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Nepřímé lagrangeovsko-eulerovské metody pro hydrodynamiku

Indirect Arbitrary Lagrangian-Eulerian methods for hydrodynamics

Summary

For hydrodynamic simulations, the Arbitrary Lagrangian-Eulerian (ALE) methods represent one of few state of the art numerical approaches, which are efficient, accurate, and robust enough for realistic calculations. In this approach, an accurate Lagrangian solver is used to advance the solution along with the computational mesh in time, while its robustness is achieved by rezoning (smoothing) of the mesh. The last step of a typical indirect ALE method is remapping, conservatively transferring all fluid quantities from the Lagrangian to the rezoned computational mesh.

Here, we briefly review all three stages of an indirect ALE method: the Lagrangian solver, mesh rezoner, and quantity remapper. Most attention is paid to the remapping stage in the staggered discretization in both single- and multi-material situations, where most research of the author was conducted. A typical application from the field of hydrodynamic simulations of laser-plasma interactions is presented, demonstrating viability of the developed methods in realistic calculations.

Souhrn

Jednou z mála numerických metod pro hydrodynamické simulace, které jsou v současné době považovány za dostatečně efektivní, přesné a robustní, jsou metody lagrangeovsko-eulerovské (ALE). Tento přístup využívá přesného lagrangeovského řešiče, který posouvá řešení v čase spolu s výpočetní sítí, přičemž robustnosti metody je dosaženo regularizací (vyhlazováním) sítě. Posledním krokem typické nepřímé ALE metody je remapování, konzervativně přesouvající všechny veličiny dané tekutiny z lagrangeovské výpočetní sítě na vyhlazenou.

V této práci stručně popíšeme všechny fáze nepřímé ALE metody, a sice lagrangeovský řešič, vyhlazování sítí a remapování stavových veličin. Nejvíce pozornosti věnujeme fázi remapování ve střídavé diskretizaci pro jednomateriálové a vícemateriálové problémy, kde autor přispěl svojí prací nejvýznamněji. V závěru práce je prezentována typická aplikace z oblasti hydrodynamických simulací interakcí laseru s plazmatem, demonstrující použitelnost vyvinutých metod pro realistické výpočty.

Klíčová slova

Lagrangeovsko-eulerovské metody,
střídavá diskretizace,
konzervativní interpolace,
multi-materiálové ALE,
remap v tokovém tvaru.

Keywords

Arbitrary Lagrangian-Eulerian methods,
staggered discretization,
Conservative interpolations,
multi-material ALE,
flux-based remap.

Contents

1 Introduction

In the numerical hydrodynamics simulations, the choice of the computational mesh is crucial. Traditionally, there have been two viewpoints utilizing the Lagrangian or the Eulerian framework, each with its own advantages and disadvantages.

The class of Eulerian methods employs a computational mesh, which remains unchanged during the whole simulation, and the fluid moves through the edges (faces) of the mesh cells in the form of mass fluxes. This approach is not well suited for certain types of simulations, typically involving strong material compressions or expansions, which is a common situation in the field of plasma hydrodynamics.

In the Lagrangian methods, the computational mesh moves with the fluid and no mass fluxes between the computational cells are present. The motion of the mesh naturally follows the fluid motion, so the computational domain changes adaptively as necessary even for strong material deformations. This is the main reason, why mostly methods based on the Lagrangian concept are used in laser-plasma hydrodynamics. The main disadvantage of the Lagrangian methods results from the mesh motion – the computational mesh can distort and invalid (non-convex, flipped, or negative-volume) cells can appear, which typically results in simulation failure.

In a pioneering paper [33], Hirt et al. developed the formalism for a mesh whose motion could be determined as an independent degree of freedom, and showed that this general framework could be used to combine the best properties of the Lagrangian and Eulerian methods. This class of methods has been termed Arbitrary Lagrangian-Eulerian or ALE. Many authors have described the ALE strategies to optimize accuracy, robustness, or computational efficiency, see for example [14, 63, 22, 56, 61, 12, 54].

In this text, we primarily focus on the indirect ALE methods, which can be typically split in three distinct steps:

1. Lagrangian solver, advancing the fluid quantities and the computational mesh to the next time level;
2. mesh rezoner, untangling and smoothing the mesh when its geometric quality becomes low;
3. remapper, conservatively interpolating (transferring) all fluid quantities from the Lagrangian to the rezoned mesh.

After a short discussion of the numerical methods, a typical application from the field of laser-plasma interactions is presented.

