An Application Process of Additive Manufacturing Based on Digital Simulation and BESO Topology Optimization

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Abstract. Additive manufacturing has now entered a wide range of areas and plays an important role. There are many factors affecting the application of additive manufacturing, such as the amount of printing supplies, print product strength, print speed and so on. These factors potentially hinder the application of additive manufacturing in some typical areas, such as spare parts producing for on-orbit maintenance in space environments. Based on the improvement of the above factors, an additive manufacturing application process based on topology optimization of variable density method and digital simulation was proposed. Print volume of product was used as an explicit constraint, and the design goal of the product, such as strength and modal, was transformed into implicit stress constraints in the topology optimization of three-dimensional model, then stress constraints were independently extracted for secondary verification, finally the checked model is put into print. This process saves computational resources during optimization calculations and printing time, reduces print product’s weight, conserves supplies, and meets initial strength or modal design goals. This process greatly exploited the advantages of additive manufacturing in product manufacturing and made up for the shortcomings of traditional manufacturing processes that can not directly output a relatively abstract model after topological optimization. Under the constraints of saving material and increasing strength, it becomes optimum solution in the manufacture of specific products.

Keywords. Additive manufacturing; Digital simulation; Topology optimization; Variable density method; Space utilization.

1. Introduction
Additive manufacturing, also known as 3D printing, rapid prototyping, directly transforms the virtual digital model into a product, which greatly simplifies the production process and shortens the design and development cycle of the product, making it possible to produce almost any complex structural parts. Not only that, the materials and equipment of additive materials that are "portable" and provide the ability to quickly create urgently needed items on-site is of great importance to space applications. There are many different implementations of additive manufacturing. Commonly used methods include selected laser sintering (SLS), stereolithography (SLA), and fused deposition modeling (FDM), which is generally applied in metal materials, photosensitive resin, polymer materials \cite{1}. The application process discussed in this article does not specific implementation of additive manufacturing.
Further, in the future manned missions to the Moon, Mars and beyond will require innovative options to shelter our explorers, to carry the construct materials from the Earth on their departure is impracticable. The above reasons show there is a wide range of demand and application prospects for additive manufacturing in the space field [2].

More in depth, in order to reduce launch mass and costs, it is not possible to carry printed materials as many as possible without restrictions in the launch of a space station or a cargo ship. Therefore, it is necessary to study how to print with the least amount of printing materials to meet the most requirements of the product. Or from another perspective, how to optimize the performance of on-orbit products, such as the strength of products, during the entire mission period, if the requirements for spare parts and the carrying material are pre-planned for launch. On the other hand, once the on-orbit additive manufacturing method is adopted, a fast print request is also made to the printing process because a certain amount of resources such as manual monitoring and electricity consumption are required for the printing process. Especially when there is a need for instant repair or other emergency conditions, it is even more necessary to shorten the printing time. Therefore, it is necessary to study how to print in the shortest time to meet the requirements of the product. These are the needs to be studied and current focus on additive manufacturing [3].

In recent years, the optimization technology for additive manufacturing has attracted the attention of many scholars, and has carried out relevant research work on the saving of printing materials and the optimization of product’s strength [4-6].

Zhou et al. discussed a method of finding one of the most adverse(Worst-Case) load case and identified the most vulnerable areas or maximum deformation zones on the model [7]. Stava et al. [8] enhanced the printed object strength by hollowing out, thickening locally and adding external supports, which could indirectly save materials. However, as the goal is to enhance the object's strength, reducing the object's volume is not a default target. Lu et al. [9] proposed an algorithm of Voronoi diagram to calculate the irregular honeycomb segments defined inside the object and the algorithm of hollowing out the interior of the object. It minimized the volume of the objects under the premise of satisfying mechanical properties, which achieved good results. However, many of the internal pore structures generated by the algorithm are obturate areas, so that they are subjected to many limitations in the actual 3D printing process. For example, the powder in the pore structure can not be discharged after selective laser sintering, and solvent is still needed after the formation of Fused Deposition Modeling to remove other support in holes. Inspired by the truss structure of buildings, Wang et al. [10] designed the internal structure of the model as a truss structure and integrated skin-truss structure as external skin to maintain strength and stiffness while significantly reduces the size of the model, and thanks to the flexibility and variability of the truss structure, it enables it to accommodate a wide variety of constraints for 3D printing and for different 3D printing process.

