AN ADAPTIVE MESHING FRAMEWORK USING OCTREE DATA STRUCTURE FOR VOXEL BASED MESHES

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Abstract

We present an adaptive meshing framework for voxel-based meshes, designed for use in various process simulations for additive manufacturing, such as thermal, distortion, grain growth, etc. The framework uses an octree data structure to represent the meshes, and a coarsening/refinement algorithm to generate coarser and finer meshes. The algorithm preserves a 2:1 ratio of coarse to fine meshes to maintain desired accuracy. Efficient tree traversal is used for fast nodal/Gaussian solution mapping. In many cases, selective element coarsening enables the reduction of the number of nodes to be solved by the iterative matrix solver. To maintain accuracy at boundary, the algorithm can be configured to maintain a certain level of fine mesh at boundary. When part and support mesh touch, they are automatically flagged to be not combined to be coarsened at any stage. Overall, the algorithm enables reduction of solution nodes while maintaining desired accuracy at areas of interest.

Introduction

In the ever-evolving landscape of modern manufacturing, Additive Manufacturing (AM) has emerged as a transformative technology, promising unprecedented flexibility, customization, and efficiency. By building intricate components layer by layer, AM processes have shattered traditional manufacturing constraints, enabling the production of complex geometries that were once thought impossible. However, the realization of this potential relies heavily on a deep understanding of the intricate interplay between virtual design and real-world production—a challenge that has brought forth the crucial role of simulation.

Simulation of additive manufacturing processes involves making various assumptions and cast the physical process into a form that can be manageable numerically and programmatically. There are multiple approaches of doing this involving varying levels of assumptions and accuracies. Particle-based simulations with µm scale phenomena delve into the intricate dynamics of powder particles during the initial stages of additive manufacturing, typically at the micrometer scale [1]. These simulations aim to model the behavior of individual particles, including powder flow, melting, and solidification. While offering high accuracy by capturing fine-grained powder interactions, they come at the cost of computational intensity. On the other hand, simulations that start with solidified material at the micro-level and solve each laser scan line focus on modeling the interaction between the laser and the material to predict thermal and mechanical effects accurately [2]. These methods, while faster than particle-based simulations, can still be prohibitively slow and computationally intensive to get a part level solution. Hatch-by-hatch coupled thermo-mechanical lumping divides the build process into discrete segments similar to laser hatches and considers thermal and mechanical interactions within each hatch [3]. While these methods are still very accurate they are not significantly faster than micro-level thermos-mechanical simulations. Layer-by-layer coupled thermo-mechanical lumping with total laser power flashing extends the simulation to a layer-by-layer analysis, taking into account the cumulative effect of multiple scan paths [4]. Total laser power flashing considers the heat input over an entire layer. This approach enhances accuracy by incorporating more build details while retaining computational efficiency by lumping within each layer. It is valuable for comprehensive analysis of part quality. For a more rapid assessment, instead of doing a coupled thermo-mechanical analysis, there are approaches [5] which assume a fixed strain for a lumped layer and perform a mechanical simulation to obtain the final distortion and residual stresses at macro scale part level.

Many of these approaches, especially involving part level simulations require a finite element mesh with enough resolution and quality. Since the laser melting phenomenon and the subsequent solidification phenomenon occur at a micro-scale the resolution required to capture this spatio-temporal process is very high and challenging. To solve this problem to an extent voxel based meshes provide an accurate three-dimensional grid structure that can faithfully capture the intricacies of these complex geometries. Additively manufactured parts often feature intricate and complex geometries, including internal voids, overhangs, and lattices. Voxel based meshes allow for a direct representation of the digital model in a way that maintains geometric fidelity, ensuring that simulation results are as close as possible to real-world outcomes. In view of these advantages voxel-based meshes have gained popularity in AM simulations for many types of approaches discussed above. One challenge with voxel-based meshes is the amount of resolution to capture feature geometry is very high which will result in a significant computational cost. It is very hard to approach a balance of mesh resolution, solution time and accuracy. Considering this, it is desirable to employ adaptive meshing that simplifies portions of the geometry when temperature, stress, or distortion exhibits limited variation. Combining neighboring voxels into a bigger voxel and mapping the solution variables to the new mesh element(voxel) is a known approach. In this paper we discuss an approach to achieve this in an automated fashion which is numerically efficient and gives accurate representation. Octree data structure and algorithms have been employed to implement this. The method preserves geometric boundaries to have the original fine mesh. It keeps the neighboring elements to not more than one level coarser. We also discuss the underlying assumptions and accuracy preserving features. It also shows the necessary controls to preserve the geometry and correct for local variations.