2 Arbitrary Lagrangian-Eulerian Methods

The indirect Arbitrary Lagrangian-Eulerian methods combine an explicit Lagrangian solver with an Eulerian step, consisting of mesh rezoner and quantity remapper. Here, we briefly discuss each step with a special focus on the last part – the remapper.

2.1 Lagrangian Solver

The fluid hydrodynamics can be described by the set of Euler equations in the Lagrangian formulation,

$$\frac{1}{\rho}\,\rho_t = -\nabla\cdot\vec{u}\,, \qquad \rho\,\vec{u}_t = -\nabla p\,, \qquad \rho\,\varepsilon_t = -p\,\nabla\cdot\vec{u}\,, \tag{1}$$

representing continuity of mass, equation of motion, and evolution of the internal energy. Here, ρ is fluid density, $\vec{u}$ is the velocity vector, p is pressure, and ε stands for the specific internal energy. The system is closed by a particular equations of state $p = \mathcal{P}(\rho, \varepsilon)$ and the computational mesh motion is defined by $\vec{x}_t = \vec{u}$.

Numerical methods for solving this non-linear system can be characterized either as cell-centered or staggered. The class of cell-centered methods uses cell-centered discretization of all fluid quantities and is becoming very popular during recent years [62, 61, 29, 28], because it allows a simpler approach for remapping. Here, we focus on the more standard staggered discretization, which present in most hydrodynamic codes nowadays.

On the other hand, the staggered hydrodynamic solvers utilize cell-centered discretization for thermodynamic (scalar) quantities only, while the remaining kinematic (vector) quantities are located on the mesh nodes. This allows a more natural treatment of realistic boundary conditions, which is crucial in realistic applications. The compatible method based on mimetic operators [19] is one of the most popular. Its main idea is the computation of pressure-gradient forces around each node, affecting its velocity. Similarly, other needed types of forces can be constructed, such are the artificial viscosity forces stabilizing the solution at shocks, the subzonal pressure forces acting against the pathological hourglass modes, gravity forces, elastic forces, etc. The same forces are reused in the computation of work due to deformation of the particular cell, which contributes to the internal energy change in the energy equation. The resulting numerical scheme is conservative in all quantities and second order accurate.

2.2 Mesh Rezoning

Rezoning fixes the computational mesh after it has been disturbed during the Lagrangian step. It can either smooth the mesh in the sense that a particular measure of its geometric quality (such as the condition number CN) is improved. The second possibility is mesh untangling, fixing severe mesh deformations resulting in overlapping or inverting of the mesh cells.

There exist a large number of methods for mesh rezoning, both general and application-specialized. Many simple and efficient methods based on averaging of nodal coordinates exist, such as the Laplacian [32] or Winslow [74, 39] algorithms. Direct local or global optimization of the CN operator [27] or its more sensitive optimization respecting the mesh reference Jacobians [40] can be used. For mesh untangling, modification of the CN operator has been developed [24], or one can switch to purely geometric methods, such an explicit construction of the nodal feasible set [16].

In a typical simulation, just minimal mesh motion is recommended as the following remapping step produces excessive numerical diffusion if the nodes move too severely. For an example of a deformed (old, Lagrangian) and smoothed (new, rezoned) computational mesh (obtained from the Lagrangian mesh by the application of the Winslow rezoning algorithm), see Figure 1. As we can see, both meshes are very close to

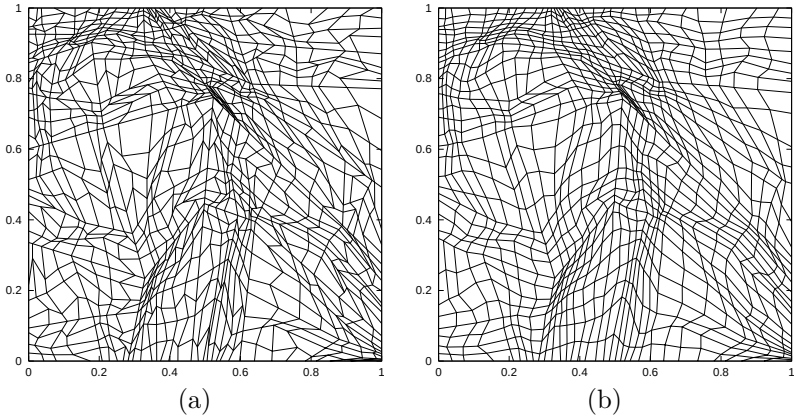


Figure 1: (a) Old (Lagrangian) mesh and (b) new mesh obtained from the old one with the Winslow rezoning algorithm.

each other and contain the same features. However, the rezoned mesh is

both numerically and even visually smoother, and more suitable for the following Lagrangian step.

