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Peridynamics-Based Fracture Animation for Elastoplastic Solids

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Figure 1: *here is ball crack wall, brittle and ductile, isotropic and anisotropic*

Abstract

In this paper, we exploit the use of peridynamics theory for graphical animation of material deformation and fracture. We present a new meshless framework for elastoplastic constitutive modeling that contrasts with previous approaches in graphics. Our peridynamics-based elastoplasticity model represents deformation behaviors of materials with high realism. We validate the model by varying the material properties and performing comparisons with FEM simulations. Besides, the integral-based nature of peridynamics makes it trivial to model material discontinuities, which outweighs differential-based methods in both accuracy and ease of implementation. We propose a simple strategy to model fracture in the setting of peridynamics discretization. We demonstrate that the fracture criterion combined with our elastoplasticity model could realistically produce ductile fracture as well as brittle fracture. Our work is the first application of peridynamics in graphics that could create a wide range of material phenomena including elasticity, plasticity, and fracture. The complete framework provides an attractive alternative to existing methods for producing modern visual effects.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation

1. Introduction

The simulation of deformable materials has been an important research topic in computer graphics for decades, since the early work by Terzopoulos and colleagues [TPBF87]. One of the strongest driving forces behind the active research is the persistently growing needs for higher realism from the visual effects industry. Materials in real-world exhibit complex behaviors, such as coupled elastoplastic deformations, fracture, etc. The complicated material behaviors are difficult to be virtually replicated by any single method despite the numerous ones that have been developed thus far. Existing approaches generally excel at some phenomena but would stumble (if not fail) at others. For instance, mesh-based methods [MG04, ITF04, TSIF05, SB12] are a good choice to simulate elastic deformations whereas not preferred for phenomena that involve topological changes. Particle-based methods [MCG03, PKA*05,SSC*13] are considered suitable for modeling topological changes, however the inherent loss of connectivity information would cause undesirable numerical fracture [LZLW11, ZZL*16] while simulating large deformations.

We build on recent developments of peridynamics theory in the computational physics community [Sil00, SEW*07, Mit11, ELP13, MO14] and propose a novel framework for graphical animation of varied deformation behaviors and fracture. Our aim is to enrich available options of simulation techniques for easier and better animation production. Peridynamics was first adopted to animation applications by Levine et al. [LBC*14]. They described a simple spring-mass system to handle brittle fracture of solids. In contrast, we handle elastoplasticiy, brittle fracture, and ductile fracture in a single framework. To this end, we propose several novel contributions in this work. We first present an elastoplastic constitutive model in the peridynamics-based framework with simple extension to anisotropy, and the model is validated against results produced by FEM. Furthermore, we show that both brittle and ductile fracture phenomena can be naturally represented with nearly no effort by integrating a simple fracture criterion into this material model. This is due to the integral-based formulation of peridynamics, in which forces at a material point are computed by gathering contributions from all material points in its interaction range through integration. On the other hand, methods based on classical continuum mechanics formulate force computations with partial differential equations that fail to be applicable directly on singularities such as a crack. This feature makes our peridynamics-based framework more attractive over existing approaches for producing animations that involve fracture. Lastly, our method is simple to implement and trivially parallelizable, providing a useful alternative to previous methods for animation production.

2. Related Work

A large body of literature has been devoted to physical simulation of natural phenomena as a result of active research. A complete literature review is beyond the scope of this paper. In the following we comment only on the representative works most related to ours.

Elastoplasticity Animation The modeling of deformable plasticity in graphics dates back to the pioneering work by Terzopoulos and Fleischer [TF88]. O'Brien and colleagues [OBH02] incorporated a similar additive plasticity model into a finite element simulation to animate ductile fracture. The strain measure was decomposed into two components, where one is due to elastic deformation and the other due to plastic deformation. Müller et al. [MKN*04] applied this model in their point-based animation framework and simulated plastic behaviors of objects. Irving et al. [ITF04] presented a multiplicative formulation of plasticity and pointed out that their model was better handling finite plastic deformation than the additive one. In contrast to the additive model, they decomposed the deformation gradient into two components through multiplication. The multiplicative model was extensively used by later works to animate phenomena that involve plasticity. Bargteil et al. simulated large viscoplastic flow [BWHT07], Gerszewski and his colleagues animated elastoplastic solids [GBB09], and Stomakhin et al. modeled plasticity of snow [SSC*13], just to name a few. Unfortunately, neither of the above plasticity models applies in the peridynamics framework because there is no concept of strain nor deformation gradient in the integral-based formulation. As a result, we present a new constitutive model for peridynamics in this work to animate elastoplastic solids.

