A Literature Review on Snow Simulation with MPM in Computer Graphics

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Abstract. Snow simulation is always a challenge in the computer graphics community due to its combined nature of solids and fluids. In the past, researchers usually applied different solvers to computationally simulate the behavior of snow at different phases, which made the simulation both slow and complicated. In 2013, the material point method, abbreviated as MPM, was first introduced for snow simulation, eliminating the need for multiple solvers. This paper investigates the history of the application of MPM to snow simulation in computer graphics specifically, and offers an overview of its evolution since the pioneering work by Stomakhin. It aims at showing the current state-of-art as well as any limitations. Nowadays, the development of MPM and snow simulation focuses on improvements of the stability and physical accuracy of the method itself, and the generalization of the application scope from snow to arbitrary granular materials. The trade-off between efficiency and accuracy remains a problem, thus it introduces more potential research directions, ranging from developing simpler mathematical models for better physical accuracy to incorporating machine learning techniques to accelerate the simulation process.

Keywords: Computer Graphics, Snow Simulation, Physically-based Simulation, Material Point Method

1. Introduction

Simulating natural phenomena aesthetically and physically accurately is an important task in computer graphics. Among all those complicated and intriguing scenes, snow simulation remains extremely significant, as its application lies in many aspects, ranging from predicting snow avalanches to making vivid movie scenes. Nevertheless, due to the dynamically varied physical properties of snow at different phases, its simulation has been a challenge for a long time.

A significant breakthrough to the bottleneck is the application of the material point method, abbreviated MPM, which rises as the generalization of Particle In Cell (PIC) and Fluid Implicit Particle Method (FLIP) to solid mechanics [1]. Actually, MPM had been studied and applied to snow simulation in the past, e.g., Lee and D. Huang studied the reaction forces and subsequent mechanical behavior of snow with simulations using realistic micro-structure and a mesh-free generalized interpolation MPM [2]. In spite of that, the innovative application of MPM for snow simulation in the computer graphics community is credited to Stomakhin et al. in the year 2013, as the previous researchers, instead of focusing on improving the efficiency of the simulation and achieving realistic visual effects, were primarily striving for better accuracy of simulation for engineering purposes [3].

This paper investigates the history of the application of MPM to snow simulation in the computer graphics community specifically. It is organized as follows: Section 2 discusses and offers a detailed overview of the important works during the evolution of snow simulation and MPM since the pioneering work by Stomakhin et al. [3]. Section 3 first discusses and evaluates those works' significance and limitations. Then it peeks at the current state-of-art with limitations, and the potential directions for future research. Then the paper closes with conclusions in Section 4. This paper touches on as many relevant aspects of mathematical modeling, thermodynamics, and computational cost as possible in the topic of snow simulation in computer graphics, aiming at providing good comprehensive bedstones of the current state-of-art and potential directions for future research.

2. Overview

2.1. Initial Proposal of MPM for Snow Simulation

In 2013, Stomakhin et al. treated snow as an elasto-plastic material, which exhibits elastic behavior while the stress is below the threshold and undergoes plastic deformation otherwise [3]. Then they apply MPM to simulate its behavior based on phenomenological observations. With their empirical model, people could easily describe the snow behavior at many different phases with one elasto-plastic constitutive relation between stress, potential energy density, and deformation gradient. Due to the reduced number of constitutive relations compared with what previous work usually does, their result sacrifices some physical accuracy for engineering purposes. But it works well for generating realistic dynamics for a wide range of visual phenomena. Based on the model, the application of MPM, a hybrid method that takes advantage of Lagrangian material particles and Eulerian Cartesian grids, helps to apply natural treatments of topological deformations and collisions. On one hand, MPM avoids the need to model every snow grain when handling plasticity and fracture compared with the Lagrangian paradigm; On the other hand, it outperforms Eulerian methods by tracking conservative quantities through Lagrangian particles. In general, the MPM shows its power by combining high simulation efficiency, which is achieved by semi-implicit time integration and parallelism, with satisfactory visual performance.

2.2. Augmented MPM for Phase Change

Despite the many advantages aforementioned, MPM still has some limitations, like the low efficiency of modeling incompressible materials (e.g., freezing snow with high stiffness). Therefore, Stomakhin et al. augment the original MPM such that it can be easily applied to solve melting and freezing issues in snow simulation in 2014 [4]. In this paper, Stomakhin et al. introduce the idea of splitting the stress of the constitutive model into elastic and dilational parts, and applying an implicit treatment of the Eulerian evolution of the dilational part to simulate arbitrarily incompressible materials [4]. As the treatment can be done with a generalized Chorin-style projection, which is implemented naturally on marker and cell (MAC) grids, they augment the original MPM and devise a staggered grid MPM [5]. Finally, with an appropriate heat model the augmented MPM solver could drive material changes within phase transitions like melting and freezing. As the paper suggests, however, simulation efficiency remains an issue. Actually, the standard Lagrangian approach such as FLIP for simulating the motion of liquids yields good melting effects with less computational cost [6]. Nonetheless the primary goal of this paper is to generalize the applicable scope of MPM such that it could handle different materials (or the same material in different phases) with one paradigm. Therefore, the augmented MPM wins the game when the users are faced with the problem of handling mixtures of materials (or the same substance that holds drastically different physical properties in different phases), notwithstanding that there exist better solvers that outperform the augmented MPM while simulating the melting and freezing of snow specifically.

