Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2018-0158

Vol. **26**, No. 1, pp. 57-86
July 2019

Improving Linked-Lists Using Tree Search Algorithms for Neighbor Finding in Variable-Resolution Smoothed Particle Hydrodynamics

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Received 10 June 2018; Accepted (in revised version) 24 October 2018

Abstract. Improving linked-lists for neighbor finding with the use of tree search algorithms is proposed here, aiming to cope with highly non-uniform resolution simulations employing a meshless method. The new procedure, coined Quadtree Cells Grid, has been implemented in Smoothed Particle Hydrodynamics (SPH). The SPH scheme employed is adaptive, thus allowing for particle refinement in desired regions of the flow. Owing to the wide range of coexisting particle mass levels, standard linked-list neighbor search algorithms become ineffective. Hence, an alternative is found based on the use of hierarchical data structures, using quadtrees (in 2D problems). The present algorithm exploits the advantages of both linked-lists and quadtree methods with the goal of increasing computational efficiency, when dealing with highly non-uniform particle distributions. Test cases involving two distinct flow problems have demonstrated that the computational cost of the current adaptive neighbor finding algorithm scales linearly with the total number of particles, thus retrieving this characteristic of linked-lists in uniform grid search. Nevertheless, the memory usage increased as a result of the more complex data structure.

AMS subject classifications: 76M28, 68P10, 76D17

Key words: Smoothed particle hydrodynamics, linked-list, quadtree, neighbor finding, variable resolution.

1 Introduction

The particle-based method known as Smoothed Particle Hydrodynamics (SPH) [1] has seen a major increase in its range of applications along the past two decades [2,3]. Briefly, this method typically uses an isotropic smoothing function to calculate field values, and

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particles carry media and flow data as these evolve according to Lagrangian governing equations. As a rule, the larger number of calculating particles required by more accurate simulations leads to increased computational cost. In the case of SPH, the number of particles demanded to achieve a desired quality of the solution may be reduced by using a variable-mass distribution of particles [4–6]. This strategy becomes especially important when considering engineering problems with truncated boundaries, where different spatial resolutions must be employed to deal with complex and/or moving geometries, such as in the cases of fluid flow through porous media [7] and fluid-structure interaction [8]. Whether uniformly distributed or not, and irrespectively of the criterion chosen for particle splitting or merging (dynamic or regional), a list of neighboring particles must be created for each field particle, to be used in the calculation of the various terms in the equations to be solved. The three main Nearest Neighboring Particle Search (NNPS) algorithms used for that purpose are as follows: all-pair (direct), linked-list (uniform grid) and tree (quadtree in 2D or octree in 3D) [1].

The all-pair search is the simplest but also the most inefficient NNPS algorithm. For a given particle i $(i=1,\cdots,N)$, where N is the total number of particles in the domain, the distance to all other j $(j=1,\cdots,N)$ particles is firstly inspected and only those falling inside a prescribed cut-off radius (the kernel compact support of SPH) will be considered in the next steps for interaction calculations. It is easy to show that the computational effort in this method is of order $\mathcal{O}(N^2)$, thus exposing the ineffectiveness of the algorithm.

In the uniform grid (linked-list) search, the domain is divided into an equally spaced mesh, which has the width of the kernel support in SPH. Subsequently, particles inside each mesh cell are found and, by arranging the particle array based on cell number, NNPS is performed. In this algorithm the search is only performed over the 3, 9 or 27 cells (in 1D, 2D or 3D, respectively) surrounding the target particle cell [1,9]. The computational effort is therefore reduced to the order $\mathcal{O}(N)$, which represents a significant improvement with respect to the method previously described. However, the same performance cannot be obtained using this method in SPH simulations containing particles with variable kernel smoothing lengths (i.e., non-uniform or adaptive SPH). As the level of adaptivity increases, the corresponding computational cost becomes exceedingly high. Hence, aiming to optimize this method for adaptive resolution simulations, an improved algorithm for linked-list neighbor search in single-CPU calculations has been implemented in the latest version of HAdynaSPH [4,10,11], as will be described in this paper.

Hierarchical data structures are particularly useful for the intended purpose because of their ability to focus on the interesting subsets of the data. Quadtree (in 2D and octree in 3D) is a hierarchical data structure based on the principle of recursive decomposition [12,13]. It has been used for the representation of data used for applications in image processing, computer graphics, geographic information systems, and robotics. In the field of Computational Fluid Dynamics (CFD), such structures are specially suitable to deal with adaptive resolution techniques [14–17]. The advantage in the use of the quadtree grids lies in the fact that those grids can be generated automatically, and managed dynamically