

IMPROVED CO-SCHEDULING OF PRINTING PATH SCANNING FOR COLLABORATIVE ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing processes, especially those based on fused filament fabrication (FFF) mechanism, have relatively low productivity and suffer from production scalability issue. One solution is to adopt a collaborative additive manufacturing system that is equipped with multiple extruders working simultaneously to improve productivity. The collaborative additive manufacturing encounters a grand challenge in the scheduling of printing path scanning by different extruders. If not properly scheduled, the extruders may collide into each other or the structures built by earlier scheduled scanning tasks. However, there existed limited research addressing this problem, in particular, lacking the determination of the scanning direction and the scheduling for sub-path scanning. This paper deals with the challenges by developing an improved method to optimally break the existing printing paths into sub-paths and assign these generated sub-paths to different extruders to obtain the lowest possible makespan. A mathematical model is formulated to characterize the problem, and a hybrid algorithm based on an evolutionary algorithm and a heuristic approach is proposed to determine the optimal solutions. The case study has demonstrated the application of the algorithms and compared the results with the existing research. It has been found that the printing time can be reduced by as much as 41.3% based on the available hardware settings.

Keywords: Additive manufacturing, path partition, path scheduling, multiple extruders

NOMENCLATURE

Set:

$R = \{1, \dots, n\}$ Set of printing path
 $J = \{1, \dots, m\}$ Set of extruders
 $K_r = \{1, \dots, q_r\}$ Set of breakpoints of path r .

$I = \{1, \dots, \sum_{r \in R} b_r\}$

Set of sub-paths

Decision Variables:

$z_{r,k}, r \in R, k \in K_r$

Equals 1 if the k -th breakpoint is selected for path r

$x_{i,j}$

Equals 1 if sub-path i is assigned to extruder j

y_i

Printing direction of sub-path i .

$ST_i, i \in I$

The start time of sub-path i

Auxiliary Variables:

$ET_i, i \in I$

The end time of path i

$C_{max} = \max(ET_i)$

Makespan of the solution

$l_j(t)$

Location of extruder j at time t

p_i

Process time of path i

Parameters:

v

Printing speed

$d_0(j_1, j_2)$

Closest distance between j_1 and j_2

b_r

Max number of breakpoints in path r

Δt

Time interval to be added for LPT

1. INTRODUCTION

Fused filament fabrication (FFF) is additive manufacturing (AM) process that uses a continuous deposition of a thermoplastic material [1]. The wide range of raw material available to be fed through a heated extruder has led FFF to gain popularity. The FFF is now the most popular process (by the number of machines) for hobbyist-grade 3D printing. However, the original motivation of developing FFF is to produce small but complex geometries. The upscaling of the FFF process and

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the process productivity is hindered by limited printing speed [2].

To improve the productivity of FFF, one solution is to adopt a collaborative additive manufacturing process, which employs multiple extruders to co-create a structure. In this process, manufacturers need to decompose the printing task into several subtasks and then assign them to different extruders simultaneously under the collision avoidance constraints [1]. The major **challenge** in the collaborative FFF is collision avoidance through printing path scheduling. For each printer, the printing paths are usually predetermined by the manufacturing process planning software. Different extruders will scan the sub-paths at prescheduled times. If not properly scheduled, the extruders may collide into each other or collide with the structure created by some previously scheduled tasks. One straightforward method is to leave a *large* safety margin between extruders. However, this strategy may lead to an unbalanced workload among extruders and long idle time of some extruders, reducing the efficiency of the process. As such, the collaboration may not always improve the printing process productivity by the desired extent. In addition, the printing path planning/generation has been determined by commercial printers' software packages. Thus, the scheduling of sub-path scanning, instead of path planning, has become a major issue affecting the effectiveness of the collaborative additive manufacturing system and its widespread applications.