2. Optimization Method Based on BESO Method

2.1. Optimization Target

In order to maximize the stiffness of the structure, the goal is that the strain energy or average compliance of the structure should be minimized. This type of optimization problem can be expressed as:

Satisfy: \[ V^* - \sum_{i=1}^{N} V_i x_i = 0 \]

Minimize: \[ C = \frac{1}{2} u^T K u \]

\[ x_i = x_{\text{min}} \text{ or } 1 \]

Where \( K \) is the global stiffness matrix of the structure and \( u \) is the displacement vector, \( V_i \) is the volume of the independent unit and \( V^* \) is the optimized target volume. The two-way design variable \( x_i \) represents the density of the \( i \)th unit. In order to avoid introducing a value of 0 to make the stiffness matrix a singular matrix, a small value such as 0.001 is used to refer to an empty element (an element with a density of 0).
2.2. Element and Node Sensitivity Values

Sensitivity is used to characterize the influence of the unit on the overall structure. It is defined as: if the first element is removed from the structure, the effect on the average compliance (strain energy) of the structure is equivalent to the strain energy of the element.

\[
\alpha_i^e = \Delta C_i = \frac{1}{2}\{u_i\}^T[K_i]\{u_i\}
\]

Where \(u_i\) is the nodal displacement vector of the \(i\)th element and \([K_i]\) is the element stiffness matrix. For an empty cell (0), its sensitivity value \(\alpha_i^c = 0\). The driving process of the ESO method is to gradually remove the cells with low sensitivity.

When using low-order bilinear elements or trilinear elements as finite elements, the above-mentioned sensitivity value \(\alpha_i^c\) may become discontinuous at the element boundaries, resulting in a checkerboard phenomenon. In order to avoid this problem, the sensitivity value of the node and its neighboring nodes are volume-weighted and averaged:

\[
\alpha_j^c = \frac{\sum_{i=1}^{M} V_i \alpha_i^c}{\sum_{i=1}^{M} V_i}
\]

Where \(M\) represents the total number of units adjacent to the node \(j\).

2.3. Finite Element Format

In order to achieve the purpose of determining the topology, the above-mentioned node-based sensitivity value must be converted to the unit. This conversion is realized by projecting the node sensitivity value to the unit. The filter function is defined based on the length scale \(r_{\text{min}}\), and the value does not change with the grid accuracy. In the filtering scheme, it is used to identify the nodes that affect the sensitivity of the \(i\)th unit. A spherical subdomain was created and use the following function to calculate the impact of the improved sensitivity of the unit:

\[
\alpha_i = \frac{\sum_{j=1}^{M} \omega(r_{ij}) \alpha_j^c}{\sum_{j=1}^{M} \omega(r_{ij})}
\]

Among them, \(M\) is the total number of nodes in the subdomain \(\Omega_i\), and \(\omega(r_{ij})\) is the distance weighting factor, through:

\[
w(r_{ij}) = r_{\text{min}} - r_{ij} (j = 1, 2, \ldots, M)
\]

Where \(r_{ij}\) is the distance from the center of the \(i\)th element to the \(j\)th node.

The above filtering scheme has two purposes: to flatten the sensitivity value of the entire design domain, and to interpolate the sensitivity of the empty cell (0).

2.4. Stability of Evolution

Although a grid-independent filtering scheme is used, the objective function and topology may still not converge. Therefore, the historical average method of sensitivity values is introduced to reduce the influence of increasing units on the sensitivity values, and the sensitivity obtained in the current iteration step is averaged with the result of the previous step:

\[
\alpha_i = \frac{\alpha_i^k + \alpha_i^{k-1}}{2}
\]

Where \(k\) is the number of steps in the current iteration. Let \(\alpha_i^k = \alpha_i\) for the next iteration. In this way, the updated sensitivity value contains the sensitivity information of all previous iteration steps.

2.5. Element Removal/Addition and Convergence Criteria

After the beginning of the optimization process iteration, each time before removing elements from the structure, the target volume of the next iteration step \((V_{k+1})\) must be determined first. Because the
target volume \( V^* \) can be larger or smaller than the initially guessed design domain, the target volume of each iteration may be increased or decreased until the target volume is reached. Therefore:

\[
V_{k+1} = V_k(1 \pm ER)(k=1,2,3,\ldots)
\]

Where \( ER \) is called the progressive volume ratio. Once the target volume is reached, the volume will remain constant in the next iteration steps:

\[
V_{k+1} = V^*
\]

Then the sensitivity values of all units are calculated according to the method in the previous section. Sort the units according to their sensitivity values from high to low. For the physical unit \( (1) \), if the following conditions are met, the unit is removed (converted to 0):

\[
\alpha_i \leq \alpha_{del}^{th}
\]

For an empty cell \( (0) \), if the following conditions are met, increase the cell (transition to 1):

\[
\alpha_i > \alpha_{add}^{th}
\]

Where \( \alpha_{del}^{th} \) and \( \alpha_{add}^{th} \) are the thresholds of the sensitivity values respectively.

