior of an instantiated system as a whole. Examples of such properties include surfaces in the virtual world off which particles bounce rather than sink in, surfaces which confine system particles rather than permit leakage/penetration (e.g. concrete forms), the number of particles to generate per time instant, and the lifetime of constituent particles. These methods together allow engineers to use simple parametric text statements to create dramatic visual representations of dynamic fuzzy construction materials. Table 1 presents the interesting statements ParticleWorks implements and briefly indicates their usage.

Table 1: Usage of Interesting ParticleWorks Statements

Statement	Usage
`FUZZYOBJECT [ObjName] […];`	Instantiate and initialize a particle system source
`[ObjName].SetVelocity [DomainType] [Parameters];`	Set the initial velocity of instantiated particles
`[ObjName].SetRate [ParticlesPerUnitTime];`	Set the number of particles entering the system at each time instant
`[ObjName].SetSink [SinkLevel];`	Set the ground level below which entering particles are destroyed
`[ObjName].SetColor [DomainType] [Parameters];`	Set the initial color of instantiated particles
`[ObjName].SetMass [Value];`	Set the mass of instantiated particles
`[ObjName].AddObstruction [DomainType] [Parameters];`	Add a physical barrier surface obstructing particle flow (e.g. concrete forms)

In ParticleWorks, each instantiated fuzzy object is an imaginary, invisible particle source. It is only after the particle source emits visible particles that the fuzzy object itself is visible. For instance, consider a sprinkler truck that distributes water over haul roads and fills on earthmoving jobsites. Water distribution is commonly used in earthmoving to increase the moisture content of the soil to the optimum range for compaction, and to reduce dust along haul routes (Peurifoy and Schexnayder 2002). Such distributor trucks drive over haul routes and fills spraying water (at varying rates) from linearly arranged nozzles on rear-mounted spray bars.

In order to visualize this operation, the spraying water (the fuzzy object) is described as a stream of particles emitted from a linear source particle system that is attached to a normal polygonal CAD model of a sprinkler truck. By linear source, we mean that particles in this system are stochastically generated along a straight line. In this example, the line corresponds to the arrangement of nozzles at the back of the sprinkler truck. The initial positions of the generated particles are thus random points sampled along this straight line. The discerning reader will quickly realize that the initial velocities of the generated particles in this case are a function of the pressure (i.e. force) with which the truck sprays water. The number of particles to generate per time instant is similarly a function of the truck's discharge rate. Figure 1 presents an annotated VITASCOPE animation trace segment that describes this operation. ParticleWorks defined statements as well as core VITASCOPE language commands are used in the description.

By introducing a ParticleWorks fuzzy object in a scene (either by attachment to another scene entity or by global placement), we merely specify the source of particles in that system and the rules that govern their dynamics. It is only after the source begins to generate and emit particles as time passes that we see the actual volume of the fuzzy material (spraying water in this example). The emitted particles are then continuously subjected to physical analysis to describe their dynamic, real world like behavior. Figure 2 presents a snapshot of the animation achieved by processing the below trace segment in the VITASCOPE virtual environment application. In a real operation, the spraying water obviously travels out of the truck's storage tank to the nozzles through pipes when the valves are opened. However, in a virtual world, we generate water droplets (i.e. particles that look like water droplets) just at the point where they are visible (i.e. at the linearly arranged nozzles).

