NERS 570 Project Proposal: Laser Scan Thermal Field Prediction

Weihao Liu[*1] and Jun Fan[†2]

[1]*Department of Climate and Space Sciences and Engineering, University of Michigan, MI, USA*
[2]*Department of Mechanical Engineering, University of Michigan, MI, USA*

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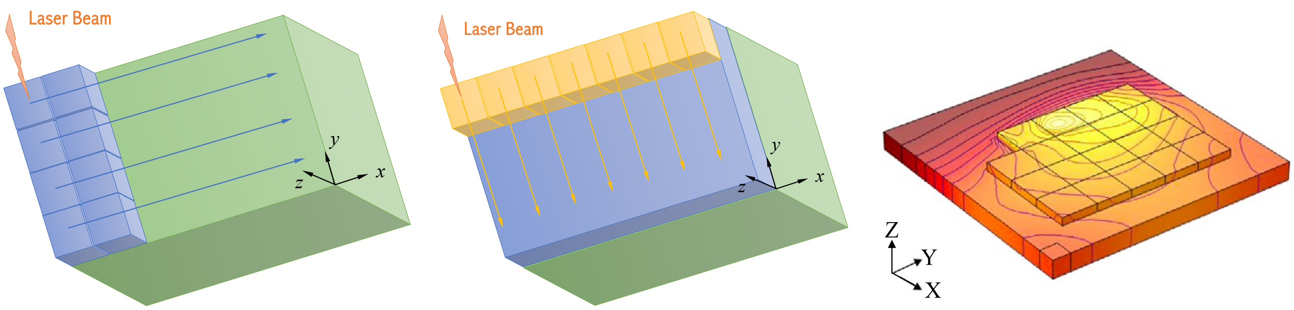
1 Introduction

Laser Additive Metal Manufacturing (LAMM) is at the forefront of technology in the field of additive manufacturing (Gu et al. 2012; Gu 2015). It involves a set of metal additive manufacturing processes that harness high power density of lasers to melt and fuse the metal powder and build the three-dimensional structure layer by layer. Benefiting from its unprecedented geometry flexibility and rapid prototyping capability, LAMM has gained significant traction across various industries including aerospace, automotive, and healthcare. Despite its widespread adoption, many aspects of LAMM are still not fully understood due to the lack of accurate in-situ monitoring techniques. Consequently, numerical modeling stands as an indispensable tool in the ongoing research and development of LAMM processes.



(a) Laser scans along x-axis. (b) Laser scans along y-axis. (c) Thermal field illustration.

Figure 1: Schematic graph for the laser scan thermal field problem: Panels (a) and (b) illustrate how the laser scans over the top surface of the part. The laser scans along x-axis and then y-axis at the next iteration. A thin layer will be piled up along z-axis after each iteration of scanning. At each scan iteration, the laser beam will also heat the surface through radiation and change the thermal field in this material. Panel (c) gives an illustration of the thermal distribution, taken from Ren et al. 2020.

In most LAMM processes, the laser beam scans a predefined pattern layer by layer to construct the desired 3D geometry of the product, as illustrated in Figure 1(a) and 1(b). This multi-layer deposition has a profound impact on the temperature field of the part, leading to the reheating of the printed layers. The reheating cycles in the thermal history can lead to residual stress concentration, micro-defects, and deformation of the printed part. Furthermore, the thermal history is critical to the grain formation during cooling, thus determining the mechanical and electrical behavior of the printed metal material. Therefore, understanding the thermal history during LAMM is essential for predicting product behavior and can assist in improving the manufacturing process.

The Laser scan Thermal Field Prediction (LTFP) project aims to develop a numerical solver to estimate the thermal field resulting from multi-layer laser scan patterns during the LAMM process, similar to

*Email: whliu@umich.edu
†Email: junfan@umich.edu

Figure 1(c). The solver should be able to handle dynamic mesh, temperature-dependent material properties, and complex boundary conditions. Later, the solver will be integrated with an established LAMM model as an upstream module that provides thermal history for micro-structure prediction.