2.3 Conservative Remapping

Remapping is of the key steps of a typical ALE algorithm, transferring conservatively all fluid quantities from the Lagrangian mesh to the rezoned one. We assume, that (as a result of the Lagrangian step) we know the geometry of the old and new meshes, and all Lagrangian fluid quantities inside the old cells as well as the nodal velocities. In the multi-material case, the material quantities need to be known also, in particular the knowledge of material volume fractions, eventually material centroids, is necessary. As a result, we want to compute the same quantities on the new mesh so that the remapping process satisfies the following properties:

- accuracy – at least second-order of accuracy is necessary to avoid excessive diffusion of the solution;
- continuity – if the computational mesh does not change, no quantity is supposed to change;
- conservation – fluid mass, volume, and internal energy have to be conserved (per material in case of multi-material remap);
- efficiency – all geometrical calculations are done only once, at the beginning of the remapping process.

In the following sections, the basic numerical approaches for remapping are summarized, with a special focus on multi-material remap in the context of multi-material ALE algorithms.

2.3.1 Function reconstruction

In order to achieve second-order accurate remapping scheme, function reconstruction must be performed to approximate the unknown function profile from the discrete data. Let us assume that there exist an unknown density function $\rho(x, y)$. Mass of each computational cell c is obtained as $m_c = \int_c \rho(x, y)\, dx\, dy$ and its density as $\rho_c = m_c/V_c$, where V_c is cell volume computed from its geometry.

To approximate the density function in the mesh cells, a piece-wise linear function in the form

$$\rho_c(x, y) = \rho_c + S_c^x\,(x - x_c) + S_c^y\,(y - y_c) \tag{2}$$

is typically used, where $[x_c, y_c]$ are the coordinates of the cell centroid. The main task of the reconstruction is the definition of the density slopes

$S_c^x = (\partial\rho/\partial x)_c$ and $S_c^y = (\partial\rho/\partial y)_c$ from the discrete mean values ρ_c. One of possible approaches is their computation by minimization of an error functional, measuring the difference (in the least-squares sense) of the linear function from the neighboring mean values [66, 48]. To avoid oscillations in the remapped quantity, limiting [13] of the slopes is typically used.

2.3.2 Intersection-based remap

The intersection-based remap (reviewed in [64]) is the most natural approach for conservative transfer of conservative quantities between general computational meshes. The new mesh cell $\tilde{c}$ can be composed from its intersections with all cells of the original mesh,

$$\tilde{c} = \bigcup_{c' \in \{c\}} \tilde{c} \cap c' \,, \tag{3}$$

as shown in Figure 2 (a). Then, remap of mass can be written in the form

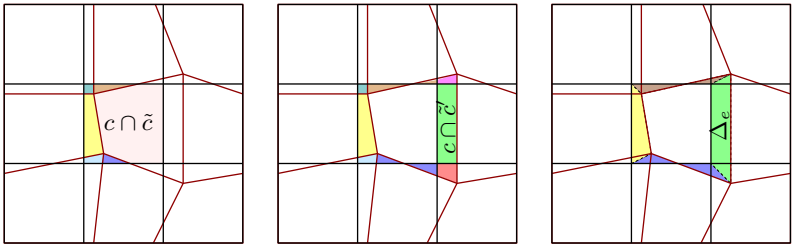


Figure 2: Comparison of basic remapping methods: (a) intersection-based remap; (b) intersection-based remap in a flux form; (c) swept-based remap. Old mesh is shown in red and new one in black color.

$$m_{\tilde{c}} = I_{\tilde{c}}^{\rho(x,y)} = I_{\bigcup_{c' \in \{c\}} \tilde{c} \cap c'}^{\rho(x,y)} = \sum_{c' \in \{c\}} I_{\tilde{c} \cap c'}^{\rho(x,y)} \approx \sum_{c' \in \{c\}} I_{\tilde{c} \cap c'}^{\rho_{c'}(x,y)} \,, \tag{4}$$

where I_P^f represents integral of an arbitrary function f over polygon p, $I_P^f = \int_P f(x,y)\,dx\,dy$.

