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Combination of peridynamics and genetic algorithm based topology optimization methods for additive manufacturing-friendly designs

Abdullah Kendibilir[1,2,3*], Mehmet Furkan Polat[1,2,3*], Omer Safa Cavus[1,2,3], Sina Khalilvandi Behrouzyar[1,2,3], Peyman Lahe Motlagh[2,3,4], Bahattin Koc[1,2,3], Adnan Kefal[1,2,3**]**

[1] *Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, Istanbul 34956, Turkey*
[2] *Composite Technologies Center of Excellence, Sabanci University-Kordsa, Istanbul Technology Development Zone, Sanayi Mah. Teknopark Blvd. No: 1/1B, Pendik, 34906 Istanbul, Turkey*
[3] *Integrated Manufacturing Technologies Research and Application Center, Sabanci University, Tuzla, 34956, Istanbul, Turkey*
[4] *Department of Mechanical Engineering, Gebze Technical University, Gebze, 41400, Kocaeli, Turkey*

[*] *The authors contributed equally to this work*
[**] *Corresponding authors: bahattin.koc@sabanciuniv.edu (B. Koc), adnankefal@sabanciuniv.edu (A. Kefal)*

Abstract

Topology optimization (TO) is a practical tool to generate light-weighted engineering structures for various manufacturing industries. However, manufacturing constraints and surface smoothing are still considerable challenges for TO algorithms. Existing TO frameworks utilize mechanical analysis approaches that discretize the whole domain with elements or particles. Therefore, obtained geometries from TO have been criticized for their complex shapes. In this study, we propose a coupled framework to generate additive manufacturing (AM)-friendly designs which result in less support structure and higher surface quality. For this purpose, the generative topology optimization method (GTO), which uses genetic algorithm to search for the best alternative set of geometry within all the possible topology results, is coupled with the peridynamics topology optimization (PD-TO) method to evolve the PD-TO results into AM-friendly shapes. The PD-TO discretizes the problem domain using equally spaced particles during the TO process. Hence, PD-TO generates a point cloud file with relevant artificial material density values in the final state. Then, the GTO method utilizes the point cloud and material densities as an input file to achieve better final geometry. AM-friendly designs achieved from GTO are compared with the initial results obtained from PD-TO to demonstrate the efficiency and capability of the proposed method.

Keywords: AM-friendly design, generative topology optimization, peridynamic, additive manufacturing, topology optimization.

1. Introduction

In recent years, the utilization of topology optimization (TO) studies according to additive manufacturing (AM) constraints has become more attractive for researchers. Since the overhang constraint has great impact on manufacturability, TO for overhang constraints is necessary for support-free manufacturing or support minimization studies [1]. Moreover, geometry redesigning after TO applications can become a complicated process due to fragmented surfaces. Several methods and studies have been conducted for overcoming those issues in the literature [2]. New TO algorithms overcome the problems of early TO methods (i.e., instability in results or occurrence of checkerboard pattern) by proposing new mathematical formulations. For instance, Bendsøe [3] proposed a homogenized TO method. Later, Solid Isotropic Material with Penalization technique (SIMP) [4] and Evolutionary Structural Optimization (ESO) [5] as well as bidirectional ESO (BESO) [6] were implemented for higher efficiency and accuracy. One of the most recent TO methods is the continuous density-based approach. The continuous methods can be categorized into two main approaches. First, the proportional approach (PO) [7], wherein the value of the objective function in the previous iteration determines the density of the elements. Next, the optimality criteria approach (OC) [8], which satisfies a set of analytically obtained criteria instead of directly optimizing the objective to solve TO problems. Besides, during TO a proper numerical method is needed to perform accurate structural analysis such as classical continuum mechanics (CCM) formulations in which particle interactions are considered between a particle and its nearest neighbor [9, 10]. Some CCM assumptions pose a modeling/analysis limitation for structures including damage, discontinuity, internal feature, or defect. Another approach to perform structural analysis during TO is non-local continuum theories referred to as Peridynamics [11]. In this approach, the material does not necessarily require remaining continuous during the simulations.

