Progress on different topology optimization approaches and optimization for additive manufacturing: a review

Tianxia Zhan*
School of Aeronautics & Astronautics, Purdue University, West Lafayette, United States 47906
*Corresponding author e-mail: zhan46@purdue.edu

Abstract. The progress of topology optimizations for the last decade has been reviewed based on the five main methods mentioned in Sigmund’s article in 2013: density, level-set, topological derivative, phase field, and evolutionary. The recent progress is mainly focusing on methods originated in density or level set method, with an inclination of combining them with the evolutionary method. The methods developed have a large number of applications, yet certain issues, e. g., guaranteeing the convergence of the results generated through evolutionary methods need further investigation. Besides, those studies specifically targeted for the optimization and designing for additive manufacturing are also discussed, as well as the ideas and guidelines for those designs. It is recognized that in order to cope with additive manufacturing, it is necessary to modify existing structures for the application of lattice structures and the reduction of support structures. Moreover, the introduction of the idea of designing for additive manufacturing (DfAM), as well as efforts to make the end-users understand and familiarize themselves with the dramatic differences in designs, are also desired changes that need more efforts to be applied on.

1. Introduction

Ever since the idea of topology optimization was developed in 1989 by Bendsøe, there has been a significant leap in terms of methods and approaches used for optimizing the design. With the growing computing capabilities as well as fabrication methods like additive manufacturing, multiple design methods have been developed to find out the optimized way for optimization. In 2013, Sigmund made a review on how different approaches have developed over time, which served as a reference and guidance for the oncoming development in topology optimization.

According to Sigmund’s article, there are five different major optimization approaches that have been developed over time. Those approaches include, but are not limited to methods of density, level set, topological derivative, phase field, evolutionary, etc. [1]. Over the last decade, a variety of attempts have been made for each of those individual methods. Besides, with the advance in manufacturing technologies like additive manufacturing, there have been opinions that the ideology and methodology of topology optimization should be adjusted to cater to the need for the development of novel manufacturing methods.

In this review, the progress for each of those five approaches mentioned in the Sigmund’s paper over the past decades has been studied in a variety of ways and aspects. In addition, the studies for optimizations targeted for additive manufacturing as well as methodologies like the design for additive manufacturing (DfAM) will also be discussed.
2. Methods

2.1. The density method

The density approach is one of those methods that were developed early. First raised by Bendsøe in 1989 [2], it is a method that made removing the discrete characteristic of modeling the space into various points by utilizing a continuous density function. From a mathematical standpoint, this method provides a mathematical way to find out the characteristic of the structure and the outcomes of this method are reasonably well for simple, idealized models with limited variation in characteristics inside. However, as a method developed in the beginning, there are a few areas in which the method does not perform as it is expected. For instance, according to the Xia [3], with degenerated materials, the density-based methods are not capable of handling the singularities points with the continuous density function. To represent the structure in those regions, other articles suggested that some specific methods may be applied according to varying characteristics. According to Brackett [4], for the sake of optimizing the structures of those areas with intermediate densities, there are a couple of methods that are applicable. Those methods include solid isotropic material with penalization (SIMP), small lattice structure with varying volume fraction, utilization of multiple materials either as composites or regions that are not continued, etc.

There have been various studies in specific areas of the density method. By utilizing the variable density method, Li’s team was able to carry out topology optimization for truncated cone insulators with graded permittivity [5]. By utilizing the variable density method for topology optimization as well as finite element analysis, the team was able to demonstrate through Figure 1 below that the E-field uniformity of the insulator has been improved significantly and the distortion of the HV triple junction was relieved, leading to the conclusion of obtaining a better E-field distribution.

![Figure 1. Comparison of (a) bulk and (b) surface E-field distribution before and after optimization [5]](image)

The density method also found itself significant in some specific designing aspects. As the industry moves to combine topology optimization with additive manufacturing, the importance of designing an overhang-free structure as well as overhang-free topology optimization is being studied more. According to Liu [6], all those methods of achieving topology optimization for overhang-free structures, e. g., post-treatments, still fall into the category of density-based methods and are being developed under
this framework.