For topologically close meshes, this approach can be formulated in a flux form derived in [23, 64], which is based on adding and removing of

pieces of the Lagrangian cell in order to obtain the rezoned one,

$$\tilde{c} = c \cup \bigcup_{c' \in C(c)} \left(\left(\tilde{c} \cap c' \right) \setminus \left(c \cap \tilde{c}' \right) \right), \tag{5}$$

as shown in Figure 2 (b). The mass remap can be formulated in an equivalent flux form

$$m_{\tilde{c}} = m_c + \sum_{c' \in C(c)} F^m_{c,c'}, \tag{6}$$

where the mass fluxes F^m are composed from their positive and negative contributions,

$$F^m_{c,c'} = I^{\rho_{c'}(x,y)}_{\tilde{c} \cap c'} - I^{\rho_c(x,y)}_{c \cap \tilde{c}'}. \tag{7}$$

These fluxes represent the masses of all the intersections, and in practice, by using (2), they can be composed from the exchange integrals I^1, I^x, I^y, (i.e. integrals of simple polynomials pre-computed at the beginning of the remapping step from the geometry of the intersections). Similar formula can be used for other quantities, for examples of nodal momenta or cell internal energy, see [48, 46].

2.3.3 Swept-region-based remap

A swept region [23] Δ_e is defined by the motion of a particular edge e between cells c and c' into its new position $\tilde{e}$ during rezoning. There always exist one quadrilateral swept region for each cell edge, see Figure 2 (c).

This allows remap of cell mass to be written in a flux form

$$m_{\tilde{c}} = m_c + \sum_{e \in E(c)} F^m_e, \tag{8}$$

where $E(c)$ stands for a set of all edges of cell c, and where the mass fluxes are computed as integrals of the reconstructed density over the swept regions

$$F^m_e = I^{\rho_{c^*}(x,y)}_{\Delta_e}. \tag{9}$$

The reconstruction $\rho_{c^*}(x, y)$ is taken from cell c^*, which is either the original cell c or its neighbor c' over the edge e, depending on the sign of algebraic area of Δ_e. The integral in the swept mass F^m_e can be again composed from the pre-computed exchange integrals $I^1_{\Delta_e}$, $I^x_{\Delta_e}$, and $I^y_{\Delta_e}$. Compared to the intersection-based remap (6), no corner fluxes exist.

The swept region methods are more popular in real ALE codes due to their efficiency and robustness, resulting from the avoidance of the

expensive and implementation-sensitive intersections. On the other hand, a special treatment for fixing the generated overshoots may be required, such as the a posteriori mass redistribution [50, 65, 58], the Flux-Corrected Transport (FCT) [51], or the Multi-dimensional Optimal Order Detection (MOOD) [20]. The swept region approach can be naturally extended to 3D [31] and for changing connectivity meshes [45].

2.3.4 Multi-material remap

In multi-material ALE, more than one material is permitted in each computational cell. This approach allows to treat different materials properly, without their artificial mixing, and leads to a significant improvement of the simulation reliability. Many authors have been working on different aspects of multi-material ALE in recent years [68, 1, 73, 42, 11, 70, 44, 29, 30, 69, 18, 26, 28, 12].

In this approach, different materials k in cell c are typically represented as polygons c_k produced by a particular material-reconstruction method, see [44] for a comparison of several most popular approaches. The volume of the material $V_{c,k}$ can be normalized and represented in the form of material volume fractions $\alpha_{c,k} = V_{c,k}/V_c$, its geometric center (centroid) $x_{c,k} = I^x_{c_k}/I^1_{c_k}$, $y_{c,k} = I^y_{c_k}/I^1_{c_k}$ is typically used to represent the material approximate position in the cell.

The intersection-based remap is preferred for multi-material problems as its generalization is straightforward – the new cell is intersected with the particular pure material polygon instead of the whole original cell, as shown in Figure 3 (a), (b). The material mass remap (6) can be formulated as

$$m_{\tilde{c},k} = m_{c,k} + \sum_{c' \in C(c)} F^m_{c,c',k}\,, \tag{10}$$

and the material k mass fluxes are

$$F^m_{c,c',k} = I^{\rho_{c',k}(x,y)}_{\tilde{c} \cap c'_k} - I^{\rho_{c,k}(x,y)}_{c_k \cap \tilde{c}'}\,. \tag{11}$$

The density reconstructions $\rho_{c,k}(x,y)$ are obtained in the same piece-wise linear manner as (2), for each material separately.

