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Physics-based deformation of subdivision surfaces for shared virtual worlds

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ABSTRACT

Creating immersive interactive virtual worlds not only requireplausible visuals, but it is also important to allow the user to interact with the virtual scene in a natural way. While rigid-body physics simulations are widely used to provide basic interaction, realistic soft-body deformations of virtual objects are challenging and therefore typically not offered in multi user environments. We present a web service for interactive deformation which can accurately replicate real world material behavior. Its architecture is highly flexible, can be used from any web enabled client, and facilitates synchronization of computed deformations across multiple users and devices at different levels of detail.

1. Introduction

The computation of physically accurate deformations of objects in response to user interaction is usually slow, which is why accurate soft-body deformations are often not available in interactive virtual reality (VR) environments. In VR, interaction and feedback need to be immediate to create a feeling of immersion. In the real world we are used to interacting with things, e.g. to assess material properties of an object upon how it responds to interaction. Therefore, having only rigid objects in VR reduces immersion since many real world objects are easily deformed.

Many virtual worlds are accessed by multiple users with various different devices ranging from mobile devices to powerful workstations, making consistent soft-body deformations even harder due to differences in computing and rendering capabilities.

To provide realistic interaction with objects in VR environments for a range of devices with various capabilities, a client–server approach which makes use of recent advances in subdivision based analysis is proposed. Deformations are computed on a central server and results are available to multiple clients. Subdivision surfaces, i.e. smooth surfaces derived through iterative refinement from a coarse control polygon, are used to represent the geometry and to perform simulations. Bandwidth usage is kept low by sending only the coarse control polygon, and different clients can easily render different levels of detail according to their capabilities by adjusting the number of subdivision steps performed on the control polygon.

Many existing techniques to deform surfaces, discussed in Section 2, are either not based on physical principles, hard to synchronize or too slow to allow real-time interaction. In Section 3 we explain how to compute physically accurate deformations of surfaces represented by subdivision surfaces and how to accelerate the computation to achieve interactive rates for moderately sized meshes. This simulation is used as the basis for our main contributions:

- We provide physically accurate deformation of surfaces through a web service. We define a client–server architecture and an HTTP API, described in Section 4, to provide analysis results to clients, ranging from web applications to high end workstations.
- Interaction with virtual objects on the client side is discussed in Section 5, where we present a new fast and simple algorithm to pick arbitrary parameter locations on a subdivision surface. We also look at simulation of different levels of detail of a surface and discuss possible solutions to the challenge of applying consistent forces and constraints across subdivision levels.
- We demonstrate the advantages of the proposed architecture in Section 6 with several applications for different use cases. Section 7 discusses the performance of the proposed architecture and shows that it is well suited for interactive use and synchronization between multiple clients.

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We conclude the paper with a discussion of limitations of the proposed architecture and possible future research directions in Section 8.

This paper is based on and extends the conference paper [1]. Here, we expand the discussion of the limitations of a linear simulation and explain what defines a *small deformation* in Section 3.4. We add Section 5.2, for a discussion on simulation of different levels of detail of a surface, and how constraints and forces can be applied consistently across different subdivision levels. Further, we expand the use cases of the proposed architecture with web related technologies in Section 6.3. Regarding the choice of solver, we provide a comparison between the CPU based solver and the CUDA based solver in Section 7.2.

2. Related work

Many existing techniques allow interactive deformation of surfaces. Good overviews can be found in [2,3]. The different approaches differ in physical accuracy and performance.

Simple mass spring systems and mesh processing based approaches are very fast, but they provide only a rough approximation of real physics. Because such methods are not based on the actual physical behavior of real materials they are sometimes difficult to tweak to get the expected results. To overcome this, methods like [4] attempt to derive the parameters for the mass spring system from an accurate simulation of a reference model. This allows mass spring systems to approximate the behavior of more realistic methods. However, because mass spring systems and mesh processing based approaches usually work directly with the dense mesh used for rendering, synchronizing the deformation to multiple users may require a lot of bandwidth, making it impractical to perform synchronization across a network.