In the aerospace industry, there have been several cases of density-based methods’ utilization. According to Zhu [7], the conceptual design of the Airbus A350 was obtained using the standard topology optimization module from SAMCEF with the maximum material usage assigned as 10%, as shown in Figure 2 below. Still, this only gives material in concept and it needs to go under further design and modifications for practical engineering applications.

![Figure 2. Topology optimization results of Airbus A350 pylon [7]](image)

2.2. The level set method

The level set method was raised at the same time period as the density method. First mentioned by Osher and Sethian in 1988 [8], the level set method mainly focuses on defining the boundary of an object using a zero-level contour of the level set function. The main difference between this method and the density method is that it doesn’t require writing the moving surface as a function. There have been a couple of level set methods developed for optimization, with each of them having different models for optimization. In spite of that, according to van Dijk [9], the density-based methods and level set methods are blending in with each other over the past decades.

Those methods can be summarized and sorted into several different categories. Those categories include level-set-function parameterization, geometry mapping, the physical/mechanical model, the information as well as the procedures to update the design and the applied regularization. As for the challenges and drawbacks of the level set method, van Dijk [9] suggested that, as a consequence of the shape optimization character of level set methods, those methods are vulnerable in terms of tackling local minima and their final results depend heavily on reasonable initial guesses. At the same time, those results rely heavily on regulation techniques, and the convergence behaviours of the results are still considered as one of the challenging parts of utilizing this method.

In terms of applications, there are a couple of methods that have been studied into. According to Picelli, a method that could be used to tackle minimum stress, stress constrained shape, and topology optimization problems has been studied and developed. It is confirmed that this method, through solving every iteration for optimal boundary velocities, has great efficiency for different load cases and capable of getting solutions with smooth boundaries. Meanwhile, according to Picelli [10], it was one of the first in level set methods to demonstrate more than one load case and different stress criteria in various design domains. Another research that was done by Wang [11] mainly focuses on an approach to structural topology optimization through representing the boundary by a level set method that is within a scalar function of a higher dimension. It is stated that with this particular approach, the level set methods are flexible in terms of handling complex topological changes and are capable of having high describing accuracy for the boundary shape.

In addition, there are also studies focused on very specific scenarios and constraints. For instance, there are studies carried out under the specific Drucker-Pager stress constraints. Amstutz [12] has developed an optimization algorithm for elastic structures under plane stress in such stress constraints, which is also based on a level set representation of the structural domain and topological derivative of the associated objective. With the algorithm, Amstutz made different trials with different structures for optimization. In one of the examples, as shown in Figure 3 and Figure 4, for a bridge in a 180 m long and 60 m high domain, the algorithm was able to generate the optimizations in 16 and 13 iterations in unconstrained and constrained case respectively, which a proof of the algorithm’s great efficiency. Both
outputs were deemed reasonable as the unconstrained case resulted in a tie-arch-shaped bridge design while the constrained case output was optimized more towards utilizing the full potential of the material’s compressive strength [12].

![Initial bridge design and boundary conditions](image1)

**Figure 3. Initial bridge design and boundary conditions [12]**

![Optimized design under (a) unconstrained and (b) constrained conditions](image2)

**Figure 4. Optimized design under (a) unconstrained and (b) constrained conditions [12]**

2.3. The topological derivative method

The topological derivative is introduced a few years later than the previous two methods by Eschenauer in 1994 [13]. Originally named bubble-method, the basic idea of this method is to first introduce an infinitely small hole in the design domain. After that, it is used as the starting point of larger holes and thus the behavior of this hole as well as the influence of this hole on the entire structure can be predicted using mathematical methods, paving the road for creating new holes to optimize the existing structure. According to Eschenauer [13], a new hole would be added to the existing structure after one iteration with the choice of iteration number following the external demands like restrictions and possibilities of manufacturing. This part is indeed a dominant restricting factor by the time this method was first raised. But as there are processes like additive manufacturing that enhanced the industry’s manufacturing capabilities with a revolutionary leap, possibilities of manufacturing are rarely a demand for construction in this scenario.