2.3.5 Hybrid remap

One possible approach for an efficiency improvement of multi-material remapping is the hybrid remapping concept introduced in a series of papers [43, 15, 47]. In this approach, both intersection- and swept-based

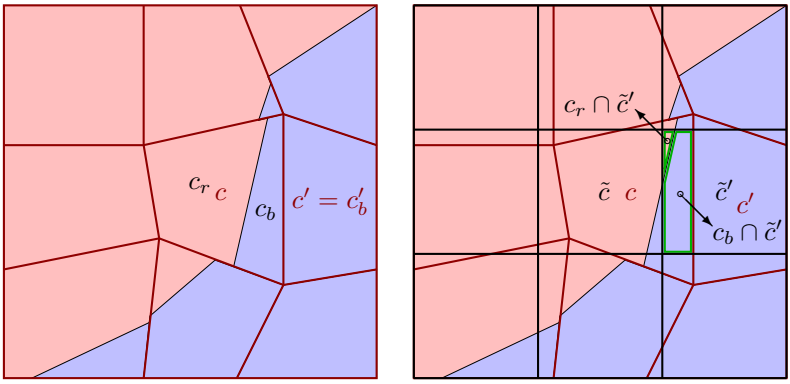


Figure 3: Multi-material remap: (a) two materials (red r and blue b) in the Lagrangian (red) mesh; (b) flux between cells c and c' split in two materials (green polygons), new mesh is shown in black color.

methods are combined in such a way, that the computationally expensive intersections are used only in the vicinity of material interfaces, while efficient swept-regions are employed inside pure material regions covering most of the computational domain. To keep consistency, a special treatment compatible with both approaches needs to be performed at the buffer region, where both methods meet.

In [43], the basic concept of hybrid remapping method was introduced and situation for logically-rectangular meshes is analyzed. To be able to use the hybrid remap in a general polygonal mesh, the whole process has been separated in two distinct steps in [15]. In the first step, only nodes belonging to the single-material cells are moved during rezoning, and remap is performed with fluxes computed by swept regions only. In the second step, the remaining mixed nodes are rezoned and remap is done with intersections. Finally, in [47], a complex one-step approach has been developed, treating all fluxes in the same swept-like manner, avoiding certain symmetry problems arising from a different treatment of mixed and pure nodes in the two-step method.

The concept of hybrid remapping can be applied also in the single-material case [35]. The main motivation is the accuracy of the remapping scheme, especially from the point of view of symmetry violations caused by the swept-based remapping scheme. Following preliminary works from [64] and [52], a full analysis of the local error of both meth-

ods has been performed in [37], identifying function properties and mesh motion patterns, for which each method is more accurate. Based on this analysis, several switches has been designed to switch between the methods in [36]. This method allows to perform remapping efficiently while keeping low numerical error of the scheme and preserving function symmetry for non-conformal meshes.

2.3.6 Remap of all fluid quantities

Up to now, remap of a single conservative quantity (fluid mass) has been considered. However, for the following Lagrangian solver, the complete set of fluid quantities has to be remapped in a consistent way. An extensive review of available methods is included in the seminal paper [14].

Due to different different location of various quantities in the staggered discretization, remapping of the whole set of fluid quantities is rather complicated. There exist several papers, addressing the remapping strategies in the staggered discretization, see for example [57, 59, 25, 55, 17]. In the preliminary work [46] and the full paper [48], a new approach for remapping of multi-material quantities in staggered discretization has been introduced. This scheme has been further studied with respect to its bound-preservation in [49]. All quantities are remapped in a flux form – material quantities (volume fractions and centroids) and material mass are remapped in the form (10). For the internal energy, a more complex flux structure must be used [23] to achieve consistency with mass remap. While material pressures are computed from the equation of state, a similar remap in a flux form has been designed for remap of $(p\,V)_c$ in order to obtain new average cell pressure needed for the construction of the pressure forces in the following Lagrangian step.

A special attention is paid to remap of nodal quantities. Nodal mass is remapped in a similar flux-form

$$m_{\tilde{n}} = m_n + \sum_{n' \in N(n)} F^m_{n,n'}, \tag{12}$$

where the inter-nodal mass fluxes $F^m_{n,n'}$ are interpolated from the inter-cell ones. Remap of the remaining nodal quantities (momentum components and kinetic energy) is performed in the same flux form (12), and the appropriate fluxes are constructed by attaching the particular reconstructed quantity to the inter-nodal mass fluxes. To avoid oscillations in the remapped quantities, the FCT scheme [51] is used for flux reduction. In [71] and [72], the FCT approach has been redesigned with a focus on the symmetry of the resulting velocity field. Total energy conservation violation resulting from the kinetic energy non-linearity is typically enforced

by the standard energy fix [14]. Moreover, a new approach inspired by [10] has been designed [9], creating the velocity reconstruction in such a way that the kinetic energy discrepancy is minimized.