In the past, collision avoidance algorithms have been widely studied in the robotics and transportation literature [3, 4]. However, most of the existing research is not suitable for the co-scheduling problem in the collaborative additive manufacturing process. Babu et al. proposed a plausible clustering method that draws a region around a set of trajectories [5]. More recently, Jose et al. used A* and genetic algorithms to generate an adaptable task schedule for a multi-robotic system when a rapid movement is detected [6]. However, it does not consider further path partitions for optimality, and the collision avoidance needs to be maintained during the entire printing process. There exist complex interactions between path scheduling and collision avoidance check.

While many FFF machines possess multiple extruders, most of them are usually designed for multi-material and/or multi-color printing rather than concurrent printing [7]. In [2], a generic toolpath allocation and scheduling methodology to achieve concurrent printing for multiple extruders was developed. The result shows that with three extruders, layer printing times were reduced by as much as 60% compared with single-extruder machines. This research is the first attempt to develop an integrated method of the collision checking and parallel scheduling for the FFF process. One drawback of this research is

that the sub-paths need to be predefined or generated by the software without considering the optimality.

Based on the review of state-of-the-art research, the following **research gaps** are identified:

- Research on the co-scheduling problems for collaborative additive manufacturing is still very limited.
- Prior research did not consider the scanning direction in the scheduling problem. However, the direction can potentially reduce the makespan of the entire scanning tasks, which is the time necessary to complete all the scanning tasks in a printing layer.
- The formation of sub-paths in each printing layer to refine the scheduling was not sufficiently addressed. Prior research specified the sub-paths without considering the impacts of the sub-path breakpoints on the optimization of makespan.
- To the best of authors' knowledge, there is a lack of research on the concurrent optimization of printing path partition (sub-path generation) and the corresponding co-scheduling problem among multiple extruders.

Thus, the objective of a scheduling problem is to minimize the makespan, which is the elapsed time between starting and finishing one product [8].

The remainder of this paper is organized as follows. Section 2 provides the mathematical formulation of the proposed problem considering path partition and scheduling problem simultaneously. In Section 3, a hybrid method is proposed to solve the problem. Section 4 shows the case study to demonstrate the application of the proposed algorithm and compares the performance with existing research. Finally, Section 5 concludes the paper.

2. CO-SCHEDULING PROBLEM FORMULATION OF COLLABORATIVE ADDITIVE MANUFACTURING SYSTEMS

The optimization model for the problem mentioned above is provided in this section to minimize the makespan of the printing process with the appropriate sub-path partitioning and scheduling subject to the collision avoidance constraints. The objective of the optimization problem is to minimize the makespan of the fabrication process. The mathematical model can be formulated as follows, i.e.,

Objective function:

Minimize the makespan:

$$f_1 = \min C_{max} \quad (1)$$

Subject to:

$$\sum_{k \in K_r} z_{r,k} \leq b_r \quad (2)$$

$$\sum_{j \in J} x_{i,j} = 1, \forall i \in I \quad (3)$$

$$|l_j(t) - l_{j'}(t)| \geq d_0 \quad (4)$$

where C_{max} is the makespan. The first and second constraints are used to ensure the total number of the sub-paths do not exceed the limitation, and the generated sub-paths can be only assigned

once to one extruder. The collision checking in this paper is simplified to the closest distance among multiple extruders. It requires the distance between extruder j_1 and extruder j_2 to be larger than $d_0(j_1, j_2)$ at any time during the printing process. The distance $d_0(j_1, j_2)$ can be chosen with a relatively small number as long as the size of the extruders can be accommodated.

To solve the proposed optimization problem, a hybrid method based on an evolutionary algorithm and heuristic approach is introduced in the next section.

3. HYBRID ALGORITHM FOR COLLABORATIVE ADDITIVE MANUFACTURING

In this paper, a hybrid algorithm is developed to solve the optimization problem. First, an Evolutionary Algorithm (EA) is developed to find the sub-paths partition for the scheduling problem within reasonable computational time for a relatively large optimization problem. Second, a collision-free heuristic scheduling algorithm is developed for the assignments of sub-path scanning tasks to extruders at appropriate times.