In addition, Sigmund stated that the topological derivative has a strong connection with other methods mentioned previously. He [1] stated that in 2D scenarios, in order to develop the optimum topology, the level set methods must be combined with topological derivatives. In recent years, there are hybrid approaches developed. One example is developed by Yamada in which the level set boundary expressions were incorporated with the phase field method. The method was tested that the proposed hybrid method was capable of obtaining a smooth and clear optimal configuration that is capable of controlling the geometrical complexity of the optimized configurations. Moreover, those optimized configurations, according to Yamada [14], does not depend on original size or configuration.

2.4. The phase field method

The phase field method is an approach that is directly dealing with the density variables. According to Sigmund [1], this approach has a very close relationship with the level set methods using ersatz material and simplified isentropic material with penalization (SIMP). In addition, it is even more difficult to differentiate those methods when a new marching scheme is used during the update of the design, such
as the Hamilton-Jacobi or the Cahn-Hillard equation. One instance of such research is done by Takezawa [15], which focuses on phase field method and sensitivity analysis. Takezawa proposed a new method that has the same capabilities as the level set method incorporating perimeter control functions. In this method, the phase field design function, which is defined in the design domain, represents the structural shape. Besides, the optimization process is done by using a time-dependent reaction diffusion equation. The method was testified using 2D and 3D cantilevered examples, perimeter control models as well as the application of a force inverter and a gripper, as shown below in Figure 5, 6, 7, to show that the objective functions have converged in all those cases.

![Figure 5. Design domain of the gripper test case [15]](image)

![Figure 6. (a) Optimization result and (b) deformed shape for the gripper [15]](image)

![Figure 7. Convergence history of the objective function for the gripper [15]](image)

In addition to the benefits mentioned previously, Takezawa [15] has discussed some of the drawbacks as well. One major drawback is that the perimeter control effect, which is the mean curvature motion of the diffuse interface, is not being able to be canceled entirely. The other major drawback is that there is still a dependence on the initial shape. However, Takezawa stated that it could be solved either by introducing topological derivative into this method or create the initial shape using topological optimization.

2.5. The evolutionary method

Although a variety of methods have been developed since the start of the topology optimization idea, most of those methods are good at solving relatively simple models, but not good enough when it comes to industrial-level design optimizations. According to Rozvany, even though methods like topological-
derivatives based and level-set based methods showed tremendous promises, they haven't reached the stage of regular industrial applications as of 2009 [16]. Therefore, a new method is needed for more complex industrial designs.

In recent years, with the growing computing capabilities and structure complexity, the evolutionary method is being researched more frequently than ever. With the idea of having the design in a continuously evolving state, it was first introduced in 1993 for structural optimization, known as Evolutionary Structural Optimization (ESO) at that time. For each of the optimization iteration, a finite element analysis is carried out with a rejecting criterion already set. The material of those elements satisfying the removing criterion will be removed. Such analysis and rejecting of material are continued until a steady state is reached and this method was originally developed to resemble those optimization processes of natural structures following the evolution path [17]. The evolutionary method can be classified as part of the so-called discrete approach, which all has the characteristics of being extremely sensitive to changes of the parameters [1]. Also, the evolutionary methods are much more straightforward due to their essence of removing the parts and elements that have the lowest strain energy in the initial design.

In addition to the comments above, there are other views about the evolutionary method. Munk has divided the field of structural topology optimization into two main parts: gradient based, and non-gradient based. Gradient based methods rely on deriving mathematical models to calculate the sensitivities of the design variables, while non-gradient based methods rely on removing or including materials using a sensitivity function [18].

There are a couple of issues with this method as well. The first one is that since every element that has the lowest strain energy in the initial design would have to be removed, it is a demanding task for the computing capabilities and the efficiency of the algorithm. One other problem is, according to Sigmund [1], is that there is a lack of algorithmic convergence and selection of appropriate stopping criteria, and the likelihood of generating a result that is non-converging is also higher for those approaches that are discrete or close to discrete. A degenerated structure may be a good stopping case in the early days, but this is no longer the case since the stopping criteria nowadays are whether the results have achieved desired volume fraction.

