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Abstract.

ALE-AMR is a new hydrocode that we are developing as a predictive modeling tool for debris and shrapnel formation in high-energy laser experiments. In this paper we present our approach to implementing laser ray-tracing in ALE-AMR. We present the equations of laser ray tracing, our approach to efficient traversal of the adaptive mesh hierarchy in which we propagate computational rays through a virtual composite mesh consisting of the finest resolution representation of the modeled space, and anticipate simulations that will be compared to experiments for code validation.

1. Introduction

Shrapnel and debris with the potential of damaging expensive optics, diagnostics, or fixturing, may be generated by the extreme conditions present in high energy laser facilities such as the National Ignition Facility (NIF), Laser Mégajoule (LMJ) and Omega. The ALE-AMR multi-physics hydrocode has been developed as a predictive modeling tool to identify and assess sources of shrapnel and debris and the hazards they pose so these may be mitigated [1–6]. Such simulations generally require large computational domains in which to track fragment formation and trajectories—much of which will remain empty during significant portions of the simulation. ALE-AMR implements arbitrary Lagrangian-Eulerian (ALE) hydrodynamics within an adaptive mesh refinement (AMR) framework. This allows the mesh to be adapted in response to the current state: applying additional mesh resolution in regions with rapidly changing dynamics while a coarser mesh may be used in regions that are currently less interesting—enhancing computational efficiency without sacrificing accuracy or resolution. In evaluating debris and shrapnel we need to be concerned not only with the 3 ω (UV) light critical to target design, but also the unconverted 1 ω and 2 ω (red and green) that may irradiate support and diagnostic structures. Laser ray tracing is an efficient means for simulating laser propagation and energy deposition and provides a realistic energy source for hydrodynamic simulations.

2. ALE-AMR

The Structured Adaptive Mesh Refinement Application Infrastructure (SAMRAI) [7] framework on which ALE-AMR is implemented provides a hierarchy of logically rectangular patches on which the problem physics are advanced. The simulation resolution can be improved in areas of interest, e.g., large gradients or fragmentation, by overlaying refined meshes that represent subsets of the domain (see Figure 1). The hydrodynamics are evolved using a Lagrange-plus-remap algorithm. After problem initialization (mesh generation and initial conditions) the problem is advanced by repeating the following steps:

Lagrange Step The mesh is deformed by evaluating the forces (pressures) acting on the nodes and the resulting accelerations and displacements.

Remap Step Periodically the current Lagrange solution is remapped to an new mesh to avoid tangling, this may be either the original mesh (Eulerian) or some arbitrary mesh (ALE), usually a relaxed mesh intermediate to Lagrange and Eulerian configurations.

Adaptive Mesh Refinement Zones are tagged for coarsening or refinement by evaluating the current solution with respect to user defined criteria. A new mesh hierarchy is then created onto which the current solution in mapped through coarsening or refining the solution variables.

Additional Physics If additional physics (heat conduction, radiation diffusion, or in this case laser ray tracing) are required they are performed at this point and the cumulative result is used for the next Lagrange step.

The code is designed to run on large parallel machines, therefore each processor is responsible for only a small subset of the problem, with communication limited to the information necessary to correctly synchronize adjacent or underlying patches through patch ghost cells or coarsened and refined solutions.

3. Laser Ray Tracing

Ray tracing is a powerful technique applied to high-energy laser simulations by Friedman [8] and Kaiser [9]. The key assumption is that the length scale of variations in the medium is larger than the laser wavelength over most of the computational domain. This allows the wave equations to be simplified as an equation of motion for rays:

$$\frac{\partial^2 \vec{x}}{\partial t^2} = \vec{\nabla}\left(-\frac{c^2}{2}\frac{n_e}{n_c}\right) \tag{3.1}$$

which are now considered to be beams of unit mass particles in a potential field V

$$V = \frac{c^2}{2}\frac{n_e}{n_c} \tag{3.2}$$

where c is the speed of light, n_e is the electron number density of the medium and n_c is the critical number density which depends on the laser frequency, ω:

$$n_c = \frac{m_e}{4\pi}\left(\frac{\omega}{e}\right)^2 \tag{3.3}$$

m_e and e are the mass and charge of an electron. In a linear potential field, the trajectory of a ray is parabolic. Laser beams are simulated by creating a large number of computational rays with each assigned a power and trajectory based on the beam intensity, origin, orientation and focus. The ray tracing algorithm tracks each ray, computing the trajectory of the ray and the power deposition.

ALE-AMR uses a structured mesh, thus quadrilateral elements (bounded by four lines) in 2D and hexahedral elements (bounded by six doubly ruled surfaces) in 3D. The intersections of the parabolic trajectories resulting from Eq. (3.1) with these zones results in quadratic (2D) and quartic (3D) equations that must be solved for each face of the current zone. Several solutions may exist within the line or ruled surface but valid solutions must lie withing the boundaries of the current face. The exit face is identified as the one with the shortest exit time. Ambiguities may arise if a ray passes close to edges and/or corners which may lead to the wrong exit face being chosen and subsequent failure to find a valid exit point in the next zone. Such ambiguities may be removed by reevaluating the ray traversal after slightly perturbing the entry point within the entry face. Discontinuities in the electron densities may exist at zone interfaces and are treated via Snell's Law.