Octree data structure for mesh encoding

An octree-based data structure is a hierarchical representation commonly used for managing spatial data and traversing three-dimensional space in an efficient manner [6]. The current method starts with a fine mesh with desired resolution for accuracy purposes. It then begins by considering the whole geometric domain with voxels as a single parent element/node of a tree structure. This parent node is divided into eight spatial elements/nodes called octants. Now, each of these further divided into another eight octants. This process is repeated until the smallest octant is equal to the original voxel size. During the sub-division process the parent child relationship is encoded into data structures. Also, when one octant encompasses a volume which doesn't contain any voxel belonging to the original geometry it is kept from any more sub-division. An example of this idea is illustrated in Fig. 1 in a simplified 2D structure comprising of quadtrees instead of octrees but are very similar in nature.

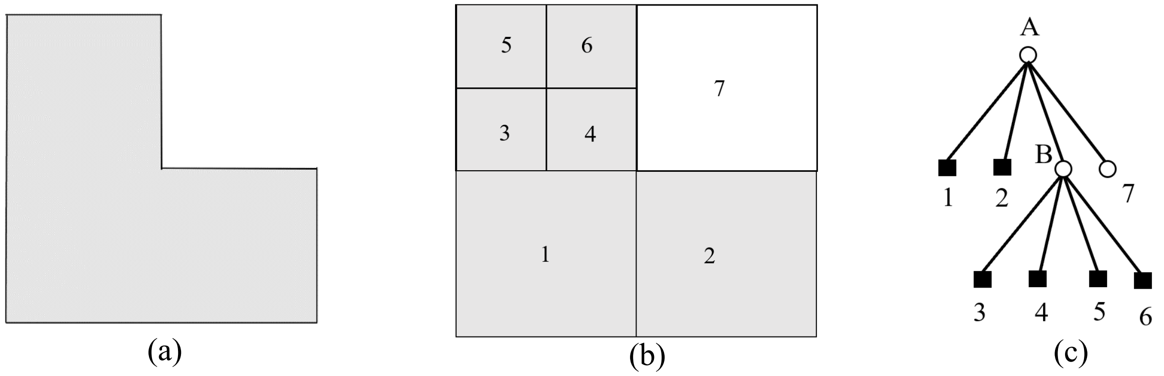


Fig. 1 a) original geometric domain; b) quadtree representation of the original geometry; c) related tree representation of the quadtree divisions

The resulting data structure will have mesh elements at leaf nodes of the tree structure. Some of the leaf nodes might, which are marked as hollow in Fig. 1 are not part of the geometry but are there for completeness of the octree structure. An example of a smaller resolution 3D mesh and corresponding octree is shown in Fig. 2.