There are highly accurate numerical methods, for example the finite element method (FEM), to solve partial differential equations describing various physical effects. FEM requires a geometry to be expressed in a dense polygon mesh for the simulation. Typically, the *simulation mesh* does not match exactly the representation used for rendering which makes it difficult to translate simulation results to the geometry used for rendering in virtual worlds. Additionally, the same restriction as for dense triangle meshes apply, i.e. because simulation meshes are dense, they require a lot of bandwidth for synchronization.

For *isogeometric analysis* (IGA) [5], a variant of FEM, a simulation mesh is no longer necessary. In IGA the basis function of the geometry representation are also used for representing the domain and the solution space for the analysis. Therefore, design, rendering, and the finite element simulation are based on the same representation of the geometry. The concept of IGA has been extended to many 3D representations used in modeling/CAD, including NURBS [5], T-splines [6] and subdivision surfaces [7–9]. Having the same representation for both simulation and rendering eliminates the problem of translating simulation results to objects in virtual environments. Instead, simulation results can be directly exported to be rendered in e.g. VR applications.

With some restrictions, IGA can also be used for interactive applications. In [10] physics-based surface design tools based on IGA of Catmull–Clark subdivision surfaces have been integrated into a standard 3D modelling software. The approach described in [10] requires integrating the simulation into the client application and is therefore unsuitable for clients with limited capabilities and provides no support for multiple users. However, it demonstrates IGA based surface deformation using constraints and forces.

Other approaches e.g. [11] or [12] do support sharing deformations with multiple users by using a client–server architecture, but are limited to mass spring simulation to approximate the physical behavior respectively a single shared object for all clients. Moreover, both approaches are based on custom network protocols which cannot be accessed e.g. behind corporate firewalls or from a web based application.

We extend ideas from [10] and present a client–server architecture for interactive simulations using IGA, that provides access to the simulation for any web enabled client and supports multiple users and deformable objects.

3. Deformation of subdivision surfaces

To define smooth surfaces of arbitrary topology using just a small number of control points, a common representation used in the entertainment industry are subdivision surfaces. A subdivision surface is the smooth limit surface of a recursive refinement operation, the subdivision algorithm, infinitely applied to a coarse polygon mesh, the control mesh. A subdivision surface is fully defined by a coarse control polygon and a subdivision algorithm. Many subdivision algorithms exist. The Catmull–Clark subdivision [13] is the de facto standard for modeling in the entertainment industry and is available in most major modeling applications. Using Catmull–Clark, each subdivision step splits all faces into n quads, where n is the number of corners in the face, by inserting new points in the middle of each face and edge [13]. In practical use this algorithm is only applied a limited number of times, until the surface appears smooth when rendered. The coarse control polygon can be efficiently sent via a network. Each application or client can apply the subdivision algorithm to the coarse control mesh to derive a smooth subdivision surface. By adjusting the number of subdivision steps applied to the control mesh, each client can render the surface at a different level of detail (LOD), thus adapting the LOD to its capabilities.

3.1. Thin shells

Typically, 3D objects in CAD or the entertainment industry are represented as surfaces, rather than volumes. To compute the response of a surface to environmental impact we perform an isogeometric *thin shell* simulation on a Catmull–Clark subdivision surface. Thin shells are structures where one dimension (the thickness) is very small compared to the other two. Such structures are very common in the automotive and aerospace industries, but also in everyday life in the form of e.g. objects made of metal sheets or thin plastic materials.

Thin shells are particularly suited for IGA because their geometry is usually defined by their middle surface, rather than a volumetric representation. This matches how such structures are typically modeled in a VR environment. Although we will interact with a range of different geometries in VR, thin shell structures cover a large array of geometries.

The control points of the subdivision surface are the only degrees of freedom (DOF) for the isogeometric thin shell simulation. They define both the initial surface geometry as well as the deformed configuration. All computations for the simulation are performed on the subdivision limit surface defined by the control points and their corresponding basis functions. The number of DOF can be easily increased without changing the surface geometry, by simply subdividing the control mesh. For regular regions of a Catmull–Clark surface, the basis functions employed to represent the design as well as the solution space, are uniform B-splines of degree 3. The basis functions around extraordinary vertices, where the topology differs from a regular grid, can be evaluated as described by Stam [14]. For more details on computing isogeometric thin shell analysis using subdivision surfaces, we refer the reader to [7–9,15,16].

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