This newly developed remapping approach is consistent, second-order accurate for all quantities, respects their continuity and conservation, and keeps their local bounds. Its efficiency is achieved by construction of all fluxes from the pre-computed exchange integrals. It has been demonstrated [48] that it is applicable to a broad range of multi-material high-accuracy ALE simulations.

3 Selected Application in Laser-Plasma Hydrodynamics

The described numerical methods have been implemented in the framework of the in-house Research Multi-Material ALE (RMALE) code, the test platform for evaluation of properties of the newly developed numerical methods. The methods, which proved their viability and usefulness have been incorporated in the Prague ALE (PALE) hydrodynamic code, resulting from the research on ALE methods conducted at the Department of Physical Electronics. This code is primarily intended for the simulations of laser/plasma interactions.

The PALE code solves the system of Euler equations (1) enhanced by the models of laser absorption and heat conductivity [53], with a realistic QEOS equation of state [67]. It is routinely used for simulations of experiments performed at the PALS laser facility [34], for a set of representative examples, see for example [54]. Here, we briefly present one particular application of the newly developed numerical methods for laser-generated plasma in the framework of the PALE hydrodynamic code.

The high-velocity impact of a laser-driven projectile using the LICPA scheme [3] has been investigated. This scheme is shown in Figure 4 and resembles the classical cannon ball setup – the laser beam enters small cavity, evaporates material of a heavy projectile (eventually covered by a layer of a low-Z ablator), which is ablatively accelerated and hits the massive target. Due to the cavity, only a small portion of the laser beam energy is allowed to escape and its most significant part is converted into the energy of the moving projectile and eventually into the energy of the spreading shock wave after the impact. Efficiency of this scheme is significantly higher than that of the standard ablative acceleration. In a series of paperes [5, 41, 60, 4, 7, 8, 2, 6], different setups of the LICPA scheme have been investigated numerically and experimentally at the PALS laser facil-

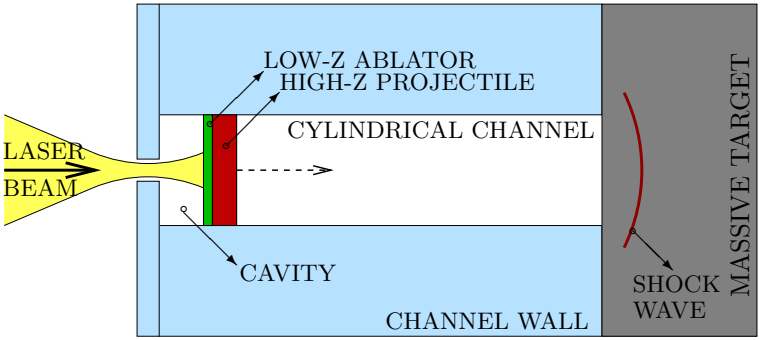
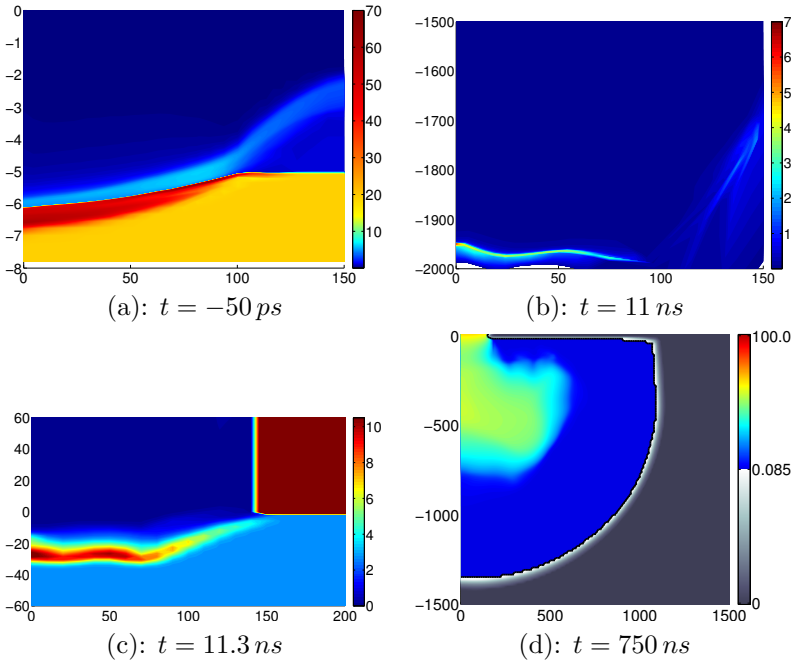