2 Method

The thermal field generated by laser scan is governed by the heat equation:

$$\begin{cases} \dfrac{\partial T}{\partial t} = \kappa \nabla^2 T + q, \\ \text{Initial Condition: } T(x, y, z, 0) = T_0, \\ \text{Boundary Condition for } T(x, y, z, t). \end{cases} \tag{1}$$

with κ being the thermal conductivity of the material, and q being the source term of the laser. Here, we propose to develop the thermal solver by the Finite Volume Method (FVM, Eymard et al. 2000). In the FVM, the computational domain is divided into non-overlapping control volumes with the state stored in each cell, typically the mean value (Thompson 1985). At cell interfaces, we define fluxes that provide information on how much of the state flow in and out of the adjacent cells, which can be applied with specific limiters to avoid numerical oscillations (e.g., Sweby 1984; Leonard 1988).

A simplified algorithm of LTFP is demonstrated in Algorithm 1. After loading the simulation configuration and initialization of the data structure, the main loop advances in time until the end time is marched. Finally, the exported data are visualized for inspection.

Algorithm 1 Solver algorithm

Load simulation configuration: Mesh and boundary condition
Initialize the data structure by the initial condition
$t \leftarrow 0$
$t_{\text{export}} \leftarrow \Delta t_{\text{export}}$
while $t < t_{\text{final}}$ **do**
    Determine time step size Δt
    Perform domain increment
    Compute laser energy distribution
    Solve thermal diffusion equation
    if $t \geqslant t_{\text{export}}$ **then**
        Export mesh and temperature
        $t_{\text{export}} \leftarrow t_{\text{export}} + \Delta t_{\text{export}}$
    end if
    $t \leftarrow t + \Delta t$
end while
Final export and visualize results

The code in this project is designed to be highly object-oriented, with each function module being an independent class object, as shown in Figure 2.

3 Tasks

In the LTFP project, we will first derive the formulas for the numerical solvers, and then construct the framework of the solver using some high-level design techniques. In our code, we will develop the input

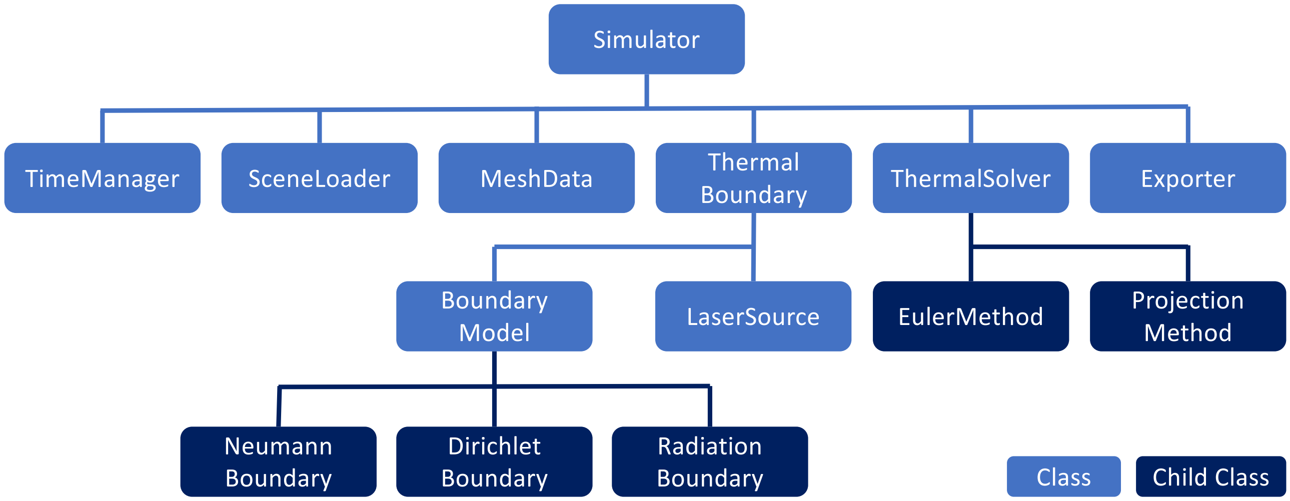


Figure 2: Diagram of class objects in LTFP.

and output loader, mesh and data structure, and the analytical (if possible) and numerical (with low or high order of accuracy), serial and parallelized FVM solvers. During this process, we will validate the solver by having some benchmark tests. The details are demonstrated in Table 1.