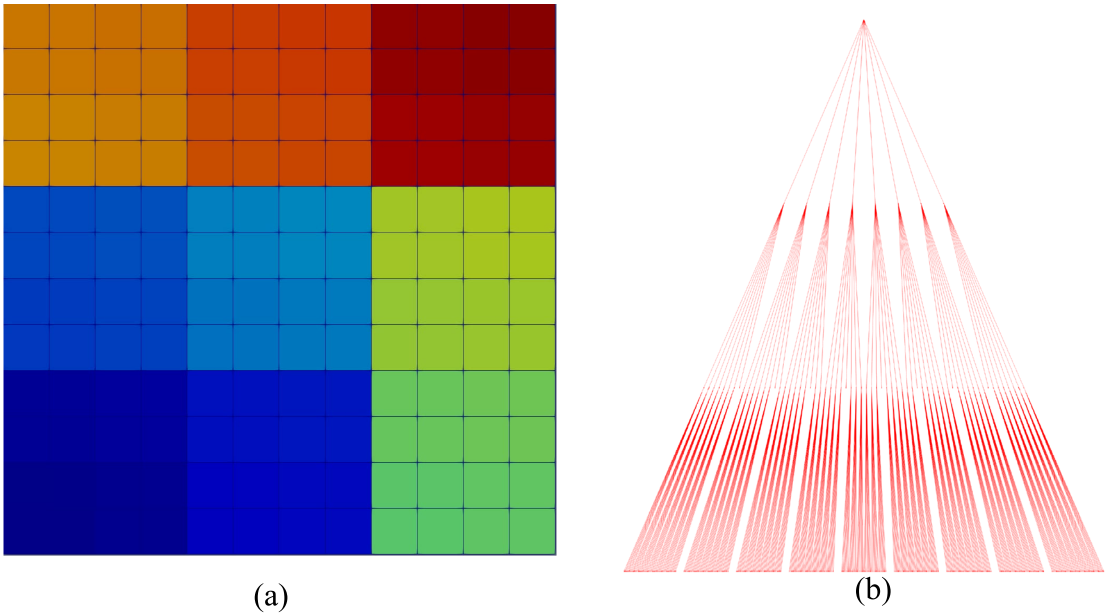


Fig. 2 a) Original geometric domain with color coding of octants; b) octree representation of the original geometry divisions

Since, the octree representation starts with a voxel mesh and voxel meshes are easy for manipulation when compared to unstructured meshes due to their inherent ease in combining smaller elements into larger ones within a given neighborhood, and vice versa. This versatility in element manipulation is further enhanced by the implementation of octrees, which provide a structured and efficient means of achieving such operations, see Fig. 3. The octree data structure serves as a key component in this context, offering a systematic approach to creating hierarchies of mesh elements.

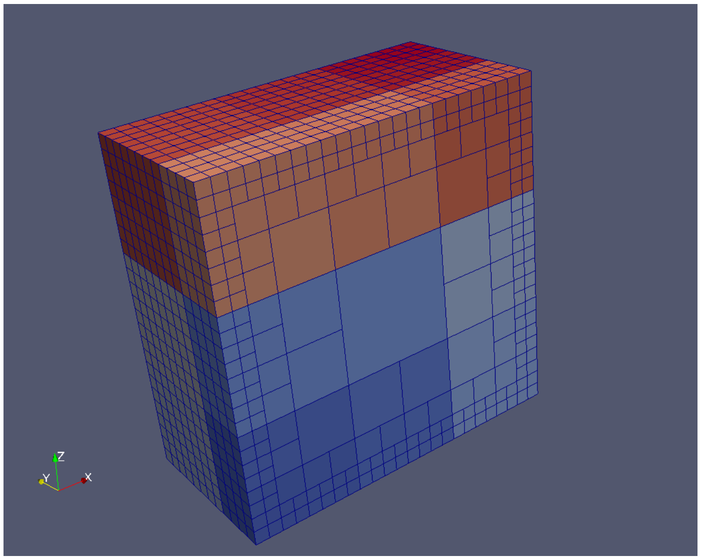


Fig. 3 Pattern mesh structures coarsened in a gradiated manner using octree data structure.

This hierarchical organization enables effortless collapsing and expansion of mesh components as needed. The octree's regularized framework ensures that the mesh retains its structural integrity while undergoing refinement or coarsening, see Fig.4. Parsing the geometric information into an octree-type data structure brings about significant benefits in terms of geometric manipulation. With this structure in place, traversing through the geometry becomes remarkably convenient, allowing for precise access to specific locations that may require coarsening or refinement. This combination of voxel meshes and octrees streamlines the process of mesh manipulation, facilitating the efficient adaptation of mesh elements to meet various computational needs.

