Advancing the Material Point Method for Brittle Shells in Computational Mechanics

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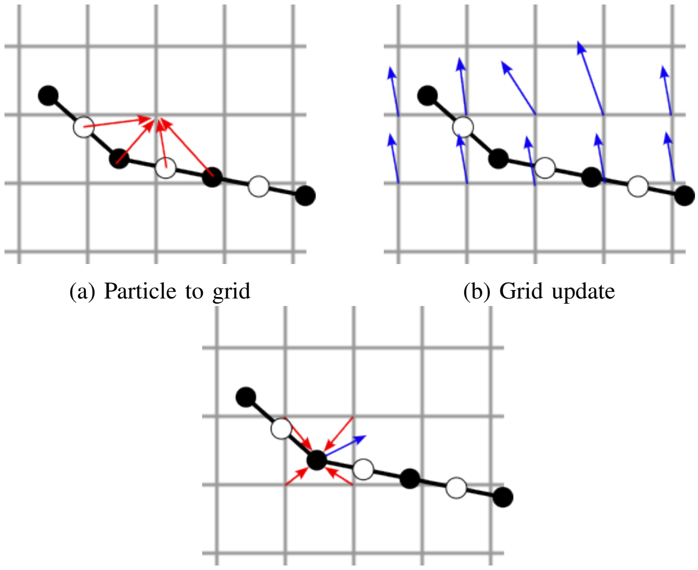

(a) Particle to grid

(b) Grid update

(c) Grid to particle, particle update and grid reset

Fig. 1: Iteration steps for a beam based in linear elements in two dimensional MPM. The black dots are vertices and the white dots are integration points. The deformation gradient is evaluated before the particle to grid step stored at the integration points. Forces are then evaluated at the vertices and transferred to the grid.

I. Introduction

The Material Point Method (MPM) is a hybrid computational approach that merges the strengths of Lagrangian and Eulerian methods for solving continuum mechanics problems. By integrating a particle-based material representation with a computational grid, MPM effectively addresses challenges such as large deformations, contact interactions, material failure, and multiphase systems. Unlike other meshless methods, MPM allows the direct adoption of constitutive models from FEM, enhancing its versatility.

MPM has gained significant traction in computer graphics, particularly for simulating dynamic phenomena like snow, sand, and soft materials. Its ability to model large deformations and complex interactions is complemented by its inherently parallelizable structure, making it well-suited for GPU-based high-performance computing. Consequently, MPM has become a popular tool in visual effects and gaming for creating realistic and visually captivating simulations.

Despite these strengths, MPM has been slow to disseminate to engineering applications. Challenges such as missing validation, unresolved numerical stability issues, and undefined applicability limits have hindered its adoption. While the computer graphics community often employs advanced continuum models for realism, these implementations prioritize visual fidelity over physical accuracy.

Other challenges of MPM include:This work aims to establish MPM as a robust tool for engineering applications, particularly for brittle shell structures, by addressing its current limitations and leveraging its unique strengths.

- Limited applicability outside large deformation scenarios,
- Energy dissipation,
- Complex boundary condition implementation.

A. Thin Shells and Membranes

Realistic simulations of cloth and hair remain a challenge in computer graphics due to extensive contact interactions, including self-contact. MPM offers an advantage here, as it handles contact implicitly, avoiding the need for complex search algorithms required in FEM. However, standard MPM struggles with "sticky-contacts," as it does not distinguish between interactions within a body and between separate bodies. To address these limitations, hybrid methods combining mesh-based models with MPM have shown promise. For instance, thin membranes modeled using simple linear triangle meshes [1], [2] (Simplified in Fig. 1) or more advanced shell models based on Kirchhoff-Love continuum theory [3] enable controlled frictional contact and incorporate bending deformation. These approaches employ subroutines to calculate internal forces taking into account surface normal and tangential traction transmitted through the grid, ensuring physically realistic simulations.

B. Damage and fracture

Plasticity can be easily included by using an elastoplastic decomposition of the deformation gradient also in classical MPM. Separation of material is also implicit when no mesh is used, but it is heavily influenced by numerical factors such as grid density, number of particles or time step size. In recent works, brittle fracture of solids [4] and shells [5] for visual effects have been modeled using a complex framework based on the local phase field method, explicit crack extraction and remeshing based on NURBS patches. Compared to FEM approaches, these methods reduce dependence on the mesh geometry and eliminate the need for additional particles during fracture phenomena, using support domains to resolve discontinuities.

II. Towards MPM based brittle shells for computational mechanics

We aim to advance the usage of MPM with its advantages in contact handling with the well understood FEM description of two dimensional continua for engineering purposes. As a first approach, we use linear triangle meshes.

Key steps in the implementation and validation of this hybrid method include:

1) Modeling in-plane deformation behavior using corotational elastoplasticity,
2) Incorporating bending behavior through a discrete bending model,
3) Enabling contact and friction interactions between solids and shells,
4) Implementing a local phase field method for failure criteria,
5) Developing fracture mechanics techniques that improve upon FEM-based crack modeling.

This work aims to establish MPM as a robust tool for engineering applications, particularly for brittle shell structures, by addressing its current limitations and leveraging its unique strengths.

References

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