Few studies have applied PD directly to TO for designing cracked structures. For instance, Kefal et al. combined PD with BESO optimization schemes for structures with/without cracks [12, 13]. Moreover, a comparative study is performed by Motlagh and Kefal to justify why TO algorithms should substitute peridynamics for the conventional finite element method (FEM) approach in the TO of cracked structures [14, 15]. Compared to the conventional method to achieve a robust TO model that can provide peridynamic TO capabilities with smooth surface results according to manufacturing constraints. Usually, support structures are optimized to use the fewest materials possible, reducing both the amount of time and cost needed to produce them and, therefore, the amount of material used.

Cellular support structures have a tendency to be developed as a result of their advantage of having a low solid volume percentage. These structures offer options to both create and remove support structures more quickly. Hussein et al. suggested brand-new, cutting-edge lattice support architectures for SLM [16]. Diamond and gyroid lattice structures have both been researched for their potential as support structures that can reduce material and production time while still meeting the structural requirements of a metallic support structure. According to the experimental findings, using a lattice support structure with reduced volume fractions may result in material savings. For instance, gyroid lattice structures may be produced using just 8% of the relative volume, which implies 92% of the loose particles can be removed and recycled easily. Low volume fraction also enables SLM components to be built quickly and with minimal energy. Although the lattice support structures exhibit outstanding manufacturing qualities, some of the sections failed during manufacturing firstly due to the small volume fraction which caused the connection of the structures to the part to be very weak, and secondly because of the deformation that occurred due to the presence of too much material that was unsupported when the cell sizes were big and the distance between the connection points and the support needed surfaces was too large. Vaidya and Anand presented a novel support generation technique for additively manufactured parts [17]. The support was built utilizing space-filling solid and hollow cellular structures. The technique created the smallest number of cellular supports for the portion using Dijkstra's shortest path algorithm. Kuo proposed a new approach to overcome cost inefficiency of support production during AM [18], but it doesn't include the effect of different orientations of the specimen. The developed structures could handle the load of the component or feature they support, according to a stress study carried out by ANSYS. When compared to a fully solid support, it was seen that the support volume, sintered area, and support contact area were all significantly reduced. The research also offered a technique for creating ideal supports while taking accessibility into account for post-processing. They suggested future research which can investigate the cellular and lattice structures by changing their volume/density for support structure production. The creation of a support architecture using a grain-based algorithm is suggested by Habib and Khoda, in order to reduce the support volume, increase contact interface, shorten fabrication times, and make fabrication easier [19]. The suggested solution creates distinct grain on the model surface interface rather than a blanket of support, which will also make it more easily breakable. Additionally, the increased surface area of this discretized grain helps accelerate the elimination of the support for dissolvable material. They stated that future point-support architecture generation for metal AM processes can be accomplished using the suggested technique. To solve real-world design issues using conventional production techniques like casting and machining, TO approaches are typically utilized. However, it is advisable to use TO in 3D printing since the field of technology continues to advance quickly. For a specific area, load, and constraint condition, TO can offer the best structural design. Gardan et al. carried out research in which the interior structure was optimized using numerical modeling, and the topology was optimized using an analysis of the mechanical strength [20]. For the topological optimization integration, a Knowledge-Based System was created to control the AM process and material characterization.

Li et al. used TO in the design process to provide a lightweight design, and a support-free design approach was created to satisfy the support-free criterion [21]. They used TO to optimize the pieces for lightness, then, the support-free design procedure was created to make it possible to produce parts using no support structures. A crossbeam component was manufactured as a case study utilizing the newly developed model. The finished part had a volume decrease of 31.4% when compared to the original part. The final part was directly produced utilizing SLM without any support structures to demonstrate the efficacy of the developed design technique. Additionally, the two-dimensional design may be created using the support-free design technique proposed in this work. The fact that the redesign process' volume increased by 20.8%, of which 13.6% was due to the support-free design process, is one of the study's limitations. In a study, Wu et al. provide a novel approach to infill optimization that considered the manufacturability of the obtained parts [22]. Rhombic structures were used as infill structures to effortlessly satisfy the overhang limitation by taking the use of their self-support feature. Regarding mechanical stiffness and static stability, several investigations had proven the validity of their developed approach.