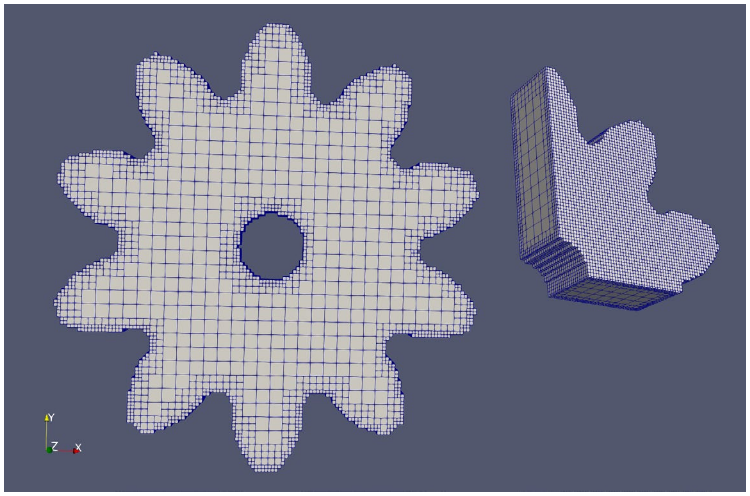


Fig. 4 Geometric integrity maintained during coarsening using octree data structures.

Additive Process Simulation Considerations

One of the most critical factors influencing the success of numerous additive manufacturing process simulations is the precise localization of laser power or energy. This phenomenon plays a pivotal role in determining the quality and integrity of the final result. In the context of scan-line-based simulations, it becomes evident that solution variables are particularly sensitive to the mesh arrangement surrounding the path of the laser beam. To accurately capture the thermal gradients, as well as the consequential locked-in residual stresses and distortion, it is imperative to employ a very fine mesh in the vicinity of the laser beam. This fine mesh ensures that the laser's energy deposition is faithfully represented in the simulation, thus allowing for a more realistic and predictive modeling of the additive manufacturing process. Similarly, in the case of layer-by-layer simulations, where laser power lumping is employed to model entire layers, a high-resolution mesh becomes vital around the uppermost layers. These upper layers, situated close to the rapidly solidifying molten material, require a fine mesh. This level of resolution is essential to accurately capture the thermal dynamics at play, ensuring that the simulation results exhibits the desired outputs verifiable with experimental results.

However, it's not only the laser power's localized effects that demand careful consideration. The boundary surfaces of the geometry also undergo significant transformation, experiencing distortions, thermal signatures, and residual stresses. Consequently, maintaining an adequate mesh resolution along the boundary surfaces is equally vital. This ensures that the impact of the additive manufacturing process is faithfully reflected in the simulation, allowing for a comprehensive assessment of the final product's quality and structural integrity.

Balancing these intricate requirements, we find that there is room for mesh coarsening in areas of the geometry that lie further away from the laser beam path and the boundary surfaces. By intelligently optimizing the mesh structure using octree data structures, we can efficiently achieve the necessary mesh refinement where it matters most while economizing computational resources in regions less critical to the simulation. This work demonstrates the efficacy and speed with which octree data structures can address these multifaceted considerations. Some of these above discussed considerations are depicted in Fig. 5.

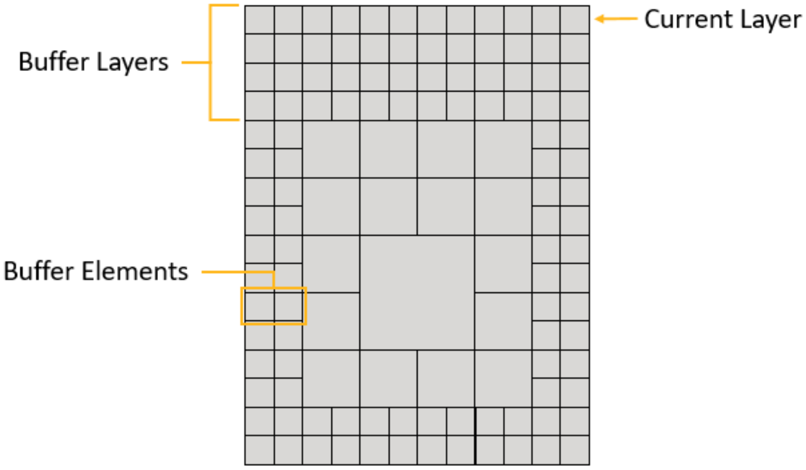


Fig. 5 Additive process simulation related considerations reflected in coarsening with octree: Fine mesh elements are maintained at top layer vicinity and boundary element vicinity.