The hybrid algorithm is derived from the standard EA in this research. The fitness evaluation step is replaced by the heuristic approach by considering the collision avoidance constraints. The flowchart for the hybrid algorithm is shown in Figure 1.

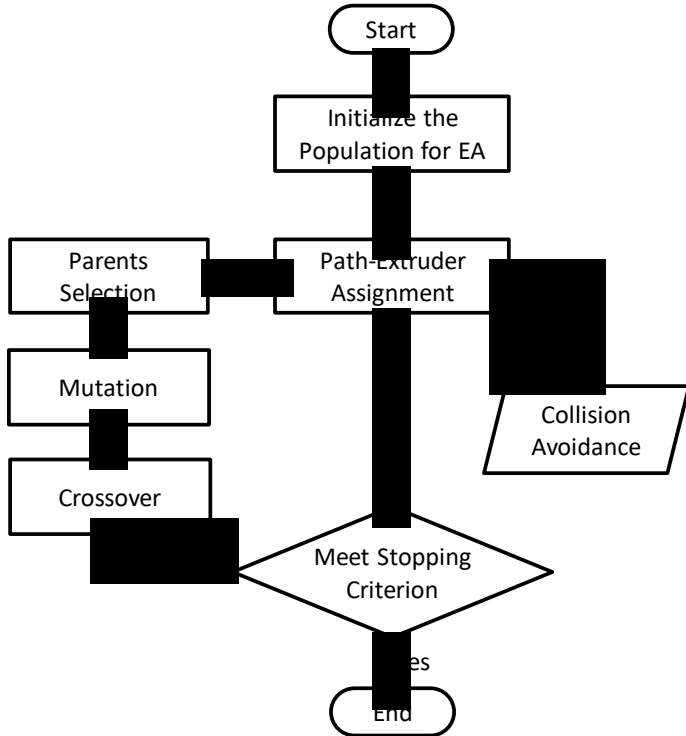


Figure 1: Flowchart of the hybrid algorithm

Different methods for the scheduling problems have been proposed including branch-and-bound enumeration [9], list scheduling (LS) [10], linear programming [11], and the longest processing time first (LPT) algorithm. This paper chooses the

LPT due to its demonstrated performance. In a regular scheduling problem to minimize the makespan, the conventional LPT algorithm assigns m longest jobs to m machines at $t=0$. After that, the longest job among those not yet processed is assigned to each machine as the machine becomes available [8]. In this research, more steps are needed to solve the scheduling problem because of the collision avoidance constraints.