3. Additive Manufacturing Process Based on Digital Simulation and Topology Optimization

3.1. Overview

In this section, topology optimization is integrated with traditional 3D printing to build a new additive manufacturing process based on digital simulation and topology optimization for engineering applications, especially in space application field. Based on the foregoing analysis, the general engineering problem can be attributed to weight-removal design, which is the optimization goal. We note that the part must meet the strength or modal requirements, which is in line with the mathematical programming problem framework set up in the previous section.

The main advantage of taking this process is that for 3D printed part design, it is only possible to pursue the optimum solution of intertwined intensity and weight design when solving the topology optimization problem (which implicitly satisfies the constraints). If not, parts can only be designed by the designer's experience, which is prone to over-strength or lack of strength. If safety margins are taken into account, they inevitably add weight and cost to aerospace applications. The manufacturing features of 3D printing make the theoretical optimal solution possible to realize.

Figure 1. Application process.
3.2. Process Decomposition

A. First identify the part’s design features, turn the functional objectives into optimization constraints (Figure I), if the constraints is stress or vibration then this flow is appropriate.

B. Second, determine the loading situation, define the boundary constraints (installation position, etc.), material properties, these can be collectively referred to as the objective property of the part, as the process input (II).

C. Digital simulation (III) with input and part model (mesh file). The output of the simulation step is the typical response (stress distribution or modal response) of the part under working conditions.

D. Next proceed to optimization step (IV). The input of the optimization step is grid file of the part and the response of each element of the part. By deleting the elements and retaining elements by the variable density method, the output is optimization result. The essence is to delete the original model and output the redesigned optimization result (V), which form is STL file.

E. Enter the re-check step (VI), this step’s input is the optimization result output of the previous step, still take the four objective attributes defined in step B as the simulation condition, the output is the response of optimized part in the working condition. In order to judge whether the optimization is feasible or not, a stress constraint should be taken as a supplementary criterion (material strength limit or resonance frequency range) to determine whether the default stress constraint is satisfied in the optimization process.

F. Finally, the printing step (VII), the stl file was sent into the slicing software for layering slice and then output as a Gcode file to print (VIII).

Next, we discuss several issues in the process of optimization based on the actual engineering. Based on the foregoing analysis, the goal of optimization is to minimize the compliance of the entire model, i.e., maximize stiffness. There are two kinds of optimization area selection criteria, one is global optimization and the other is local optimization. However, no matter which type of optimization scheme is selected, the boundary condition of the part during the actual working can not be optimized. Otherwise, the original boundary load or constraint can not be applied, and the pre-determined function of the part is affected or the way components are used is forcibly changed by optimization, which does not match the intent of topology optimization. In addition, we also set some areas as non-optimized areas that hinder the identification of the part or have an impact on ergonomics. In summary, the choice of optimization solution is not unique, but it does affect the appearance and stress distribution of the optimized part.

4. Case Study

We conducted topology optimization analysis of the NASA wrench model that has been validated on the ISS. This isn't the first 3D-printed object made in space, but it is the first created to meet the needs of an astronaut. This is the first time an object has been designed on Earth and then transmitted to space for manufacture. [11]

The wrench has a internal ratchet and teeth to facilitate one-handed operation of astronauts. This design eliminates the need to frequently insert and remove the bolt head to be screwed in during operation, but increases the structural complexity and hence has a high demand on the accuracy of the 3D printer in which it is manufactured. Secondly, because of the small size of the internal gear, the local structural stress may lead to local damage. So we ignored the internal structure of the wrench. Printing material is Polylactic acid(PLA), by its own characteristics and processing conditions, polylactic acid products can be non-crystalline, partially crystalline and fully crystalline state, these conditions will affect the product's melt temperature and strength. Here we use ordinary non-crystalline poly Lactic acid (aPLA).

Taking the process of loosening the bolt as an example, when the wrench is in use, the quadrilateral head is fully inserted into the sleeve and the handle body is gripped by the astronaut to exert a force in the X-axis direction. Before the bolts are loosened, the force applied by the astronauts increases until the bolts' tightening force is reached, the bolts are loosened, and the bolt can be unscrewed by applying a small force. The most demanding moment of mechanics throughout the process is the moment before unscrewing, so we analyze the forces at this moment.
The force exerted on the wrench is shown in Figure 3. Since the quadrilateral head is nested inside the adapter, we treat the four faces of the quadrilateral head as fixed and the force exerted by the operator's hand on the handle of the wrench is treated as applied to a contact surface, which is 40N. The hand force is about 76 mm from the square head. According to Saint Venant's Principle, the effect of the operating force on the position of the four faces is equivalent to applying a moment. The side length quadrilateral head is about 10 mm. In the whole wrench model, the root of wrench head is the weak point of fracture. The intersection between the head and the wrench body is a dangerous cross-section, which is the most prone to fracture failure under working conditions. We calculate the bending moment and stress on the wrench head. First, we calculate the moment of inertia of the head:

\[ I_z = \int_A y^2 dA = \frac{bh^3}{12} \]

Where \( I_z \) is the moment of inertia of the wrench head rectangular section to the \( x \) axis and \( y \) is the distance from any point on the cross section to the \( x \) axis, \( A \) is the cross sectional area, \( b \) and \( h \) are the two side length of the rectangular section respectively, for qudrate section these two are equal.