2.3. Adapted Model for Porous Snow

Except for the low efficiency of handling the phase changes of snow, there are some other problems with MPM. As aforementioned snow is an exceptionally complex material since its physical properties vary a lot depending on external conditions like temperature, pressure, and the time of snowfall. In a large-scale scene, simulating the motion of a single snowball is far from enough. Usually, the structure of the snow accumulated over a certain range of space at the beginning of a snowfall is very different from that at the end of the same snowfall. As MPM has already shown its power, Gaume et al. take the work by Stomakhin et al. and utilize it to model full scale slab avalanches [3][7]. Nevertheless, they do find that the simple constitutive model given by Stomakhin et al. can not properly model the weak snow layer cohesion and volume reduction that are crucial to replicating the propagation effect in large snow avalanches [3]. They thus propose the Large-strain elasto-plastic model, which accounts for cohesion softening and volume reduction, to accommodate dynamic anticrack propagation. Finally, they applied MPM to deal with large strains and showed that the adapted model successfully simulates the release and flow of slab avalanches.

2.4. Methods Other Than MPM

As seen from the previous three papers, to apply the MPM and simulate certain snow scenes, the construction of a good constitutive model is significant. For porous snow, the model is modified to allow for large strain deformation but for small-scale snow scenes the simple model given by Stomakhin et al. is good enough [3]. Then is it possible to work on the simulation method instead of changing the constitutive model for different scenes? [8] Gissler et al. offer an answer by taking the physical models from Stomakhin et al. but implementing the simulation using the Smoothed Particle Hydrodynamics (SPH) method [3]. This modification enables properly simulating individual snow particles and thus promotes better interactions with other materials. As snow particles can be modeled individually, the method can represent the whole life cycle of snow from snowfall to accumulation and covers by using only a single model. Although they do not relate their work to thermodynamics effects nor the big deformation scenario like avalanches, Gissler's method shows the possibility of long-term and consuming simulations, which may take great advantage of the parallelism enabled by modern GPUs [8].

3. Discussion

As seen from the previous review, a visually compelling simulation of snow consists of two parts: a physically accurate constitutive model, and a clever choice of simulation method. The previous part determines the visual and mathematical correctness of the behavior of snow, plus any extra properties, e.g., the phase transition, required by a certain simulation goal. The latter part, based on the model, will impact the algorithm design and computational efficiency of the simulation. Currently, the most widely used constitutive model of snow simulation in computer graphics treats the snow as an elasto-plastic material. Such a model successfully describes the behavior of snow like clumping and breaking under an unchanged condition. Nevertheless, as the temperature changes it will no longer work for snow in other phases. A natural way to overcome this issue is to add more constitutive relationships into the model and apply treatment to them , which is similar to the work given by Stomakhin et al. and Gaume et al. [4][7]. But then the simulation method will potentially complain and show a severe decrease in computational efficiency. After all, the elasto-plastic model is a decent starting point for developing better, uniform constitutive models on snow simulation.

Instead of making additions to the model, another potential solution is to abandon the MPM and incorporate other methods like SPH, as Gissler et al. suggest [8]. This approach does alleviate the pain of working on an enormous model, as the particles are an intuitive and extremely flexible representation for simulation in the computer graphics community. However, it has trouble simulating other scenarios like full-scale slab avalanches because of the gigantic amount of particles involved in these scenes.

This paper only gets into the most fundamental ideas in snow simulation with MPM without touching on every related work. It turns out that there are many other directions in this field that would expand the scope of the study. For instance, Gao et al. proposed an adaptive variant of the Generalized Interpolation MPM (GIMPM) to promote particle-grid transfer efficiency and reduce computational cost [9][10]; Hagenmuller et al. take snow as granular material and apply the Discrete Element Method (DEM) to model hardened snow under deformations [11]. This idea further initiates the work by Goswami et al., where snow is simulated in real-time [12]. Furthermore, Tumanov et al. signify the power of AI and deep learning techniques to accelerate physics-based simulations using approximation [13]. These works' foci go beyond the scope of this thesis, but they are credited as promising research directions. Overall, the field of physically based snow simulation remains an open space, waiting for many more improvements and possibilities.

4. Conclusion

This paper briefly outlines the big achievements in physically based snow simulation using the Material Point Method, with a particular interest in its application in the computer graphics community. A constitutive model of the snow deformation and dynamical change lays the groundwork for accurately reproducing the simulation. Based on the physical model, a wise choice of simulation method would greatly impact the efficiency and capacity of all kinds of numerical calculations. MPM is especially powerful while calculating the deformation change and handling the collision within an elasto-plastic model, but it does not capture all aspects of snow. Phase transition could be handled by the augmented MPM but its efficiency remains a problem. As such, this paper contributes with a discussion of the advantages and limitations of the MPM in snow simulation and a simple contrast to other simulation methods like SPH. It touches on as many relevant aspects of mathematical modeling, thermodynamics, and computational cost as possible in this topic, aiming at providing good comprehensive bedstones of the current state-of-art and potential direction of future models and simulation techniques to describe the behavior of snow. simultaneously this paper lacks an in-depth analysis of the involved methods and quantitative comparisons and contrasts between them. The potential extension of this paper could lie in the implementation of those methods and the presentation of a quantitative analysis of their significance.

Acknowledgment

I, the author of this thesis, would like to show my deepest gratitude to the instructors and professors at my university, who have provided me with valuable guidance in every stage of the writing of this thesis. Further, I would like to thank all my friends and parents for their encouragement and support. Lastly, I also thank the anonymous reviewers for their suggestions.

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