Figure 4: Setup of the cylindrical LICPA scheme.

ity. In particular, different projectile materials/widths and different laser energies/wavelengths has been studied, as well as different massive target materials. All phases of the experiments has been studied numerically, such as laser absorption process, ablative acceleration of the projectile, its motion through the guiding channel and impact on the massive target, formation of a generated shock wave, its spreading through the massive target, melting and evaporation of the target material, and development of a crater. For an example of a $200\,J$ at $3\,\omega$ laser pulse accelerating a $2.8\,\mu m$ Au projectile covered by a $5\,\mu m$ CH ablator, hitting an Al massive target [6], see Figure 5. Several plasma quantities have been compared with the experimental results – velocity, temperature, and density profile of the impacting projectile, or shape and volume of the generated crater. It has been demonstrated that the numerical results correspond reasonably well (both quantitatively and quantitatively) to the experimental data.

4 Conclusions

In this study, we have summarized the numerical algorithms and contributions of the author in the field of Arbitrary Lagrangian-Eulerian methods, especially for conservative remapping of fluid quantities. The described numerical methods have been tested in the context of a research RMALE code and selected methods were implemented in the hydrodynamic code PALE, which is under development in our research group, helping to improve its reliability, accuracy, robustness, stability, and efficiency. Beside the numerical methods, one selected application has been presented to



(a): $t = -50\,ps$ (b): $t = 11\,ns$

(c): $t = 11.3\,ns$ (d): $t = 750\,ns$

Figure 5: Numerical simulation of 200 J, 3 ω laser pulse, Au projectile, and Al massive target at different times after the pulse maximum: (a) density profile $[g/cm^3]$ during laser absorption at ablator/projectile interface; (b) density profile $[g/cm^3]$ of the projectile before the impact; (c) density profile $[g/cm^3]$ of shock wave formation after the impact; (d) temperature profile $[eV]$ inside the crater.

show applicability of the developed approaches in realistic laser-plasma calculations, and their viability in a staggered ALE code. Next to the demonstration of the methods' properties and suitability, several significant contribution to the research on the physics of laser/plasma interactions have been made, mostly motivated by the study of the inertial confinement fusion physics.

Nevertheless, there still exist many unsolved problems in the theory of ALE methods and conservative interpolations, providing a large room for future research in this field. As examples, let us mention three important topics which require more detailed investigation. The first topic is the problem of energy conservation due to the non-linear dependence of kinetic

energy on the remapped velocity. Although there exist approaches minimizing this discrepancy [9], a new, consistent, fully minimization-based remapping approach needs to be designed to eliminate it completely. The second future topic is related to the multi-material elastic/plastic simulations, which are well investigated in the Lagrangian framework, however, remap (and especially limiting [38]) of the involved stress tensor with respect to preserving its invariants is very important for full ALE simulations. Finally, let us mention the problem of remapping in case of curvilinear computational meshes [21], which is a modern and fast evolving concept nowadays. Not much work has been done in the investigation of intersections and integration along curved edges, and an increasing demand for a curvilinear remap is expected in the near future.

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Education

2002-2006	Ph.D., FNSPE, CTU in Prague, Czech Republic. Field: Physical Engineering.
1996-2002	Ing., FNSPE, CTU in Prague, Czech Republic. Field: Computational Physics.
2000	One semester as Research Scholar at the University of New Mexico, Albuquerque, USA.

Work experience

Since 2009	Assistant professor, FNSPE, CTU in Prague.
2006-2009	Postdoc in Mathematical Modeling and Analysis Group, Los Alamos National Laboratory, Los Alamos, USA.
2005	Graduate Research Assistant (3 months), Los Alamos National Laboratory, Los Alamos, USA.
2005-2006	Technical Staff Member, FNSPE, CTU in Prague.
2003	Graduate Research Assistant (3 months), Los Alamos National Laboratory, Los Alamos, USA.
2002	Graduate Research Assistant (3 months), Los Alamos National Laboratory, Los Alamos, USA.

Grant projects (as principal investigator)

2010-2012	Multi-Material Arbitrary Lagrangian-Eulerian (ALE) Methods for Hydrodynamic Plasma Simulations, GAČR, P201/10/P086.
2004	Arbitrary Lagrangian-Eulerian Methods for Plasma Hydrodynamic, MŠMT, FRVS 2087/2004.
2004	Development of Arbitrary Lagrangian-Eulerian (ALE) Methods in Plasma Physics, CTU in Prague, CTU0410914.
2003	Arbitrary Lagrangian-Eulerian (ALE) Methods in Plasma Physics, CTU in Prague, CTU0310614.