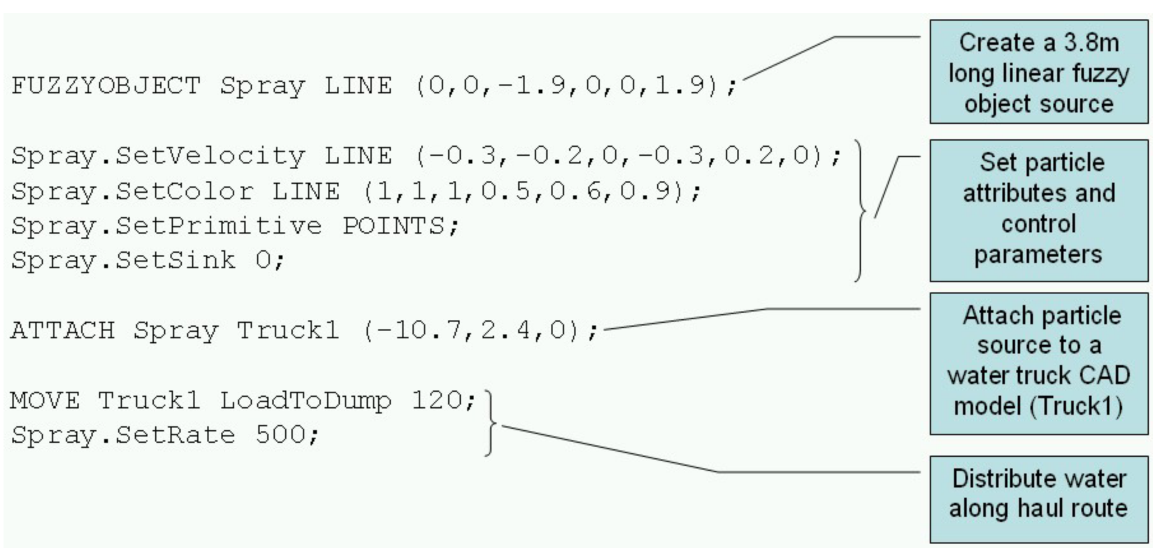

Figure 1: Defining a Water Distribution Truck

Figure 2: Animation Snapshot of a Water Distribution Process

It should be obvious from this discussion now, that in order to describe a mass of concrete pouring out from a bucket, all we must do is attach a circular disc shaped particle source on the underside of the concrete bucket model. When the latch is released, the source must emit particles that together resemble a mass of flowing concrete. Figure 3 presents a trace file segment that describes such a process. A snapshot of the dramatic animation achieved by processing this segment is then presented in figure 4. Engineers cannot visualize such operations using only traditional surface based CAD models. Particle systems make all the difference.

