A Collocated Spatially Adaptive Approach to Smoke Simulation in Bifrost

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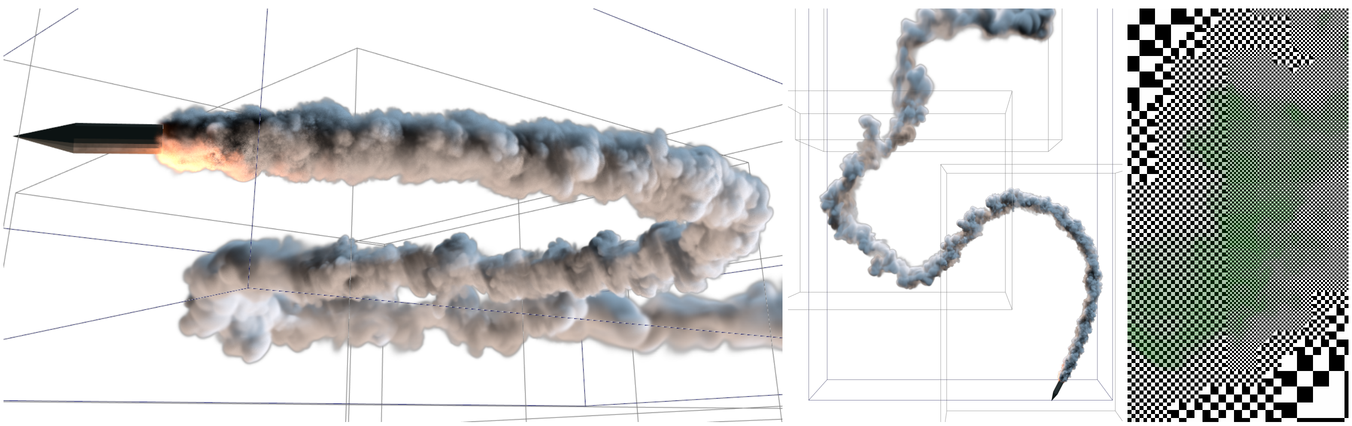

Figure 1: Our new collocated velocity approach to smoke simulation enables a rocket trail (left) with an effective bounding box of $1100 \times 1500 \times 220$ voxels to be simulated with adaptive resolution both away from and along the trail as illustrated by the closeup of a resolution jump (right), where in this case boxes define the adaptivity (middle). Employing adaptivity along and away from the trail does not exactly match the result obtained with adaptivity away from and uniform resolution along the trail from the viewpoint of the left image, but the adaptive trail simulates in 8 minutes and 55 seconds on a 32 core machine — 2.3 times faster. This demonstrates the potential of and performance improvements achievable by our adaptive method.

CCS CONCEPTS

• **Computing methodologies → Physical simulation**;

KEYWORDS

fluid simulation, smoke simulation

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Simulations of smoke are pervasive in the production of visual effects for commercials, movies and games: from cigarette smoke and subtle dust to large-scale clouds of soot and vapor emanating from fires and explosions. In this talk we present a new Eulerian method that targets the simulation of such phenomena on a structured spatially adaptive voxel grid — thereby achieving an improvement in memory usage and computational performance over regular dense and sparse grids at uniform resolution. Contrary to e.g. Setaluri et al. [2014], we use velocities collocated at voxel corners which allows sharper interpolation for spatially adaptive simulations, is faster for sampling, and promotes ease-of-use in an open procedural environment where technical artists often construct small computational graphs that apply forces, dissipation etc. to the velocities. The collocated method requires special treatment when projecting out the divergent velocity modes to prevent non-physical high frequency oscillations (not addressed by Ferstl et al. [2014]). To this end we explored discretization and filtering methods from computational physics, combining them with a matrix-free adaptive multigrid scheme based on MLAT and FAS [Trottenberg and Schuller 2001]. Finally we contribute a new volumetric quadrature approach to temporally smooth emission which outperforms e.g. Gaussian quadrature at large time steps. We have implemented our method in the cross-platform Autodesk Bifrost procedural environment which facilitates customization by the individual technical artist, and our implementation is in production use at several major studios. We refer the reader to the accompanying video for examples that illustrate our novel workflows for spatially adaptive simulations and the benefits of our approach. We note that several methods for adaptive fluid simulation have been proposed in recent years, e.g. [Ferstl et al. 2014; Setaluri et al. 2014], and we have drawn a lot of inspiration from these. However, to the best of our knowledge we are the first in computer graphics to propose a collocated velocity, spatially adaptive and matrix-free smoke simulation method that explicitly mitigates non-physical divergent modes.

