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Part decomposition and 2D batch placement in single-machine additive manufacturing systems

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ABSTRACT

To produce a large object within a limited workspace of an Additive Manufacturing (AM) machine, this study proposes a two-phase method: (1) part decomposition to separate a part into several pieces; and (2) 2D batch placement to place the decomposed parts onto multiple batches. In Phase 1, the large object is re-designed into small pieces by a *Binary Space Partitioning (BSP)* with a hyperplane, where parts are decomposed recursively until no parts are oversize the limited size of the workspace. In Phase 2, the decomposed parts are grouped as batches to go through serial build processes using a single AM machine. Within a batch, the decomposed parts are placed based on a 2D packing method in which parts are not placed over other parts to avoid potential surface damage caused by support structure between parts. A *genetic algorithm (GA)* for the 2D batch placement is applied to find near-optimal solutions for build orientations, placement positions, and batch number for each part. As an objective function, the total process time including build time and post-processing time is minimized. This research provides some insights into the relation between part decomposition and 2D batch placement. It shows that minimizing the number of decomposed parts could be more critical than minimizing the size of decomposed parts for reducing the overall process time in serial batch processes.

1. Introduction

Researchers and practitioners have considered *Additive Manufacturing (AM)* as a supplement to the traditional manufacturing (subtractive and formative) [1,2]. However, the AM technology still has several practical limitations such as the finite workspace size of an AM machine [3]. In some cases like houses [4,5] and automobiles [6] that the size of a product is non-scalable and larger than the buildable size, a sufficiently large AM machine might be one solution. However, developing large-scale AM machines does not seem practical, since it requires a huge investment and causes other limitations such as less flexibility of storages and difficulty of transportation. Another solution is to re-design an initial model into assemblies to fit in smaller-scale workspaces. For decades, researchers have worked on methods to decompose an object, *Part Decomposition for AM* [7,8], and methods to pack multiple parts into the limited space, *Part Packing or Placement for AM* [9]. These two issues have been addressed independently and sometimes simultaneously, *Decomposition-and-Packing (DAP) problems for AM* [10].

This paper provides three main research contributions. First, it expands the research boundary of DAP by applying multiple batches rather than a single batch. This is a practical need as an AM machine has a limited workspace and multiple batches are often required to print the whole product. Second, this study presents the relation between the part decomposition and the multiple batches. It discusses that the number of decomposed parts could be more critical than minimizing the size of decomposed parts in terms of reducing the overall process time of serial batch processes. Third, it shows that the 2D packing could be preferred to 3D packing for multiple batches in terms of minimizing the support amount. It validates the claim by Zhang et al. [9] that 2D packing is effective in terms of improving the surface quality by avoiding overlapping parts [9].

In this study, an original model is decomposed into several pieces to fit in the limited space of an AM machine, and then the decomposed parts are placed in multiple batches with 2D packing that is named as 2D batch placement. Fig. 1 illustrates the overall procedure of the proposed approach for a rabbit model. First, an initial solid model goes through the part decomposition algorithm and is decomposed into seven pieces. Then, the pieces enter into the *genetic algorithm (GA)* for the 2D batch placement. In this example, the decomposed parts are placed over three batches as shown in Fig. 1-(b).

The proposed method in this study is suitable for large-size and non-scalable objects since it includes a part decomposition method to fit in

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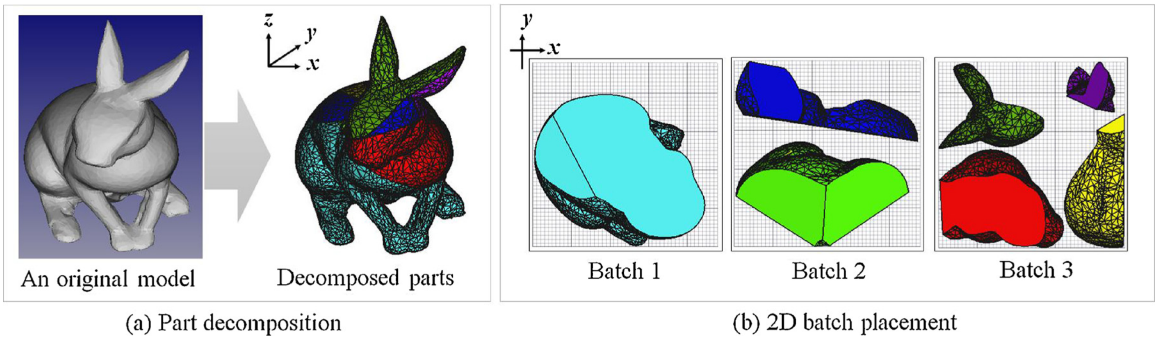

(a) Part decomposition (b) 2D batch placement

Fig. 1. A Two-Phase approach: (a) part decomposition and (b) 2D batch placement.

the limited workspace. In addition, since the batch placement is based on 2D packing, this study can be effective for the AM technologies with support structure issues, such as *Stereolithography (SLA)* and *Fused Deposition Modeling (FDM)* [11].