To the best of the authors' knowledge, there are few multi-objective TO that consider support constraints; consequently, there is a need to provide an efficient and robust approach that can be utilized for optimal performance. For the first time, a meshless approach (PD) is combined with in-house Generative Design (GD) to overcome not only support minimization during TO but also discontinuities such as defects, cracks, and voids. Unlike traditional GDs, the methodology used in this study considers alternative designs without determining the actual support volume by using normalized support and compliance values. The rest of the paper is organized as follows, PD-TO and GTO methods will be explained separately. After giving those two methods with detailed features, the combination of those methods and their advantages are explained. Finally, the result of the combination of the two novel methods is analyzed and the results will be discussed.

2. Methods and materials

2.1. PD-TO Method

In this study, a novel Genetic Algorithm (GA) based approach is developed to create a TO process that includes AM constraints and obtain a parametric surface outcome that is ready to print. This approach will utilize PD-TO results as input to generate smooth and ready-to-print AM-friendly designs by the GTO method for the first time. The general PD equation of motion for a material point initially located at x can be written as:

$$\rho(\boldsymbol{x})\ddot{\boldsymbol{u}}(\boldsymbol{x},t)=\int_{H_x}\begin{pmatrix}\boldsymbol{t}(\boldsymbol{u}'-\boldsymbol{u},\boldsymbol{x}'-\boldsymbol{x})\\ -\boldsymbol{t}'(\boldsymbol{u}-\boldsymbol{u}',\boldsymbol{x}-\boldsymbol{x}')\end{pmatrix}dH_x+\boldsymbol{b}(\boldsymbol{x},t) \quad (1)$$

Here, ρ and $\ddot{u}$ are corresponding to the density and acceleration of a particle located at x. Moreover, t is the force density vector on a particle. H defines the horizon of material point for the integration of acting forces utilizing the family of each point inside the horizon. Additionally, b is the body force acting on a particle. Finally, it should be noted that $\boldsymbol{u}'-\boldsymbol{u}$ and $\boldsymbol{x}'-\boldsymbol{x}$ are corresponding to relative position and displacement vector, respectively.The non-local nature of the PD approach can be illustrated as shown in Fig. 1.

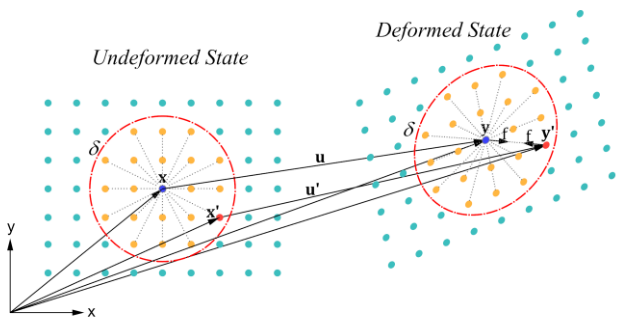

Fig 1. Interactions between a material point x and its family members.

The general minimization of compliance problem of topology optimization can be written in the following form as (Kefal et al., 2019):

$$\min_{\kappa} C(\kappa_i)\equiv C=\sum_{i=1}^{N}W(\mathbf{x}_i)V_i \text{ s.t. } \begin{cases}\mathbf{KD}=\mathbf{B}\\ \dfrac{\sum_{i=1}^{N}\kappa_i V_i}{\sum_{i=1}^{N}V_i}=\bar{V}\\ 0\le\kappa(\mathbf{x})\le 1,\forall\mathbf{x}\in\beta\end{cases} \quad (2)$$

Where C represents the compliance of the structure where κ is the design variable of a particle. Moreover, $\bar{V}$ is the target volume of the optimization problem and W is the strain energy density of a material point. We performed PD analysis in each step of this optimization procedure for solving the static-structural problem (KD=B). Discretized PD domain of the problem is generated by using the Rhino-Grasshopper tool. General purpose discretization scheme which can be applied to any complex geometry is generated for creating equally spaced material points. Moreover, the optimality criteria method is selected for the design variable updating algorithm in the optimization process.