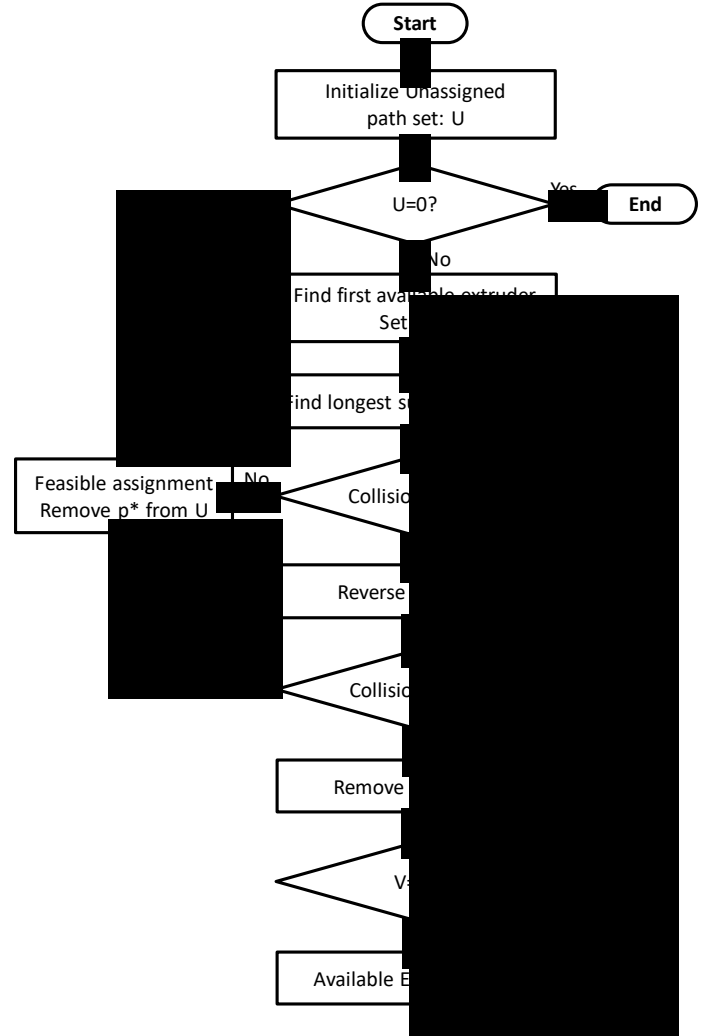


Figure 2: Flowchart of LPT algorithm

Figure 2 shows the flowchart of the LPT algorithm. The LPT starts by assigning the longest sub-path to the first available extruder (when several extruders are available, the assignment starts from the extruder with the minimum number). Then the algorithm searches for the remaining sub-paths from longest to shortest until an assignment can be made without violating the collision avoidance constraints. In this step, each sub-path will be evaluated again by reversing its printing direction if its predefined printing direction does not meet the requirement of the collision avoidance algorithm. If none of the remaining sub-paths can be assigned to the available extruder(s), a predefined

time interval Δt will be added to the starting time of the earliest available extruder(s). The process repeats until one sub-path can be assigned to one extruder without causing a collision and all the sub-paths have been assigned to different extruders with the optimized printing directions.

4. CASE STUDY

In order to make comparisons with the existing research, a similar case is borrowed from [2]. The layer to be printed is shown in Figure 3. It is a 20 unit $\times$ 20 unit circle that includes some concave features.

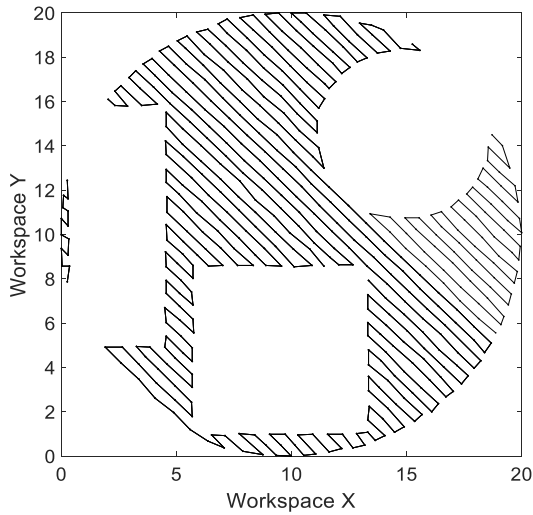


Figure 3: Example of one printing layer

In [2], there is an assumption that the sub-paths are pre-known and derived from single-extruder toolpath discontinuities. For the layer shown in Figure 4, four different sub-paths are pre-defined. Due to the hardware setup in our facility, the closest distance among extruders is defined as 10 unit to ensure the collision avoidance. By following the LPT above, the optimal scheduling for the 3 extruders is shown in Figure 4 with both 2D and 3D plots. The 3D plot shows the position of the different extruders along the time axis. Following this way, a makespan of 382 can be obtained, which is significantly less than 463 under one extruder.

If the path partitioning problem is further considered, a more optimal makespan could be obtained as follows in Figure 5. The result shows that the paths have been partitioned into multiple sub-paths, which are assigned to different extruders by using the LPT method. The 2D and 3D plots are shown in Figure 5. The makespan is calculated as 293, which saves 23.3% of the printing time compared with the result that does not consider the path partitioning.