1 ADAPTIVE COLLOCATED VOXEL GRID

Our method computes the solution to the Inviscid Euler Equations on a spatially adaptive grid everywhere inside the bounding box of the simulation. The adaptive fields are stored on the Tile Tree which essentially is a generalized LOD octree – see Nielsen et al. [Nielsen and Bridson 2016] for details. Each node in the tree stores data in tiles of size m^3 and has n^3 children. We use $m = 4$ and $n = 2$. This implies that resolution jumps by a factor of 2^3 between levels similar to octrees, but computations are performed on tiles of size 4^3 which exhibit better cache coherency. Our algorithms are expressed as computational kernels operating on *halo tiles*: tiles of size $(m + 2)^3$ with direct access to neighboring values to compute differential properties. The halos are pre-filled during tree traversals. While Setaluri et al. [2014] do present linear interpolation without error for affine fields, their method requires an additional averaging to voxel corners plus error correction computation. Our method facilitates direct interpolation with a more compact stencil, and we also present an approach to cubic interpolation. Basic interpolation inside a voxel is done by tri-linearly interpolating from the values at the eight corners. To ensure continuity at resolution jumps we recursively interpolate values at hanging nodes from coarser levels. The same approach applies to C^0 cubic and C^1 Catmull-Rom interpolation, but in addition we interpolate from coarser levels at cubic stencil points not corresponding to degrees of freedom, and incorporate varying sample spacing across resolution jumps into the interpolation.

2 VELOCITY FIELD PROJECTION

Typically, a staggered MAC grid velocity arrangement is used in computer graphics [Fedkiw et al. 2001]. This facilitates an exact projection solving for a velocity field which is discretely divergence free up to round off error. While convenient when solving for pressure, the staggered representation requires averaging to corners when interpolated on a spatially adaptive grid with state of the art methods. It also needs three times more sample evaluations than a collocated method due to the staggered sample placement. To solve for pressure from collocated velocities we instead employ an approximate projection method [Rider 1995] with differential operators discretized by finite differences. This does not lead to a discretely divergence free solution, but the local truncation errors are comparable to those obtained by exact projection methods. As opposed to the collocated method by Ferstl et al. [2014], we make the observation that placing pressure samples in voxel centers reduces the number of non-physical divergent modes. The cell centered divergence is computed from collocated velocities at the eight corners of the voxel. The gradient of pressure is computed at the corner of a voxel from the eight surrounding cell centers. The Laplacian is computed at cell centers using a 7-point finite difference (as opposed to the more expensive 27-point stencil used by Ferstl et al. [2014]). Pressures are computed by the adaptive MLAT and FAS method [Trottenberg and Schuller 2001] with multigrid cycles running directly on our LOD data structure. This multigrid approach currently restricts the tree to be graded, whereas our interpolation scheme does not. To obtain a matrix-free method we combine with the Iterated Orthogonal Projection method for smoke-collider coupling. A collocated velocity approach can lead to non-physical divergent modes contained in the null space of the divergence operator which cannot be projected out by the computed pressures. However, the modes can be mitigated by a spatially varying truncation-error-preserving filter applied only in areas where the modes are detected, thus limiting velocity-diffusion.

3 TEMPORALLY SMOOTH EMISSION

To facilitate temporally smooth emission in conjunction with large time steps we numerically integrate the emitter position and other properties over the duration of the time step (see the accompanying video). The quadrature at each point in space is independent and thus all points can be integrated in parallel. Methods such as Gaussian quadrature that are well suited for integrating smooth functions up to some order require many quadrature points to converge if the emission field contains high frequencies. To avoid computational overhead due to an excessive number of quadrature points we instead employ a mid-point quadrature rule and pseudo-randomly jitter the sample positions within each interval independently (yet deterministically) at each point in space. This results in a smoother appearance of the emission with a low number of quadrature points.

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