Research interests

- Computational Physics, Applied Mathematics.
- Conservation Laws, PDEs in multiple dimensions.
- Development and analysis of Arbitrary Lagrangian-Eulerian (ALE) methods for gas dynamics and plasma physics.
- Lagrangian models, mesh rezoning, and remapping algorithms for multimaterial ALE code.
- Applications of ALE methodology in simulations of laser plasma interactions.
- Simulations of laser beam interactions with various targets.
- Analysis of hydrodynamic laser/plasma simulations.
- Multi-material Lagrangian and ALE algorithms.

International collaboration

- T-5/XCP4 Groups, LANL, Los Alamos, NM, USA – Dr. Shashkov, Prof. Wendroff, Dr. Berndt, Dr. Garimella: all aspects of numerical fluid/continuum simulations.
- CNRS/Toulouse University/Bordeaux University, France – Dr. Loubère: material/viscosity models, numerical methods in cylindrical geometry.
- CEA/CELIA/Bordeaux University, France – Dr. Breil, Dr. Maire: hybrid remapping methods.
- IPPLM, Warsaw, Poland – Prof. Badziak: all aspects of laser/plasma interactions.
- MNF, FBK, Trento, Italy – Dr. Picciotto: simulations of high-yield laser experiments.
- Duke University, Durham, NC, USA – Prof. Scovazzi: hourglass control methods.

Pedagogical activities

Since 2013	Supervising 4 students in bachelor study, 3 students in master study, and 2 students in Ph.D. study.
Since 2011	Lectures in Conception of Computational Physics.
Since 2009	Lectures in Methods of Computational Physics.
2004	Exercises in Numerical Methods.
2002-2013	Exercises in Practical Informatics.

Publication activities

- Papers in impacted journals: 31.
- Papers in non-impacted journals/proceedings: 29.
- Presented conference contributions: 38 (2 invited).
- Citations in WoS: 504 (257 without self-citations).
- H-index: 13.

Selected recent publications

- M. Kucharik, G. Scovazzi, et al.: A Multi-Scale Residual-Based Anti-Hourglass Control for Compatible Staggered Lagrangian Hydrodynamics, J. Comput. Phys. 354:1-25, 2018. IF: 2.864.
- M. Klima, M. Kucharik, M. Shashkov: Local Error Analysis and Comparison of the Swept- and Intersection-Based Remapping Methods, Comm. Comput. Phys. 21(2):526-558, 2017. IF: 3.748.
- M. Klima, M. Kucharik, M. Shashkov: Combined swept region and intersection-based single-material remapping method, Int. J. Numer. Methods Fluids 85(6):363-382, 2017. IF: 1.673.
- D. Margarone, A. Velyhan, et al.: Proton Acceleration Driven by a Nanosecond Laser from a Cryogenic Thin Solid-Hydrogen Ribbon, Phys. Rev. X 6(4):041030, 2016. IF: 14.385.
- J. Badziak, M. Rosinski, et al.: Enhanced efficiency of plasma acceleration in the laser-induced cavity pressure acceleration scheme, Plasma Phys. Control. Fusion 57(1):014007, 2015. IF: 3.032.
- A. Picciotto, D. Margarone, et al.: Boron-Proton Nuclear-Fusion Enhancement Induced in Boron-Doped Silicon Targets by Low-Contrast Pulsed Laser, Phys. Rev. X 4(3):031030, 2014. IF: 14.385.
- M. Kucharik, M. Shashkov: Conservative Multi-Material Remap for Staggered Multi-Material Arbitrary Lagrangian-Eulerian Methods, J. Comput. Phys. 258:268-304, 2014. IF: 2.864.
- J. Velechovsky, M. Kucharik, et al.: Symmetry- and Essentially-Bound-Preserving Flux-Corrected Remapping of Momentum in Staggered ALE Hydrodynamics, J. Comput. Phys. 255:590-611, 2013. IF: 2.864.
- M. Kucharik, R. Loubere, et al.: Enhancement of Lagrangian Slide Lines as a Combined Force and Velocity Boundary Condition, Comput. Fluids 83: 3-14, 2013. IF: 2.221.
- M. Kucharik, M. Shashkov: One-Step Hybrid Remapping Algorithm for Multi-Material Arbitrary Lagrangian-Eulerian Methods, J. Comput. Phys. 231(7):2851-2864, 2012. IF: 2.864.