The rest of this paper is organized as follows. Section 2 reviews the related literature on part decomposition and packing issues for AM. The proposed methods and algorithms are introduced in Section 3. A numerical example is described in Section 4. Finally, Section 5 concludes the study and suggests the future research directions.

2. Literature review

To clearly categorize the literature, we define two groups of multiple parts based on component relations: *independent parts* and *dependent parts*. The independent parts are literally not related to each other for assembly. For instance, the relation of a rabbit model and a cat model. On the other hand, the dependent parts are sub-assemblies needed to complete a final product such as table legs and a table board. Section 2.1 reviews AM studies on how dependent parts are generated from an initial object and how they are packed in a limited workspace. The literature for packing issue of independent parts is covered in Section 2.2.

2.1. Part decomposition and packing of dependent parts (assemblies)

2.1.1. Part decomposition methods to fit an object into a limited work size

Part decomposition has been studied for several purposes: to fit a large object into the limited workspace of an AM machine [12]; to minimize process time [13]; to remove support structure [14]; to improve surface quality [15]; to have interchangeability among parts [16]; and for artistic purpose [17]. The current paper focuses on the first purpose, known as *printability*.

To fit an object into the limited workspace of an AM machine, several decomposition methods have been developed. For example, Chan and Tan [18] proposed a decomposition method [18], in which a solid model is cut with split tool surfaces, a hyperplane or a curved surface, to fit in a rectangular or cylindrical chamber. Medellin et al. (2006) suggested a decomposition algorithm to generate octants [19]. They developed a recursive decomposition process that divides a cube into two spaces for the three axes (x, y, and z) by a hyperplane, and finally, an octree structure is generated in which each parent node has eight child nodes. The octants are cubes of leaf nodes in the octree structure. Hao et al. [20] presented a curvature-based partitioning method to fit a large complex model to the buildable space [20]. In their algorithm, the best-fit loop is selected and then cut with a hyperplane. Luo et al. [7] suggested a framework for decomposing a large solid 3D model into smaller pieces to fit into the working volume of the 3D printer, known as *the Chopper*. They adopted a BSP and cut an initial model with a hyperplane [7]. A binary tree represents decomposition processes and the leaf nodes are final decomposed parts. In their algorithm, cutting is recursively conducted until the part volume is less than a certain threshold parameter. However, the focus of the above-mentioned studies was only on the part decomposition not packing issues.

2.1.2. Considering both decomposition and packing issues

Some studies have addressed both decomposition and packing topics known as *PackMerger* [21], *decompose-and-pack* [10], *partitioning and packing* [22] or *split-and-pack* [23]. Vanek et al. [21] were the first group who expanded the object decomposition issue to packing problems for AM, which affected later studies such as Chen et al. [10]. In PackMerger, an initial model is decomposed into several parts using a bottom-up approach in which several starting seeds are getting merged with adjacent cells. Then, build orientations and packing of resulting parts are optimized sequentially [21]. Later, other studies have optimized both orientation and packing issues simultaneously [10,22,23]. For example, Chen et al. [10] adopted a pyramidal shape [24] to solve both part decomposition and 3D packing issues, known as DAP problems [10]. They proposed a global optimization algorithm for solving DAP problems, named as Dapper. The Dapper algorithm aims to minimize support material, build time and assembly cost, and considers several constraints including the bounding container, and the assembly thresholds such as cut area and part thickness. Yao et al. [22] developed the decomposition and packing system based on level-set methods [22]. The level-set method is used to refine segmentation boundary between parts with free forms such as curved seams. The authors showed a locking issue that prevents decomposed parts from being assembled back into the original shape. However, the above-mentioned decomposition and packing studies only consider 3D packing assuming the full placement of all parts. This still leaves the subset placement issue that all parts cannot be placed on one AM machine.

2.2. Packing optimization of independent parts

The packing problem deals with how to optimally place independent multiple parts (with same or different shapes) into a limited build space (3D packing) or onto the build tray (2D packing) with respect to user-defined objectives [9].

2.2.1. 3D packing

To name several studies that have been focused on 3D packing, Ikonen et al. [25] developed a GA for packing 3D non-convex parts with cavities and holes into the build cylinder of a *Selective Laser Sintering (SLS)* machine [25]. Parts are randomly selected from a specified group to form a subset of parts in which each part had 24 pre-defined alternative orientations (45 degrees of increment in three directions). The parts are placed one by one with finite relative positions constrained by a pre-set including five attachment points for each part. Hur et al. [26] proposed a part placement optimization strategy for SLS to maximize the utilization of workspace and reduce the total build time [26]. Before