EA does not guarantee the global optimality. The outcome of EA is the “best-discovered solution” under a given stopping criterion. The computational complexity is related to multiple factors, such as the total number of the candidate breakpoints (chromosome size), population size, maximum number of

generations, replications, etc. The selection of these parameters is a tradeoff between the optimality and the complexity. In this case study, 463 candidate breakpoints are predefined, the population size is 10, the algorithm will be terminated after 100 generations without replication. The computational time to obtain the optimal solution in Figure 5 is within 10 seconds.

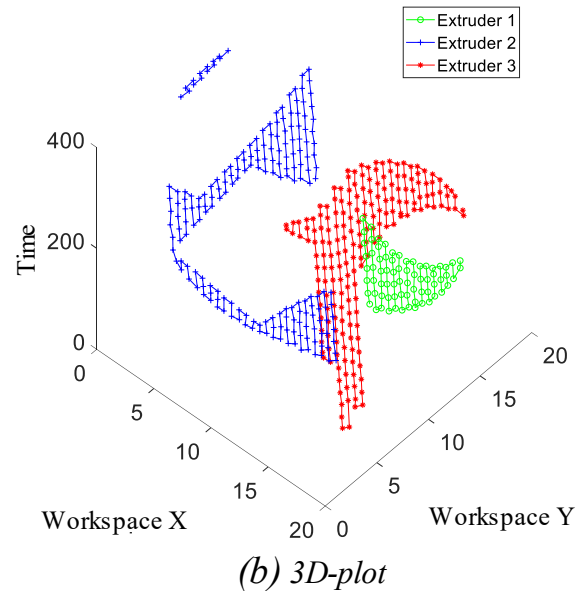
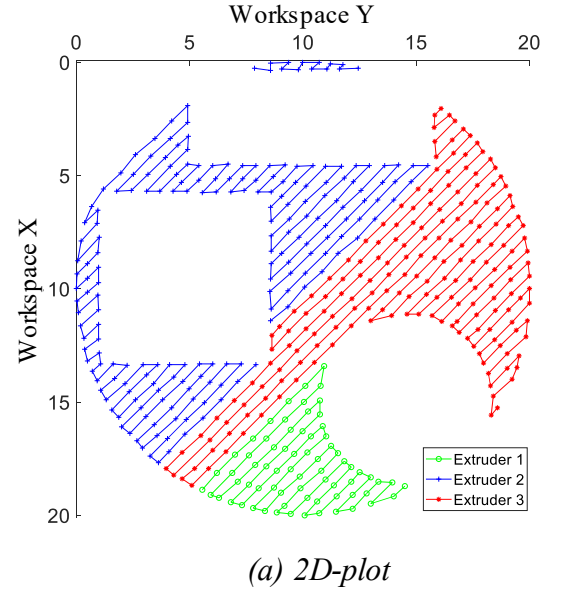


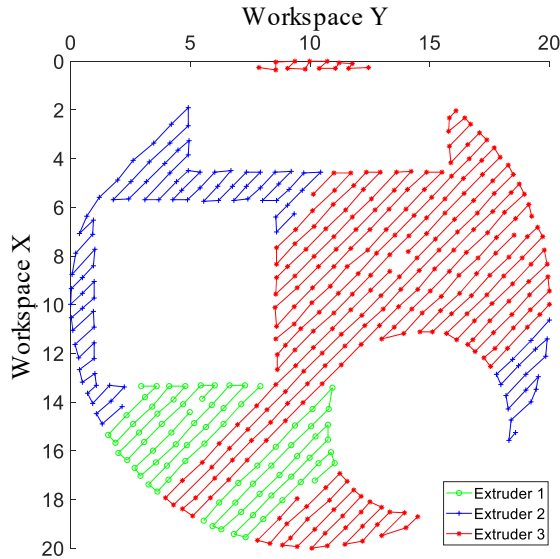
Figure 4: Graphic illustration of the scheduling result without optimal path partition

