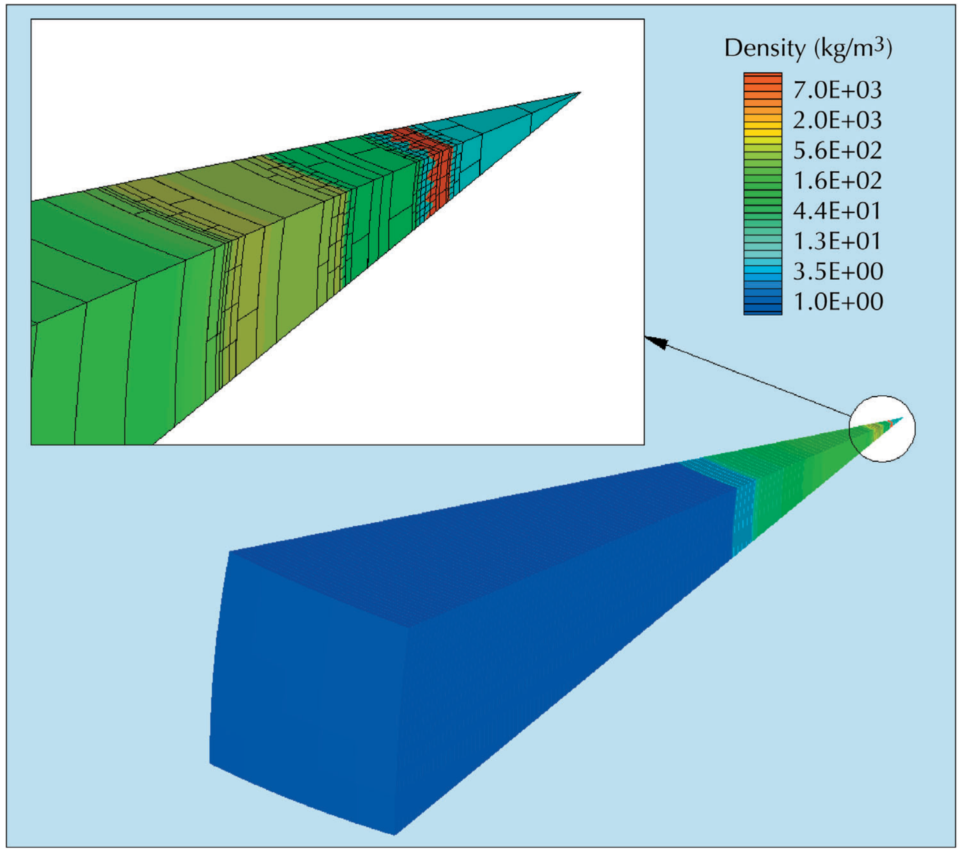
Center for Applied Scientific Computing

ALE–AMR

Arbitrary Lagrangian–Eulerian (ALE) Hydrodynamics with Adaptive Mesh Refinement (AMR)



This ICF hydrodynamics test problem involves both large-scale shock driven motion and small-scale hydrodynamic instabilities, which is precisely the type of problem for which the ALE-AMR method excels.

Overview

The simulation of complex, three-dimensional hydrodynamic systems is a computational challenge at the heart of a broad range of LLNL's science applications. The collapse of inertial confinement fusion (ICF) targets in the National Ignition Facility (NIF), the evolution of stars and stellar systems, and the future of the earth's own atmosphere and climate are but three examples for which hydrodynamic motion is a central component of predictive modeling capabilities. The ALE–AMR project brings the efficiency of adaptive mesh refinement (AMR) techniques to the arbitrary Lagrangian–Eulerian (ALE) hydrodynamics methods to create a new, more powerful technique for addressing a range of important problems through computational simulation.