Another important consideration for finite element mesh during mesh coarsening is the introduction of hanging nodes are elements faces and edges, see Fig 6. It is important to maintain a 2:1 element size ratio between neighboring elements to maintain non-linear material evolution around these boundaries. Fig. 7 shows undesirable neighboring elements with excessive hanging nodes. Another side effect of excessive hanging nodes is the stiffness matrix rank degradation which results in slower convergence of iterative equation solvers generally used in finite element (FEM) simulations.

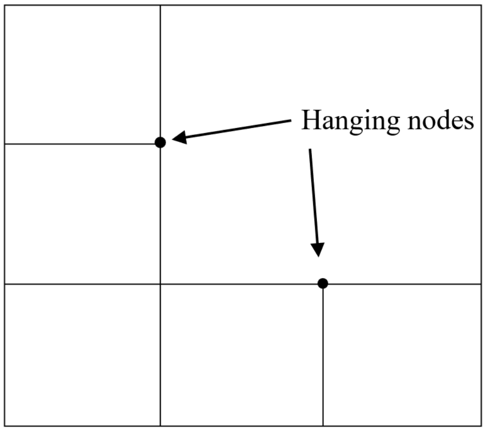


Fig. 6 Coarsened elements with hanging nodes maintain 2:1 ratio.

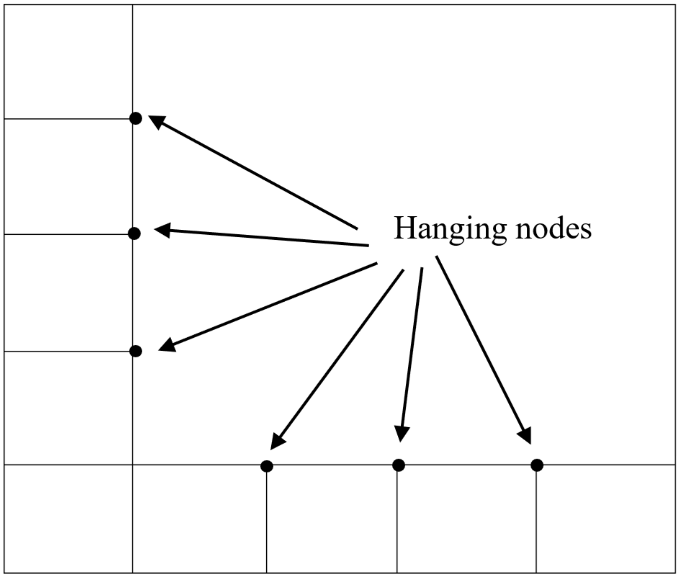


Fig. 7 Excessive coarsening resulting in undesirable hanging node pattern.

During the process of mesh refinement, a crucial step involves transferring solution variables from the old mesh to the new mesh. This transfer is essential for maintaining a continuous record of the material point's temporal evolution, and its significance becomes particularly pronounced in non-linear finite element method (FEM) simulations. In our work, we've leveraged the 2:1 ratio-keeping principle to streamline this mapping process, significantly enhancing its speed and efficiency. This principle comes into play because, as we transition to a coarser level of mesh, the Gaussian points where material point calculations occur are situated in close proximity. This proximity allows us to simplify the transfer of material point values to the new coarser mesh. Essentially, we achieve this by directly copying material point values from the nearest neighboring old material points. This seamless association of nodes, critical for maintaining the continuity of solution variables, is efficiently facilitated through the use of the octree data structure. The octree data structure allows for an easy establishment of parent-child relationships between the old and new elements, ensuring that the material point values are accurately transferred, and thus, enabling the preservation of essential temporal information throughout the mesh refinement process., see Fig. 8