Next, calculate the shear force when it is twisted:

\[ \tau_p = \frac{T}{W_t} = \frac{T \cdot \rho}{I_p} \]

Where \( T = F_{hand} \cdot l \) is the equivalent moment of the operating force to the square head position, \( W_t \) is the torsional coefficient of the section, \( I_p \) is the polar moment of inertia of the points \( \rho \) apart to the \( x \)-axis, and the shear force calculation result is \( \tau_p = 18.24 \text{Mpa} \).

In the Ansys software, the mesh and boundary conditions are defined. The maximum Von Mises stress of the wrench is 43.3361 Mpa and the stress area is concentrated at the root of the square head, which is consistent with the previous analysis. X-Z plane shear analysis shows that the maximum and minimum shear forces are 17.903MPa and -16.095MPa respectively, which are only 1.86% different from values manual calculated. It is considered that the simulation results are accurate. The direction of the two shear forces is the opposite, located in the four corners of the square head, which is consistent with the actual situation when torsion applied, and also match up to shearing stress theorem. We define the material as plastic PLA (isotropic) with a Young's modulus of 1100 MPa, a Poisson's ratio of 0.42, and a tensile limit of 44-66 MPa [12].

Under normal use, the maximum stress on the wrench does not exceed the elastic limit, that means the design meet the requirements. At the same time, we noticed that the stress of most other parts of the wrench is very small. Therefore, the wrench can be topologically optimized to remove the unwanted spatial structure for the purpose of weight reduction and material saving.

The topological optimization based on the variable density method is carried out. The constraint conditions are the volume and boundary constraints, the specified volume constraints are respectively 30% -70% of the original volume, the designated optimization area is the geometric distribution area of the entire wrench space, the designated optimization exclusion area is all the boundaries conditions such as the side profile of the wrench and the outer surface of the square head. Because if these areas
are optimized, wrench appearance features will be lost, causing astronauts to identify the wrench difficult.

Figure 3. Wrench optimization results for different optimization goals. The results of optimization under the 50% volume constraint were used to print the model. The weight, printing time and printing supplies decreased compared with those before optimization, decreasing by 23.7%, 22.8% and 19.5% respectively. See Figure 4.

Figure 4. Printing time, material and weight comparison before and after Optimization.

Table 1. Printing and Simulation Parameters.

| Printing parameters                  | Value       |
|--------------------------------------|-------------|
| Density                              | 1000kg\*m^-3|
| Young's Modulus                      | 1100MPa     |
| Poison Ratio(dimENSIONLESS)          | 0.42        |
| Layer Height                         | 0.06mm      |
| Wall Thickness                       | 0.8mm       |
| Print Speed                          | 60mm/s      |

Based on the optimized model, we reprinted and produced the wrench using FDM, parameters used were shown in Table 1.
5. Conclusion

In order to meet the requirements of high strength, low weight and fast printing of additive manufacturing products in these occasions, such as the future space station, manned lunar landing, etc., which adopt additive manufacturing as a tool manufacturing and spare parts supplement, the paper proposes the additive manufacturing application process. The products of additive manufacturing based on this process can avoid the over-intensity or under-intensity design of the traditional design method, and remove the part affected by the generalized stress considering the function of the part.

The proposed method was verified by both simulation and experiment. With proposed filling scheme in [13], the test results suggested that the properties of the specimens under the process proposed by this paper were superior to the CURA counterparts filled with grids and triangles (control group). The tensile stiffness-to-weight ratio was increased by 43.06%, and the compressive stiffness-to-weight ratio was increased by 23.18%. When compared to previous works, it also demonstrated great superiority in the tensile modulus. Akhoundi et al. [14] reported that the tensile modulus of several generally-used filling patterns with different filling percentages ranged between 28 and 62 MPa. Besides, Torres et al. [15], Jamshidian et al. [16], and Bijarimi et al. [17] reported that the tensile modulus of raw PLA ranges between 1968 and 3500 MPa based on the preparation process, while the proposed method can provide a maximum modulus of 1496 MPa with only 66% material input[13].

The parts produced in this way have the characteristics of saving materials, saving printing time, intensity and basically unchanged before optimization, not only meeting the high requirements under the situations of manned spacecraft and ocean-going ships, but also being applicable to general occasions.

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