So far, there have been a couple of application cases for the evolutionary method over the last decade. Abdi’s research [19] has looked into the geometrically non-linear structures by utilizing the Iso-XFEM method. The Iso-XFEM method is an isoline/isosurface way to represent the design boundary. Within this approach, the design domain is first defined and characterized using the void, boundary, and solid phase. Later, the XFEM, or extended finite element method, is utilized to make three corresponding elements in the design space. In terms of the boundary element, solid nodes of the boundary element are used to define the solid domains and different decomposition approaches were used to deal with those solid elements lying on the boundary with different shapes. For the optimization iteration, the algorithm first proceeds until the desired volume fraction is achieved. The desired volume fraction for the current iteration, according to Abdi, is given by [19]

$$V_{it} = \max\left(V_{it-1} \cdot (1 - ER), V^C\right)$$

(1)

Where ER is the volume evolution rate and $V^C$ is the specified volume constraint. Following that, the volume fraction is fixed while the iteration carries on until the changes in objective function in the last five iterations are within the specified tolerance. This method was tested using a nonlinear cantilever beam and a slender beam. In both cases, the Iso-XFEM method benefited from the non-linear evolutionary modeling, but a significant increase in computing time for the non-linear modeling was also mentioned, as shown in Figure 8 and Table 1 below.

Figure 8. Test case used [19]
Table 1. Time cost differences for linear modeling and non-linear modeling [19]

|            | Iterations | Time (s) |
|------------|------------|----------|
| Linear     | 100        | 3020     |
| Non-linear | 100        | 15895    |

Moreover, Kunakote [20] had researched into the application of multi-objective evolutionary algorithms for topology optimization. For this research comparison, all the methods were based upon the ground elements filtering techniques and various evolutionary optimizers were used for solving four multi-objective optimization problems. The results showed that the PBIL is an efficient method for multi-objective topology optimization with the potential of further performance improvements through methods like including the multi-resolution design variables.

3. Optimization for additive manufacturing

In recent years, with the development in techniques like additive manufacturing, topology optimization has been orienting toward adapting and designing for additive manufacturing. This is largely due to the fact that with additive manufacturing, the manufacturing capabilities have been increased by a huge margin and most of the design restrictions for traditional manufacturing techniques no longer exist or do not matter as much as it once was. Therefore, there have been researches with increased design complexity and new ideas for optimize existing designs as well as optimize designs from the scratch.

3.1. Application of lattice-based structures and materials

One aspect of the topology optimization that involves this increased design complexity is the introduction of lattices and lattice-based materials. This kind of structure was introduced to imitate the existing natural structural patterns, which have already been optimization for thousands of years through the process of natural evolution to enhance the structural properties and reduce weight. Over the last decade, there have been a significant amount of studies focusing on the characteristics and applications of substituting solid material elements with lattice structures.

For instance, Cheng’s group has been studying how coupling the lattice structure with the design-dependent structure would impact the heat conduction design that is fabricated through additive manufacturing [21]. Within the proposed method, the parametric level set methods are implemented first to define the feature geometry and thermal boundary conditions. With a sensitivity analysis for several examples, the team was able to prove the significant increase in performance of the structure comparing to the traditional level set methods. Besides, the accuracy of the results was proved through full-scale simulation, as displayed in Figure 9, showing that lattice structures have great potential for heat transfer, including natural convection and forced convection.

![Figure 9. Full-scale simulation results for (a) concurrent optimization; (b) LSTO result with fixed cooling channel layout; (c) no optimization [21]](image)

There are studies focusing on mesostructure as well. In Wang’s article [22], a design method targeted for graded lattice structures is mentioned. In this case, two cantilevered beams were optimized and fabricated for testing. The testing shows that the optimized design can provide a 24% higher stiffness than the uniformed beam, as shown in Figure 10. In addition, it is stated that there are no difficulties in terms of extending this method for more complex designs. However, there should be attention to
fabricating those parts as the removal of supports used for manufacturing those design may lead to unwanted distortions, which could be solved through the utilization of methods like making the design free of support or optimize the design parameters.

Figure 10. The load-displacement curve for experimental verifications of UM beam and GM beam, in which shading regions stand for ranges of deviation analysis [22]

As the lattice structure is mainly utilized in metal additive manufacturing and implantation of structures like metal alloy foams, there are a variety of researches that are specifically focusing on the optimization for metal additive manufacturing. This is especially critical for industries like aerospace due to the increased attention on materials like the Ti-6Al-4V alloy due to its combined strength, fracture toughness, low density, low coefficient of thermal expansion, and high corrosion resistance [23].