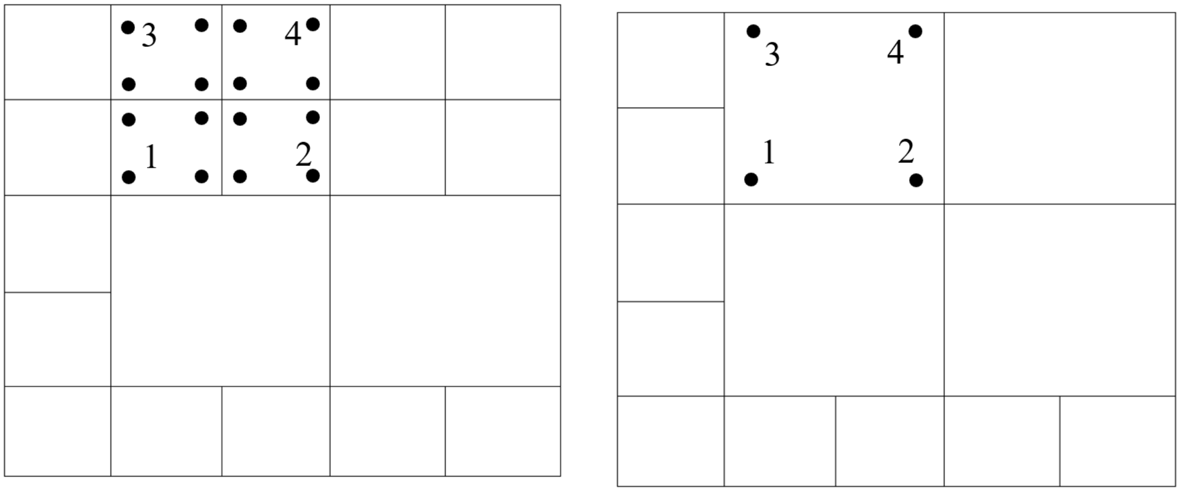


Fig. 8 Material point association between old and new mesh

Example

To demonstrate the above discussed considerations, we use an example to showcase the various aspects of achieving a coarse mesh which keeps the required accuracy at the desired location in the geometry. In Fig. 8 we take a typical geometry built using additive manufacturing and get a fine mesh representation of the domain. During the layer-by-layer build process various coarsening can be started after building a certain number of layers to reach a steady state in the bottom layers. In this case we started coarsening at layer 50 and did a couple of more coarsening steps at layer 60 and layer 70. We can see in Fig. 9 that the total number of elements reduces rapidly on the first coarsening and only reduces slightly on the second and third coarsening on those given layers. So, it is important to choose the start layer for coarsening and the mesh coarsening frequency. This example also demonstrates the earlier discussed aspects such as the 2:1 neighborhood, boundary fine mesh and top layer fine mesh arrangement.