2.2. Generative Topology Optimization Method

In this study, after obtaining the final geometry by PD-TO some extra steps are needed. For instance, topology should be smooth and by considering AM process constraints, a ready-to-print structure would be generated. For this matter, a new in-house generative TO methodology was developed for smoothing the final geometry generated for AM processes. Here, AM constraints are defined as minimizing support structures while satisfying the minimum feature size in addition to the compliance. Since the GTO method is a multi-objective optimization framework, it considers several factors such as boundary conditions, paths from loading to boundary condition, and achieving smooth surfaces. In design optimization processes definition of the optimization, scheme is considerably important. Since the constraint and objective functions can be defined in different ways, the structure of the optimization scheme has great effects on the overall optimization process. In the case of multi-objective optimization problems like in our case, optimizing the geometry with the support structure is a kind of multi-objective case that must be constructed carefully. Since our objective functions are nonlinear, it is hard to solve them efficiently via deterministic methods. To overcome non-linear multi-objective problems, a heuristic search algorithm method was chosen. The proposed method is based on the generative design approaches, based on that the best solution among various design alternatives has been studied utilizing genetic search algorithms. Even self-supported geometries that can be stand-alone without requiring support structure to be built with AM methods can be achieved. Moreover, smooth, and ready-to-AM final surfaces could be obtained with the proposed method.

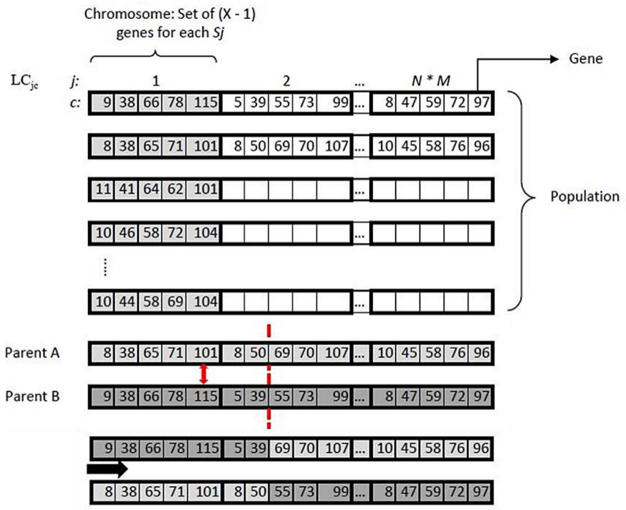

Fig 2. Genotypes of the chromosomes and the individuals.

In this study, to create AM-friendly designs with smooth surfaces, the proposed method generates auxiliary geometries called skeletons inside the design space considering the point cloud obtained by PD-TO analysis. The produced geometry is represented by smooth parametric surfaces so they can be directly used in AM processes without any further surface smoothing or fitting operations. By implementing this method, a well-known geometry so-called GE bracket is optimized. Firstly, the geometry is optimized by the PD-TO framework and the resultant point cloud with the relevant material density values is extracted. Around the boundary conditions, specific boundary volumes are defined to be sure that they will remain during the optimization. Depending on the volume fraction minimum amount of support structure is calculated. By assuring the paths are going through the point cloud the final topology is generated.

To create GA optimization, a set of auxiliary curves were created that allows us to search for the best design altering the different design parameters. Each fix-force couple has its own unique connection, and it is called skeleton. Those possible skeletons are defined in an integer array shown in Fig. 2. Each line represents the phenotype of the final geometry that consists of a set of chromosomes. Each chromosome carries the list of index belongs to the auxiliary curves that are used to create single fix-forced connections. All the possible connections between fixed and forced points are represented with those chromosomes. This final topology is a combination of PD-TO and GTO methods which can be utilized directly for AM since the surfaces are smoothed. The results showed that the proposed method can satisfy AM constraints without compromising the mechanical properties. The alternative connections were chosen with the alternative selections of the circles from each plane that are perpendicular to its related skeleton. After this step, each curve is divided into a certain number of equally divided curve segments with points and finally auxiliary planes are created on those points that are perpendicular to their skeleton curves.