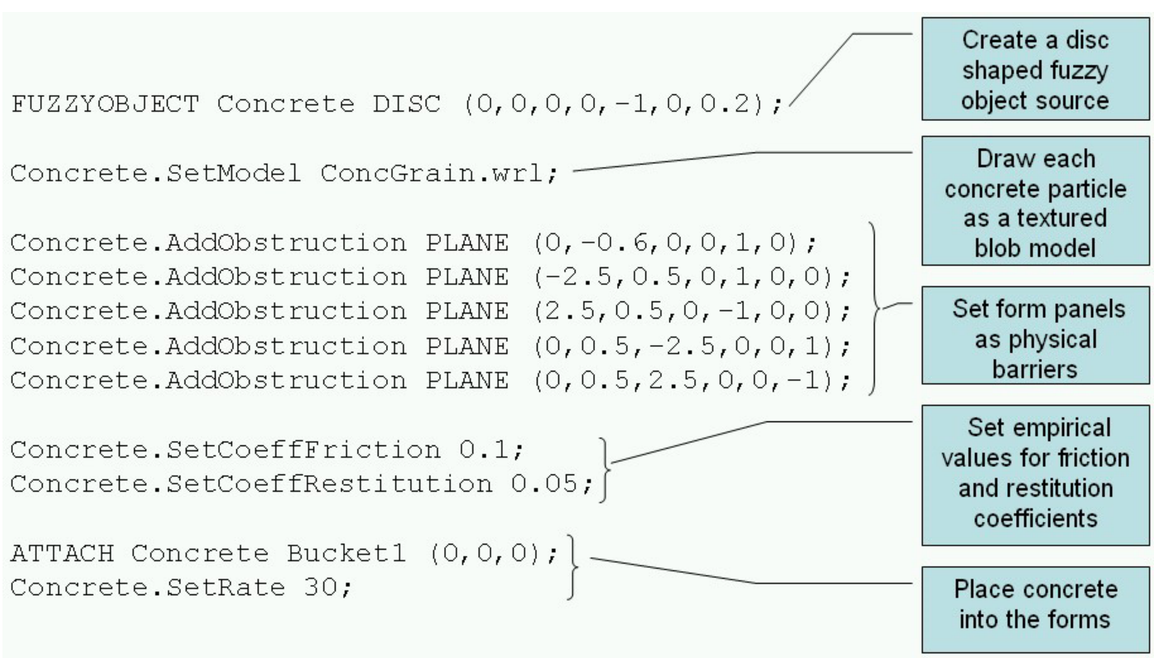

Figure 3: Describing Concrete Placement Processes

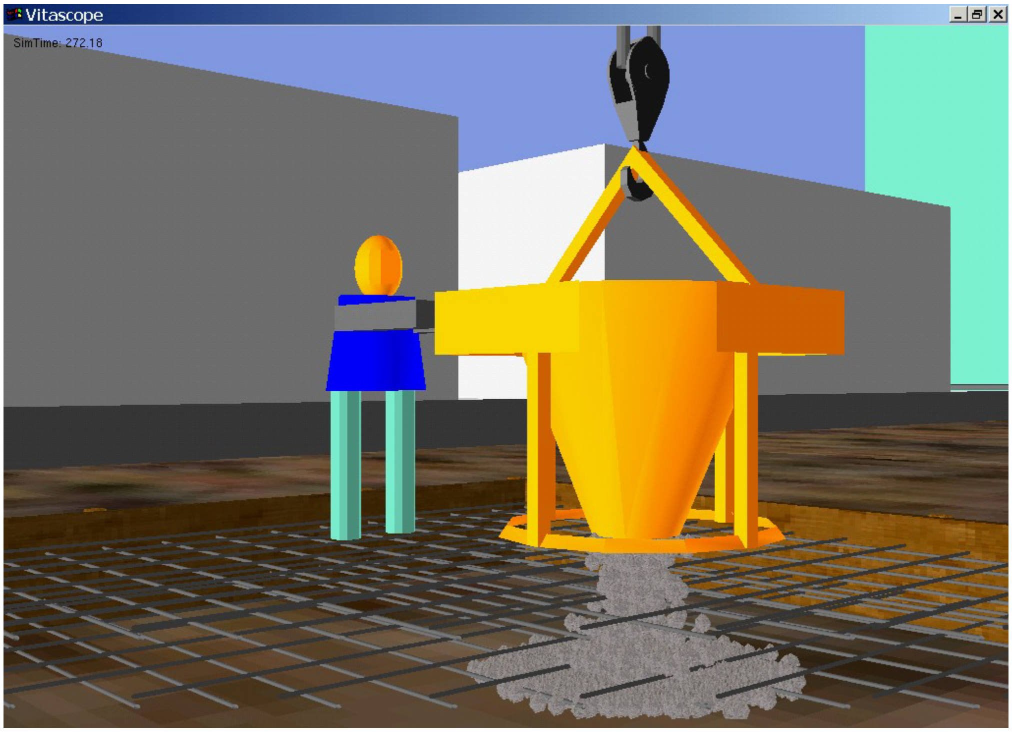

Figure 4: Animation Snapshot of a Concrete Placement Process

Discussion and Conclusions

The measure of virtual realism necessary or sufficient to fully exploit scientific visualization of simulated construction processes is often a matter of subjective opinion. While simple, symbolic, iconic 2D animation is adequate for some, others (including the authors) strive for detailed 3D visualization in immersive, photorealistic virtual worlds. Notwithstanding the scientific community's polarization, it is undeniable that in general, engineers' expectations from computer graphics have increased manifold in recent years. This can be largely attributed to the impressive computer-generated sequences the motion picture industry creates in animated films and special effects.

What these expectations signify for scientific visualization of simulated processes is that displayed graphics must be faithful, comprehensive, and should not need any verbal or textual clarification (Rohrer 2000). Since visualization is principally a communication tool, engineers must be able to animate faithful, realistic depictions of all modeled real-world processes (Farr and Sisti 1994). Construction engineers, for instance, must be able to graphically see processes such as concrete being placed into virtual forms, dirt pouring out from virtual dump trucks, and mortar being projected at high velocity from virtual shotcrete applicators.

The presented work explored several original concepts to design effective process simulation driven methods to describe the dynamics of unstructured construction materials in 3D virtual worlds. Using principles of Newtonian mechanics where appropriate and classical computer graphics concepts, we designed methods that allow engineers to express the accurate motion, changes of form, and dynamics of unstructured, non-rigid material volumes using simple parametric statements of text. The work thus puts in place the methodology that allows engineers to create realistic scientific construction process visualizations involving any operation that commonly handles and processes unstructured "fuzzy" construction materials.

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