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Two-dimensional placement optimization for multi-parts production in additive manufacturing

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ABSTRACT

Additive Manufacturing (AM) processes build parts in a layer by layer manner. This unique characteristic enables AM machines to fabricate different parts simultaneously without using tools or fixtures. However, how to optimally place multi-parts (with same or different geometries) into a specified build space or onto the build platform with respect to user-defined objectives is a complex NP-hard problem. This problem is a special variant of classical nesting or packing problems. Moreover it owns specific constraints from AM. In this paper, the multi-parts placement problem in AM is analyzed and an integrated strategy is proposed to solve one category of the problem, two-dimensional placement of multi-parts. The proposed strategy is composed of two main steps, Applying an “AM feature-based orientation optimization method” to optimize each part's build orientation to guarantee the production quality and Applying a designed “parallel nesting” algorithm for increasing the compactness of placement by using the parts' projection profiles so as to decrease the total build time and cost. Computational examples are presented in the end for demonstration.

1. Introduction

Additive Manufacturing (AM), derived from Rapid Prototyping (RP), has been investigated and developed for more than three decades. It can not only provide prototypes rapidly to support the product development, but also produce functional or end-use parts for diverse application areas [1,10,12,20]. Due to its unique processing manner, layer by layer, it owns a great advantage of manufacturing customized parts with extremely complex geometries against traditional processes. Furthermore, AM technologies can realize manufacturing a group of parts with same or different geometries in the same build vat or on a same build platform simultaneously without using any tools or fixtures (Fig. 1) since multiple contours of different parts can be placed within one common slice/layer to be built. Therefore, it is a real and ideal technology for the ‘concurrent manufacturing’ [24]. Significant savings in cost and time can be achieved in rapid prototyping (RP) by manufacturing multiple parts in a single setup to achieve efficient machine volume utilization [6]. Intuitively, to improve the machine utilization, more parts should be placed as compactly as possible to harness the build volume so as to reduce the total build time and cost per machine run. It seems that this is a classical nesting or packing problem, which is usually NP-hard. However, due to the special constraints of AM, the placement problem is different from other classical nesting or packing problems, e.g. box-pack, knapsack. When placing multi-parts into a build volume, not only the compactness should be maximized to reduce the total build time and cost, but also the part's production quality should be guaranteed. In addition, the characteristics of AM processes, the features of part group, the production contexts of AM service bureaus and the specific preferences and requirements of users should be taken into consideration when doing the multi-parts placement. Hence, these factors form the customized constraints of AM to make this problem a special variant of classical nesting or packing problem. Currently, due to the insufficient maturity of manufacturing functional parts and little research attention paid on the process planning or scheduling in AM, only a few solutions were proposed in literature to deal with the part placement problem. Till now, in AM service bureaus, the problem is mainly solved manually by skilled technicians who place parts as many as possible [4]. However, doing the part placement manually in a graphic environment is time-consuming, and it becomes more complicated when placing a batch of parts with a large quantity and very complex geometries [22]. Obviously, it is very difficult or even impossible for an operator to find an optimal part placement solution manually when facing such a NP-hard problem. To enhance the research in this direction and compensate current solutions' several drawbacks, this paper introduces a

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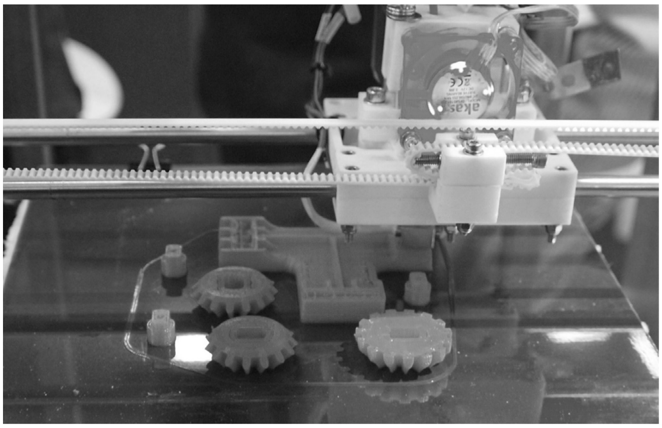

Fig. 1. Multi-parts building on an AM machine build platform.

new two-dimensional placement strategy. It can not only improve the nesting compactness by using a "parallel nesting" algorithm, but also guarantee the production quality by using an "AM feature-based orientation optimization method" to optimize each part's build orientation. Furthermore, due to the use of projection profile as nesting stencils, smaller oriented parts represented by smaller profiles can be nested into the open bigger cavities of other parts without collisions, which can further improve the compactness and save the build space.