3. Results and discussion

In this study, we selected the GE bracket to reduce its weight utilizing PD-based TO. After that, the GTO method is performed to generate smoother final geometry for AM processes. The initial domain of the geometry is given in Fig. 3 with the relevant boundary and load conditions. Fig. 3(a) shows the 3D CAD model of the GE bracket geometry. Since geometry has many details, only the main dimensions can be given. The length, width, and height of the bounding box of this geometry are

L=178 [mm], W=108 [mm], H=63 [mm]

,respectively.

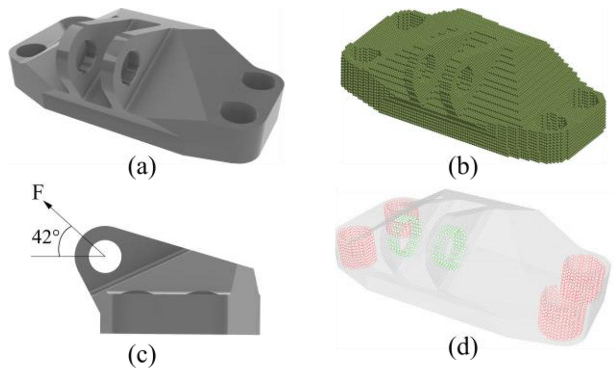

Fig 3. (a) Problem domain, (b) Peridynamic discretization of the problem domain, (c) loading angle, (d) material points in the boundary and loading regions.

After applying PD discretization, the equally distanced material point cloud is given in Fig. 3(b). In this model, we discretize the problem domain into 70280 material points. The distance between two material points is dx = 1.73 [mm]. Force load is applied to the two parallel holes with an angle as shown in Fig. 3(c). The magnitude of the applied load is F = 42 [kN]. The force is applied as body force density for PD analysis. To find the body force density acting on a material point existing in the force applied region, the magnitude of the force is firstly divided into the total number of points in this region and divided by the volume of a material point. Hence, the total force is distributed equally to body force density. Moreover, the displacement boundary conditions are applied to the holes in the left and right sides of the geometry as depicted in Fig. 3(d). Here, displacement and force boundary regions are colored with red and green colors, respectively. Furthermore, it is worth noting that all the selected points shown in Fig. 3(d) are defined as passive points which means that these points will keep the same density value as $\kappa = 1$ that corresponds to a solid material. We have created three different case scenarios by changing the target volume of the optimization process. These volumes are selected as $\bar{V} = 0.6, \bar{V} = 0.5$, and $\bar{V} = 0.4$ from the highest to the lowest. The final topologies obtained by PD-TO can be investigated in Fig. 4. These geometries are shown by two different isometric views to understand the geometric features of the whole structure. As our approach is a non-local meshless method, the problem domain is represented by the accumulation of equally distanced identical material points. Therefore, the optimized topologies by PD-TO have sharp corners which makes these results be criticized as intricate or inappropriate for manufacturing.

After smoothing with GTO methods, parametric smooth surfaces were obtained. Overall, GTO considers the need for the structural supports thus the optimized geometry is changed. Due to this fact, the topology obtained by PD-TO may have some differences compared to GTO. However, by considering the point cloud in both methods we tried to achieve similar geometries. As it can be seen from Fig. 5, the final ready-to-print structures obtained by GTO have smooth parametric surfaces that is ready to print with minimum support structure.

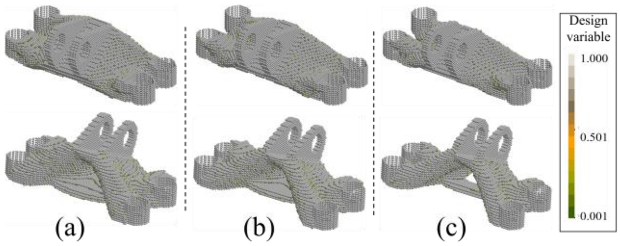

Fig 4. Detailed isometric views of the final geometries obtained by PD-TO analysis for three different target volumes: (a) $\bar{V} = 0.6$, (b) $\bar{V} = 0.5$, (c) $\bar{V} = 0.4$