For implementations, Hussein’s team [24] has developed a new structure to tackle the issue of support structures in metal additive manufacturing. During the experiment, two types of lattice cell structures, diamond and gyroid, were tested for their suitability. The results showed that it is possible to restrict the gyroid lattice structure at 8% of the relative volume while still being able to fabricate the design through metal additive manufacturing, as shown in Figure 11. This means minimum material and build-time are required for the support structure. Hussein also mentioned that in order to achieve a viable design, the struts of the support structure must be thick enough to prevent fragility from happening in the fabrication process. Meanwhile, cell sizes must be controlled in a reasonable region to prevent distortion.

Figure 11. The geometry of the cantilever part and lattice support structure [24]

There are also researches focusing on the graded lattice structure. Cheng’s team has looked into the methodology of designing graded lattice structures under stress constraints to generate structures that are light in weight yet predictable in yield performances [25]. The team utilized asymptotic homogenization methods to achieve the effective elastic properties with a fourth-order polynomial for fitting the curve within the density range. For the numerical analysis, two examples, one L-bracket and a three-point bending beam, were used for testing and the results showed that the optimized yield loading fell into the band of the load-displacement curve. That is to say, the proposed homogenization model can be utilized efficiently for enhancing both the elastic and plastic properties of the design.
3.2. Design for additive manufacturing (DfAM)
With the development of optimization as well as the technologies available for additive manufacturing, the need for exploiting the full potential of additive manufacturing is becoming more and more critical. Thus, the idea of designing for additive manufacturing (DfAM) is on the rise. This method requires jumping out of the existing design and rethink how should people carry out the design from the scratch. This is largely due to the fact that with additive manufacturing, people need to think differently to make their design catered towards the unique characteristics of additive manufacturing in order to unleash its full capabilities. A workshop held by NSF has identified that people in academia, industry, and government need to have the design practices and tools that are able to leverage the design freedom enabled by additive manufacturing [26]. In addition, François claimed that in terms of additive manufacturing, creativity is often limited by the cognitive barrier implemented through the long-time experiences in traditional manufacturing. Therefore, for specific parts like microwave parts that could not have operating performances if manufactured layer by layer, it is required to start the design over to produce the additive manufacturing optimized part [27].

There are some proposals about how people should do and keep in mind during the redesigning phase as well. For instance, Montero mentioned that by following a function-driven approach, the optimized products are light, cheaper, and faster to fabricate. It is also mentioned that for specific industries like military maintenance, customers may be conservative and prefer the 'previous' product if the original product can already do what they need. This inclination is especially obvious when the optimized product is dramatically different than the previous one and due to the rigid standard of military maintenance [28]. Therefore, increasing the practice and application for additive manufacturing, especially communicating the results and characteristics of the design like reliability to the end-user or customer, is a crucial part for end-users to understand the DfAM mindset. This could be done in two ways. On the one hand, the end-users need to understand the restrictions and limitations on design applied by traditional methods like CNC machining. On the other hand, it is critical to make the end-users fully understand that despite the dramatic change in shapes that are hard to accept at the beginning, it is the trend for novel developments in the industry. Moreover, the new designs are not inferior in terms of characteristics like resistance to forces and reliability.

4. Conclusion
In summary, it is discovered that in recent years, especially the last five years, the major focus for these topology optimizations are the approaches based on the method of density, level-set, evolutionary, or a combination of those methods. Each of those methods has drawbacks. Thus, it is a good strategy to develop a new method through combining various traditional methods together, especially involving the evolutionary method which enabled designs that never had been thought of. However, the combination of different methods still needs more research as it is still in a relatively early phase of development. Moreover, with the introduction of advanced technologies in additive manufacturing, some dramatic changes need to be calculated for the purpose of exploiting the full potential of topology optimization and design. Specifically, it would be a new way of thinking that copes with additive manufacturing, as well as having the capability of conveying a novel method of thinking to end-users.

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