Discussion: Algorithm efficiency

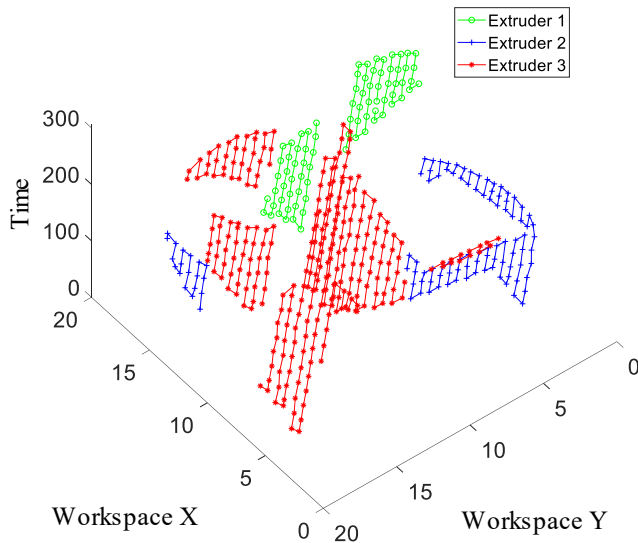
The efficiency of the algorithm is also related to the hardware setting. Based on the simulation, if the closest distance among extruder can be optimized to 3 unit, the makespan under

optimal path partition can be further decreased to 224 unit time, which is a 41.2% reduction on printing time.

It has been pointed out that the LPT algorithm requires repeated collision avoidance checks, which can become computationally expensive for some layer geometries. In the developed hybrid algorithm framework, the formulation of the EA can be further refined to improve the computational efficiency. In addition, the heuristic approach is not limited to the LPT, and it can be replaced by other alternative algorithms.



(a) 2D-plot



(b) 3D-plot

Figure 5: Graphic illustration of the scheduling result considering optimal path partition

5. CONCLUSION AND FUTURE WORK

The objective of this research was to develop a methodology to jointly determine the path partitioning and task scheduling along with scanning directions to facilitate collaborative additive manufacturing with multiple independently operating extruders. This challenge was formulated as a mathematical programming problem with collision constraints. An optimization model was developed to minimize the potential makespan of the printing task. A hybrid algorithm was proposed to solve the problem. The EA was introduced to solve the optimal path partitioning problem, and the one heuristic approach based on LPT scheduling algorithm was used to solve the NP-hard problem efficiently. The application and effectiveness of the proposed hybrid algorithm have been demonstrated based on a case study compared with existing research.

The results show that the research on optimal path partitioning can significantly improve the efficiency on concurrent extruder scheduling problem. Fabrication times for the case study were reduced by 23.3% to 41.2% considering different hardware setting. When the printing layer becomes even larger, it can be envisioned that the optimal path partitioning problem will play a more significant role in reducing the fabrication time.

Future Work: The collaborative path co-scheduling algorithm will be tested via in-house robotic manipulators for experimental validation. As shown in Figure 6 [12], the proximity of the robotic arms in Dexter act as a testbed in which collision-free operation can be performed and measured. Future publications will investigate collision free collaborative operation in an FFF application utilizing this apparatus.

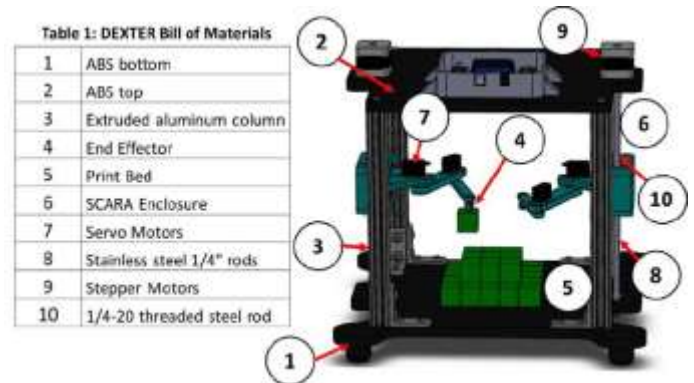


Figure 6: Experimental validation platform- DEXTER

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