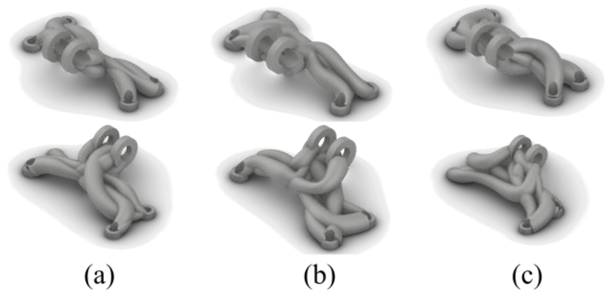

Fig 5. Isometric views of the final geometries after GTO analysis for three different target volumes: (a) $\bar{V} = 0.6$, (b) $\bar{V} = 0.5$, (c) $\bar{V} = 0.4$

After the PD-TO results for varying volumes of $\bar{V} = 0.4$, $\bar{V} = 0.5$ and $\bar{V} = 0.6$are utilized as an input in GTO, the final volume fractions of the GTO results are found as 0.4, 0.33, and 0.32 respectively.

Table 1. Comparison of the compliance values between PD-TO and GTO results.

Target volume	0.4		0.5		0.6	
Approach	PDTO	GTO	PDTO	GTO	PDTO	GTO
Compliance [Nm]	2.08	2.06	1.79	4.32	1.57	4.97

Since the final geometry has changed during GTO, the final part obtained by GTO and the PD-TO results are analyzed to compare their compliance using their optimized states. These values are presented in Table 1.

It can be revealed that the structures generated by GTO generally stored much more energy. This result can be attributed to the less volume in the parts optimized by GTO. Moreover, energy distributions over the optimized structures are depicted in Fig. 6.

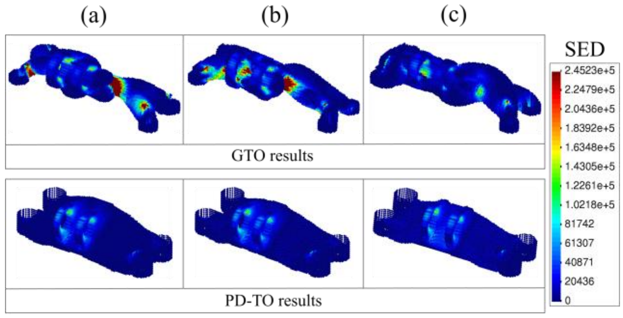

Fig 6. Strain energy density distributions for PD-TO and GTO results for three different target volumes (a) $\bar{V} = 0.6$, (b) $\bar{V} = 0.5$ (c) $\bar{V} = 0.4$.

4. Conclusions

We performed the PD-TO and GTO methods sequentially to obtain topologically optimized and smooth designs while minimizing the support structures for AM processes. The results showed that the proposed method can decrease the support volume drastically compared to the results obtained from commercial software while having less maximum displacement value. In addition to those enhancements, the resultant geometries have smoother surfaces, so the local stress concentration of the resultant part can also be reduced. The framework introduced here can calculate the support structure volume during the optimization, thus it can reduce the total amount of required support structure volume by using normalized support/compliance calculation. It can also be extended in the future with the addition of thermal analysis to decrease residual stresseThe GTOcan be used as an input design to an AM process simulation model in order to model the manufacturing steps in a real and commercialized AM machine to find and calculate the critical locations which will be created during the AM process due to various factors that affect the final manufactured product. Thermal, mechanical, and coupled thermomechanical simulations can lead us through finding the critical locations such as locations with the highest residual stresses or the points with large distortions which will enable us to have a better glance at the designed part and change it accordingly to prevent the above-mentioned defects in the final part. As TO offers complicated designs, customized scanning strategies can be used instead of scanning strategies used in the literature and industry. Due to the microstructure, mechanical characteristics, and residual stresses of 3D printed objects are significantly influenced by the scanning method, one of the main AM processing parameters. To illustrate the effectiveness and feasibility of the suggested method, the last design can be again simulated by the AM process simulation model and the results can be compared with the preliminary outcomes obtained via PD-TO.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: n/a.

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