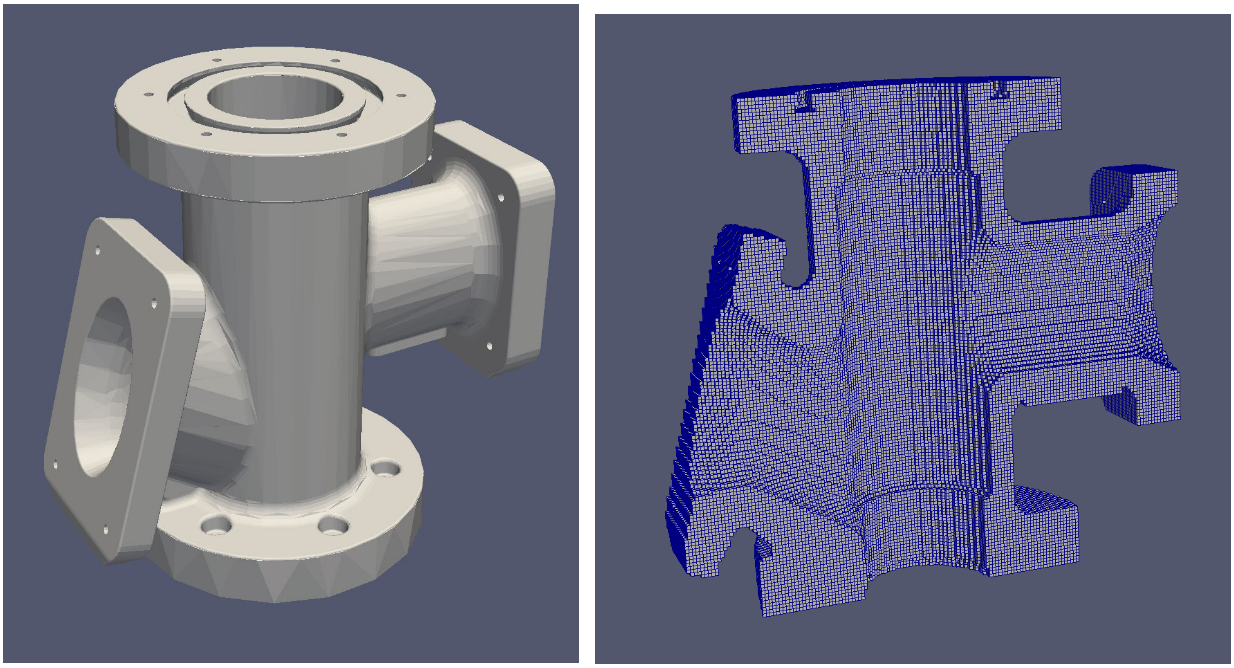
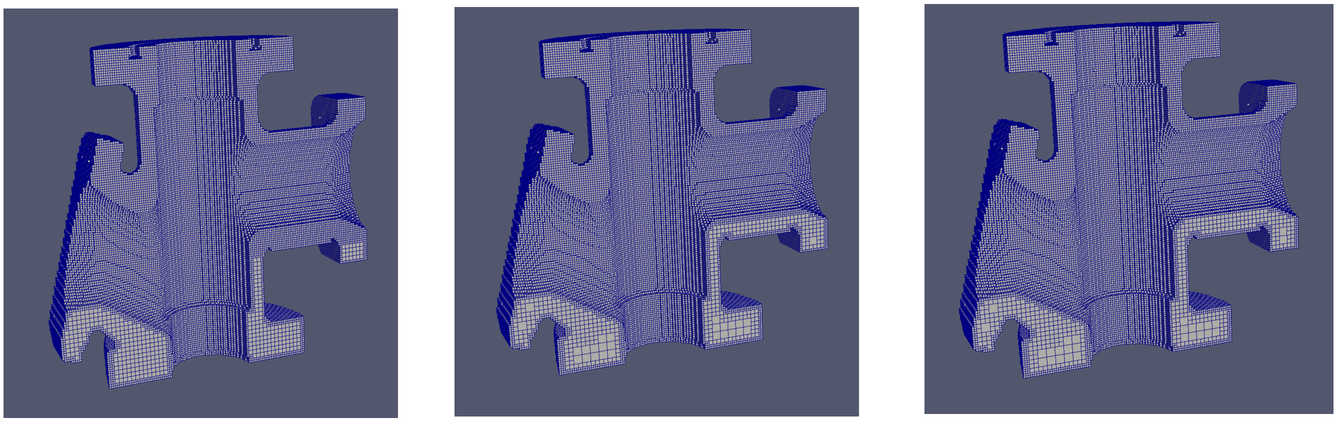


Fig. 8 AM geometry and its voxelized representation with 515,799 elements



(a) First coarsening at layer 50 – 408,846

(b) Next coarsening at layer 60 – 388,770 elements.

(c) Next coarsening at layer 70 – 372,243 elements.

Fig. 9 Mesh coarsening at layer 50 and subsequent coarsening at layers 60 and 70 of above example geometry.

Conclusions

In summary, the field of additive manufacturing and simulation has seen remarkable progress, with layer-by-layer inherent strain and coupled thermo-mechanical simulations gaining widespread recognition. Central to the success of these simulations is the adoption of voxel-based meshes, which excel in accurately discretizing complex geometries. The seamless integration of voxel meshes into octree data structures further enhances their versatility, enabling efficient mesh manipulation to achieve precise resolution where it matters most. The localized nature of phenomena in many additive processes underscores the significance of tailored mesh refinement. Octree-based voxel meshes prove indispensable, offering computational efficiencies and streamlined data storage solutions. The incorporation of a parent-child relationship between old and new elements effectively addresses non-linear material evolution, ensuring the fidelity of simulations to real-world dynamics. The concept of geometry-specific refinement, achieved through strategic buffer elements, enhances the precision of simulations. Lastly, the strategic selection of remeshing points within the build process emerges as a critical factor, directly influencing both efficiency and accuracy.

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