Fracture Animation Numerous methods have been proposed on fracture animation [MBP14, WWD15] because the stunning phenomenon of fracture and failure is an indispensable visual element in animated movies and video games. Early approaches use simple schemes to model fracture, such as the finite difference method [TF88], the mass-spring system [NTB*91], and the mass-point constraint system [SWB01]. O'Brien and colleagues [OH99] adopted techniques from continuum mechanics and presented a FEM-based method to simulate brittle fracture of solids. They later extended their method to ductile fracture by incorporating a plasticity model [OBH02]. Müller et al. [MMDJ01] employed a quasi-static finite element analysis to animate brittle fracture of stiff materials undergoing collisions. Parker et al. [PO09] presented some useful techniques for real-time simulation of fracture in game environment. One major issue in FEM-based methods is the generation of fracture patterns on meshes, which would alter the underlying mesh topology. Early methods typically made use of simple separation along mesh element boundaries [NTB*91, MMA99, SWB01, MMDJ01] or even element deletion [FDA02]. Mesh subdivision prior to splitting could somewhat increase the available geometric details [MK00, BG00], whereas this tended to introduce elements with poor aspect ratios. Allowing failure along more arbitrary paths could generate more geometrically rich fracture patterns [NF99, OH99, OBH02], albeit with the expense of complicated re-meshing. Molino et al. [MBF04] proposed a virtual node algorithm to avoid the complexity of re-meshing, where elements were duplicated into partially filled counterparts with virtual nodes. The virtual node algorithm was frequently used by subsequent works on fracture animation [BHTF07] and mesh cutting [SDF07, WJST14] due to its simplicity compared to re-meshing methods. Other representative mesh-based methods resorted to modal analysis [GMD13] and pure geometric mesh decompositions [MCK13, SO14] for real-time brittle fracture. Most recently, several works explored the boundary element method for rigid body fracture [ZBG15, HW15] where only surface meshes were employed for both representation and computation.

In contrast to mesh-based approaches, meshless methods are generally considered as a better solution for animating topological changes. Based on the moving least square (MLS) meshless framework by Müller et al. [MKN*04], Pauly and colleagues [PKA*05] developed a novel meshless method for fracture animation of elastoplastic solids. Steinemann et al. [SOG09] employed surface mesh representation in meshless framework and presented a novel surface tracking technique to efficiently split the meshless deforming objects. Inspired by the rigid body assumption for simulating brittle fracture, Liu et al. [LHLW11] employed quasi-static analysis in a meshless local Petrov-Galerkin framework. Stomakhin et al. modeled the fracture of snow using a meshless material point method [SSC*13]. Hegemann et al. [HJST13] combined a level set based mesh embedding technique with the material point method to animate dynamic ductile fracture.

Peridynamics The peridynamics theory was first proposed by Silling [Sil00] as a nonlocal reformulation of classical solid mechanics. It contrasts with classical (local) theory in that the state of a material point is influenced by not necessarily the material points located in its immediate vicinity, but also those over long distances. The governing equations of the peridynamics theory are spatial integral equations instead of partial differential equations. The theory was further developed by subsequent works [SEW*07, ELP13], and its applications to the engineering field such as multi-scale material modeling [ABL*08, SC14] and fracture modeling [AXS06, SWAB10, SA14] were studied. A comprehensive review of the research literature in the computational physics community is beyond our scope, we refer the readers to the book by Madenci and Oterkus [MO14]. Levine et al. [LBC*14] first introduced peridynamics to graphics for fracture animation. Their method was limited to brittle fracture of isotropic elastic materials with a single Poisson ratio of 0.25. Our work, on the other hand, is a complete framework that models elastoplasticity and anisotropy under various parameter settings, representing brittle and ductile fracture with high realism.

3. Background

This section describes background of peridynamics theory, and conceptual comparsion with traditional particle methods.0.5 page.

4. Overview

This section briefly describes the algorithm pipeline.

5. Elastoplastic Model

This section introduces the constitutive model. 1.5 page.

6. Fracture

This section describes the fracture criterion, and the mesh split strategy. 0.5 page.

7. Results

This section demonstrates some results. 1.5 page.

8. Discussions

This section concludes the paper, and discusses the limitations. 0.5 page.

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