The left of this paper is organized as follows: the second section will review some representative works on part placement optimization for AM with some comments; the third section will systematically analyze the multi-parts placement problem and give a comprehensive description; the forth section will introduce the proposed two-dimensional placement strategy; the fifth section will present illustrative computational examples to demonstrate the feasibility and advantages of the proposed strategy; the last section will give conclusions and further discussions.

2. Related works

Wodziak et al. [19] firstly investigated the placement of parts (Note: in this paper, a part can be a single component or a set of assembled components) for AM in 1994. They proposed a Genetic Algorithm (GA) based method to obtain a near optimal placement of parts by using their bounding boxes to tackle the difficulty of placing multi-parts by hand for SLA (stereo-lithography) machine. Subset of a group of selected parts was placed into the build vat both in two dimensional and three dimensional nesting forms. The parts are placed on the same layer sequentially one by one. The three dimensional nesting was realized by adding sequentially-constructed part layers from the bottom to the top of a build vat. Before placing a part, rotation of the part on the bottom by an increment of 90 degrees was conducted to find a better positioning. The ratio of the loaded parts among total parts and the percentage of the vat volume taken up by the loaded parts were two optimization objectives. However, part's build orientation was not optimized during the nesting. The three dimensional packing proposal for SLA is controversial since support structures are required among part layers. This would possibly damage the surface quality and cause much additional post-processing time. The method is fast to obtain a packing solution. But, it waste a lot of space when packing parts with concave features due to the use of bounding box and it cannot guarantee the quality of the obtained solution since no backtracking is done [14]. This is a common drawback of serial packing methods. Nyaluke et al. [15] proposed a similar GA-based placement solution for SLS (selective laser sintering). In SLS, parts can be packed one upon another since there is no need of support structure. In their method, at first, parts were ordered according to their size; then, rectangular boxes were used to represent real parts for packing which began from the largest one to the smallest one or vice versa. Part's build orientation was considered and fixed one by one according to part's key surface feature during packing. However, the parts cannot be rotated during the packing, which could not guarantee the obtained result is an optimal packing solution. Ikonen et al. [8] developed a GA for packing 3D non-convex parts with cavities and holes into the SLS machine build cylinder. Parts were randomly selected from a specified group to form a subset of which each part had pre-defined 24 alternative orientations (45 degrees of increment in three directions). The parts were placed into the build cylinder one by one with finite relative positions constrained by pre-set 5 'attachment points' on each part. Three indicators, the sum of distances of parts from the global origin, the amount of intersection between parts and the amount of intersection between parts and the build cylinder, were integrated by weight factors and used for evaluating the packing solutions. As the authors stated, the packing quality depended heavily on weight factors employed in the evaluation function. It is difficult to pack large quantity of complex parts. In addition, the part's build orientation was not optimized, which could not guarantee the production quality of an obtained packing solution. Besides, the authors neglected an important issue, interlock checking, when packing parts with holes and cavities. Small parts would be placed into the enclosed or near-enclosed cavities of big parts, which would result in that parts cannot be separated after being built. One year later, one of the authors [9] commented this in his PhD dissertation. The authors said that their method did not use part order and permutation of parts was randomly-generated. However, the pre-set 'attachment points' implied a different part order or packing rule. Therefore, this method is still an improved serial packing method but it owns some characteristics of parallel packing method. Dickinson [4] carried out intensive research on packing subsets of arbitrary 3D objects. He regarded the three dimensional packing as a continuous problem and proposed to solve it by using another continuous problem-oriented evolutionary algorithm, Simulated Annealing (SA) algorithm. Point moment metric was defined and proposed to evaluate the alternative packing solutions. In his method, parts can be rotated freely and were represented by depth map to avoid packing parts inside each other. This method is the current state-of-the-art in published 3D packing methods [14]. However, it was more focusing on the graphical aspect of the packing problem but paid little attention to the real packing problem in AM. Parts in AM usually cannot be rotated freely during packing since the build orientation of parts cannot be randomly selected. And the point moment metric is not enough to evaluate the packing solutions when diverse user-defined packing objectives are set but not merely the packing compactness. Though the depth map representation method can totally avoid the interlock phenomenon, it missed the possibility of placing small parts into the unclosed cavities where parts would not interlock with each other. Apart from these, the method was mainly developed for packing subset of a specified group of parts. This is just one type of multi-parts production context in AM. Hence, it would have limitations for other production contexts.

After 2000, the nesting or packing research in AM took more considerations of AM process' constraints in practice. Hur et al. [7] proposed a part placement optimization strategy for SLS to maximize the utilization of work space and reduce the total build time. Before packing, parts' build orientations were optimized by considering part's build height and surface quality. Then, a modified Bottom-Left (BL) approach implemented by genetic algorithm was used to search an optimal packing solution within a cylindrical