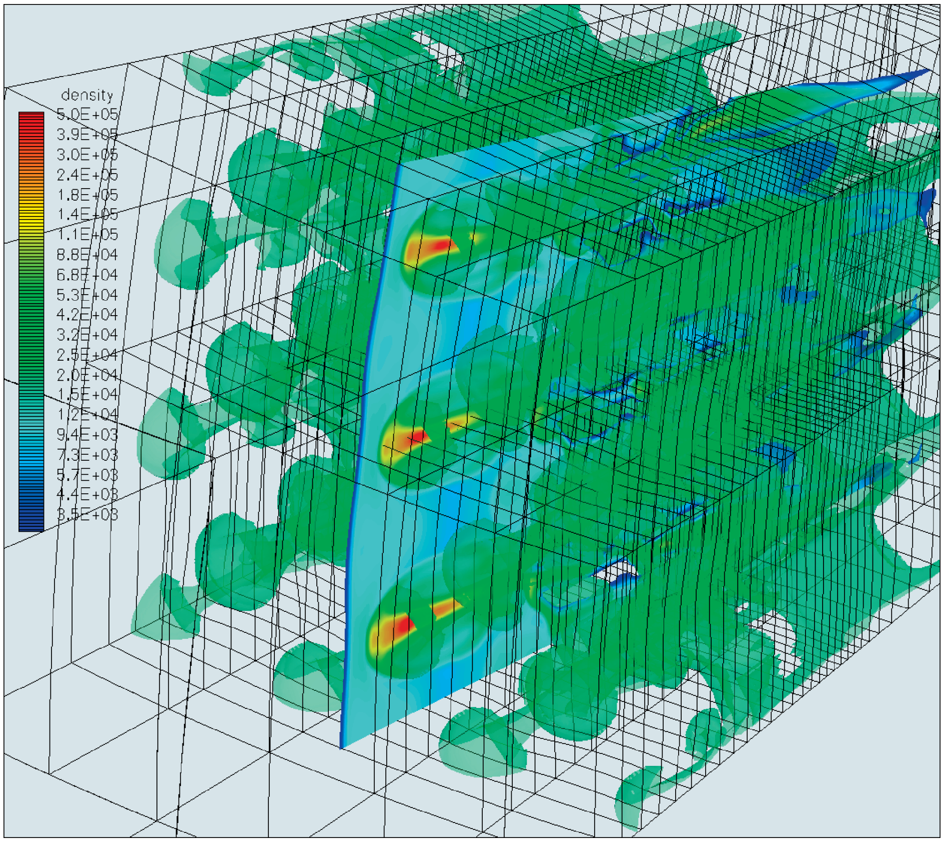
Background

There are many specific technical challenges associated with the modeling of hydrodynamic motion, but one recurring and difficult theme is that the level of detail required to provide useful predictions ranges over a wide spectrum, and will change in space and time in ways that are unpredictable at the outset. Specific examples of hydrodynamic features that often require additional detail to model properly are chemical reaction fronts, shock waves, and fluid mechanical phenomena such as Richtmyer–Meshkov, Rayleigh–Taylor, and Kelvin–Helmholtz instabilities. However, the computational resource requirements grow so rapidly as we add additional detail to a calculation, that even with today's very powerful computers, it is difficult to avoid overwhelming the available resources in superfluous pursuit of detail in regions of space and time that do not require it.

Adaptive mesh refinement (AMR) is a technique for applying computational resources to only the salient features of the calculation in an automated way. The ALE–AMR project seeks to develop and adapt AMR techniques for use with the ALE class of hydrodynamics methods, which have shown particular utility for computationally challenging systems consisting of moving boundaries and multiple materials, sometimes consisting of both solids and fluids interacting with one another through their respective motions.

Approach

AMR has historically been applied to methods that compute the evolution of systems at fixed points in space, known as the Eulerian methods. Eulerian methods exhibit both advantages and disadvantages in various applications. In particular, moving boundaries and multiple materials are less natural to express in an Eulerian method than in a Lagrangian method, in which computation proceeds at elements of fixed identity as they move in time through space. Lagrangian methods tend to exhibit their own advantages and disadvantages that mostly complement those of the Eulerian methods. In particular,



This three-dimensional, time-dependent Richtmyer–Meshkov instability is generated in a very small region of the full ICF test problem depicted in Figure 1, and is typical of the types of features that the ALE–AMR method can capture without exponentially increasing computational resource requirements.

while they handle moving boundaries and multiple materials very naturally, they tend to perform poorly in flows exhibiting strong shearing and vortical motion. The ALE methods seek a compromise between the Eulerian and Lagrangian descriptions that can accurately make predictions for problems that involve all of the aforementioned characteristics: moving boundaries, multiple materials, and regions of strong shearing and vortical flow. We are building upon well-established ALE methods that have demonstrated their utility in laboratory science over the last several decades. If we then add in addition to this the efficiency of automatically applying computational resources only where they are required in time and space, we have a new and powerful tool for tackling a wide range of challenging problems. Developing methods of this type involves new and fundamental computational and algorithmic considerations: interlevel transfer operators for staggered, moving, and deforming grids and multi-level, time-refined elliptic mesh relaxation operators are but two examples of new algorithmic components which have been developed and analyzed for use in the ALE–AMR method. Currently, the coupling of implicit methods for the solution of the radiation diffusion equations into the model is under investigation.

Application

Inertial confinement fusion (ICF) is a technique for generating nuclear fusion reactions by compressing a small target that contains a nuclear fuel such as deuterium-tritium gas (DT), either directly or indirectly using very intense laser light. For the design of targets for use in the NIF facility, computational simulation tools are indispensible, since the extreme conditions of temperature and pressure in a compressed ICF capsule cannot be replicated in other laboratory experiments. The process of compressing an ICF capsule generates a Richtmyer–Meshkov fluid mechanical instability, the behavior of which is very important in determining the overall performance of the target. The instability growth happens on small scales compared to the overall size of the target, and so AMR techniques can be very helpful in accurately capturing these phenomena without exponential growth in computational resource requirements.

Figure 1 shows an ICF-type hydrodynamics problem. As the laser (not shown) strikes the outer surface of the target, a shock wave is generated that travels inward to begin compressing the target. As the shock wave strikes an inner shell of a different material that has some imperfections or perturbations on its surface, a Richtmyer–Meshkov instability is generated and grows in a classical pattern of "bubbles and spikes," a motion that is driven by the dynamics of vorticity. That pattern is shown in Figure 2 in a colormap of density.

Capturing the detailed evolution of such instabilities is but one important application of the ALE–AMR method. Ongoing work on additional physics capabilities such as chemistry, radiation fields, and solid mechanics will provide many more opportunities to provide predictive capabilities facilitating new simulations with unprecedented fidelity.

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