Table 1: Task description and assignment

Task	**Description**	**Member**	**Related topics**
Derivation	Derive math formulas for numerical solver(s)	Weihao	
High-level design	Develop high-level design of solver and maintain main function	Jun	High-level design, Object-orientated programming
Pre-processing	Load and save configuration of simulation, initialize class objects and solver environment	Jun	
Mesh and data	Generate mesh and save mesh-based data inclding temperature field	Weihao	Matrix storage
Boundary models	Store three types of thermal boundary model and manage laser heat source	Jun	
FVM solvers	Solve thermal diffusion using multiple types of finite volume solvers	Weihao	Solving linear systems
FVM solver parallelization	Parallelize FVM solvers to increase solver performance	Weihao	Parallel computing using OpenMP
Post-processing	Export data to vtk files and visualize results	Jun	
Validation	Validate solver using benchmark cases	Both	Software development
Documentation	Generate documentation using Doxygen	Both	

4 Project Plans

4.1 Deliverables

For the detailed tasks listed in Table 1, the expected deliverables for each of them are shown in Table 2. We will use the version control tricks on the repository of `https://github.com/Lazy-Beee/ners570f23-LTFP`. Ultimately, we hope to give the numerical solutions for LTFP and see how well our solvers work and predict the thermal field in time.

Table 2: Task deliverables

Task	**Deliverables**
Derivation	Formulas for the numerical FVM solvers
High-level design	UML diagrams and the main function
Pre-processing	Loaders and writers for meshes and outputs, and the ready objects
Mesh and data	Visualized mesh for the tests and actual case
Boundary models	Code and tests for boundary conditions implemented in solvers
FVM solvers	Simulated results by the specific solver
FVM solver parallelization	Parallel code and performance analysis
Post-processing	Animation of domain increment and thermal field
Validation	Comparison with analytical results in benchmark cases
Documentation	Generated documents including reports and presentation slides

4.2 Timeline

To be more specific for each of the tasks in Table 1, here we provide a gantt chart for our schedule as shown in Figure 3, and hope to finish this project by early December.

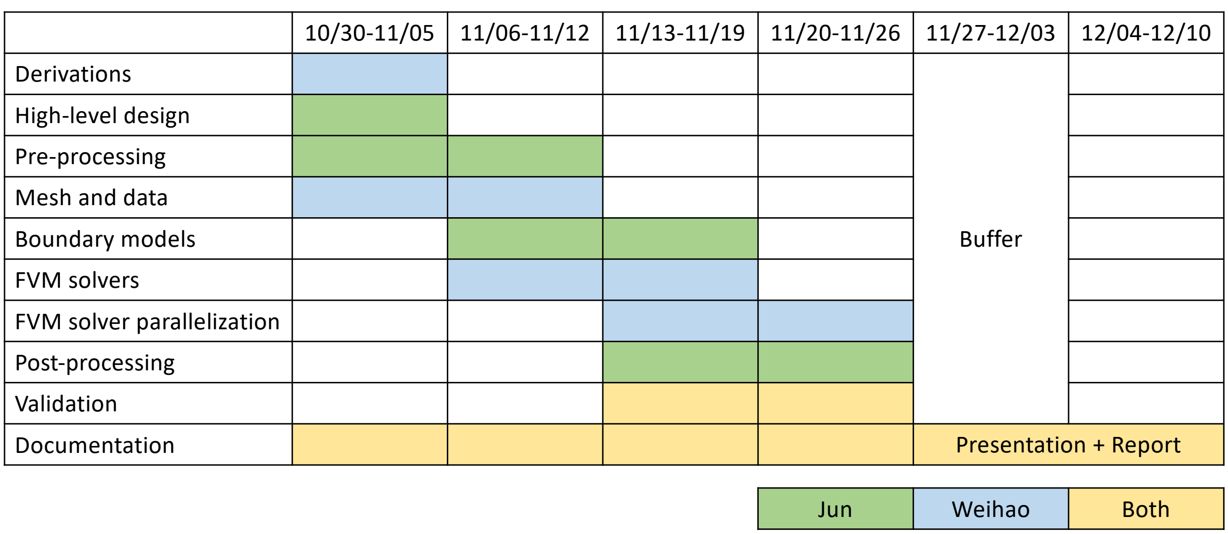


Figure 3: Timeline of this project.

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