As each zone is traversed the energy deposition is computed based on the inverse bremsstrahlung process with the rate of energy loss from the ray given by a linearized form of

$$\nu_{ib} = \frac{4}{3}\sqrt{\frac{2\pi}{m_e}}\frac{n_e^2\, Z\, e^4\ \ln\Lambda}{n_c\,(k_B\,T)^{3/2}} \tag{3.4}$$

where Z is the charge state, k_B is the Boltzmann constant, T is the electron temperature, and $\ln\Lambda$ is the Coulomb logarithm (a function of number density, electron temperature, charge state, and critical density, see [10]). Integrating this rate over the zone traversal time yields the energy to be deposited in the zone and removed from the ray.

4. Logical Patches and AMR

We implemented laser ray tracing in ALE-AMR by considering the AMR hierarchy as a virtual composite mesh, i.e., rays are only propagated through the finest representation of the physical space as shown in Figure 1. At the end of a zone traversal the physical exit point and the logical index of the apparent destination zone are known. We then check to see if the destination zone exists in the current patch, if so we check for finer representations of the logical space and refine until the finest representation is found and the ray then processed. Identification of the refined destination is facilitated by the fact that nodes defining the transitions between levels are constrained to be evenly spaced in the parametric space of the coarser face in which they lie (nodes internal to the refined space are not subject to these constraints).

If the destination zone does not exist in the current patch we search the hierarchy, using an efficient lookup provided by the SAMRAI library, to identify the finest representation of the physical space. The result of this search may be either that zone exists on a different patch (at the current level) or that it does not exist in the hierarchy (at the current level): If the former then the ray is passed to the correct patch/processor and we again test for finer representations and continue processing; If the latter then the logical index is coarsened until a valid zone/patch/processor is identified and processing continues at a coarser level of refinement.

Once the correct destination—which is the finest computational representation of the physical coordinates—has been identified processing continues until either the ray power is depleted or the ray leaves the simulation domain. Energy deposited by all rays is accumulated in the zones and coarsened down to underlying patches at the end of the ray tracing step. This may then be deposited directly as an addition to the zonal internal energies or used as a source term in a subsequent diffusion step.

We do not currently do explicit load balancing but do process rays in batches to evenly distribute rays on the processors that will participate in ray tracing (some processors may hold patches or levels that are traversed by few if any rays and may remain largely idle during a given laser ray tracing step).

5. Applications

We are currently working on simulations a series of experiments performed on the Janus laser in order to validate the laser ray tracing package. These consisted of nominally 200 J 3 ns shots with 2 ω light on 75 μm tantalum and vanadium foils. Debris ejected from the backside was captured in Aerogel and on glass plates and analyzed with x-ray radiography to determine particles sizes and penetration (see Figure 2(a)). These simulations have not been completed at the time of this writing but will be completed shortly (Figure 2(b) shows a rays interacting with a vanadium foil in a preliminary simulation).

6. Conclusions and Future Work

We have implemented laser ray tracing in the ALE-AMR hydrocode to provides an efficient means for modeling laser energy deposition. This provides the means to deposit energy in a realistic manner

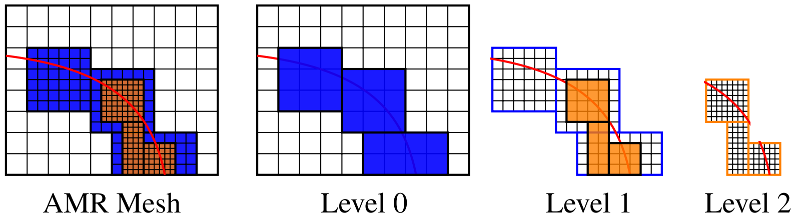
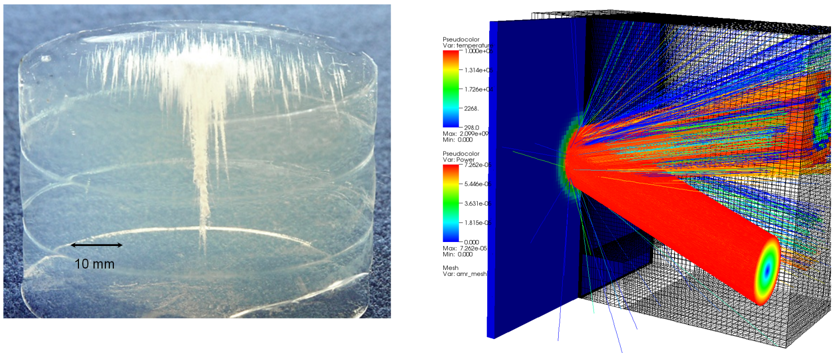


Figure 1. Rays traverse a virtual composite mesh. Rays are passed to the appropriate patch which may be at a higher, lower, or the same level of refinement



(a) Debris from one of the Janus experiments captured in aerogel

(b) Preliminary ALE-AMR simulation of a Janus experiment with laser ray tracing

Figure 2. Experimental validation of the ALE-AMR ray tracing using Janus experiments

as we seek to mitigate damage through predictive modeling of debris and shrapnel. Future work will complete simulations of our Janus experimental shot campaign to evaluate the capabilities of the ALE-AMR code, including laser ray tracing, hydrodynamics, and predictive modeling of the formation of debris by comparison to the collected experimental data.

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