3D PRINTING OF LARGE PARTS USING MULTIPLE COLLABORATIVE DEPOSITION HEADS – A CASE STUDY WITH FDM

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ABSTRACT: The objective of this work is to identify the challenges for the manufacturing of a large part with special focus on the fused modelling deposition (FDM) and to propose one solution for multiple collaborative deposition heads. A trilemma is identified among the build time, the quality and the dimensions of the parts. Current proposals to address this trilemma are evaluated.

KEYWORDS: (3D printing, PLA, Mechanical properties, water absorption, printing parameters)

INTRODUCTION

The additive manufacturing process (AM) encompasses the group of methods or technologies for the production of three-dimensional objects directly from a virtual 3D model through the addition of material (Gibson, Rosen, and Stucker 2015).

The techniques of additive manufacturing are diverse, but in several there is a deposition of material through a nozzle, such as fused deposition modeling (FDM), concrete printing or direct metal deposition (Gibson, Rosen, and Stucker 2010). Material extrusion is the process which deposits a material by extruding it through a nozzle, typically by moving the nozzle in a pattern that produces the cross-section of the part. The thickness of the layer is important to establish the quality of the piece, since the deposition of layers causes the so-called stair effect, causing volumetric errors (Panda et al. 2016). Reducing the staircase effect to improve the quality of the finished part increases the number of layers and hence the nozzle displacement, increasing the fabrication time for the part. In current FDM machines, the compromise is between the manufacturing time, the quality of the part and the dimensions of the part (Figure 1). Current
systems opt for part quality and reduced manufacturing time resulting in small parts. This trilemma states that you can have only two out of three: whether you want to manufacture small parts with high quality and low build time, or get larger dimensions with lower quality or higher manufacturing times.

Figure 1 – Trilemma around FDM additive manufacturing process.

ARCHITECTURE FOR FDM MACHINES WITH MULTIPLE PRINT HEADS

Fused Deposition Modeling with multiple print heads is the FDM technology applied to deposition using simultaneously more than one print head, mechanically independent one from each other and working on the same machine. This change in the architecture means that both machine and process planning must be changed to address the coordination among print heads. The increase of the build area seek to satisfy the need of printing larger objects, or, for smaller objects, the need to increase production volume. Considering a larger printing area, a larger number of equal print heads can be used to increase number of parts produced at the same time. A few concepts of multiple print head machines are shown in Figure 2 and described above. The Stacker company commercializes a machine capable of fabricating up to 4 parts simultaneously and they have a patent for a modular system in which the print heads are attached to the same axis in static distances from each other allowing for the replication of (up to) 4 parts simultaneously (Fontaine 2016). Jian (2015) presents a machine configuration with rotary print heads distributed around a rotating shaft perpendicular to the build platform. The multiple print heads move independently in the radial direction. In situations where parts are large enough or multiple different parts are being fabricate on build platform, then multiple independent extruders could be used to build parts simultaneously (Wachsmuth 2008). Other example of decreasing build time with parallel fabrication is the Contour Crafting technique with multiple nozzles, although the deposition being made in a different scale than FDM. The work of Zhang and Khoshnevis (2013) proposes two machines. The first machine is composed by one X-Y stage with independent gantries. The second is a machine composed by one overhead platform containing several co-planar gantries. In Project Escher from Autodesk the concept of multiple independent gantries was also proposed. Very few information was available and at the moment of this work, the authors did not get a response to the request for more details on the project. Anyway, the project claims not to have been developed nor will a machine be release, but a parallel processing system will be developed instead (Autodesk 2016). Another example of multiple print head is the patented Additive Manufacturing Device assigned to Massivit company (Uzan and Yakubov 2015). The system is composed by one or multiple tracks parallel to one axis (X axis) of the build platform. Multiple carriages, along these
tracks and parallel to the other axis (Y axis), allow for multiple print heads to move independently from each other.

![Figure 2](image)

Figure 2 – Multiple heads equipment: a) Stacker 3d printer (Fontaine 2016); b) Rotary system (Jian 2015); c) Multiple independent heads (Wachsmuth 2008); d) Independent parallel deposition (Zhang and Khoshevis 2013; Autodesk 2016); e) Multiple independent heads (Uzan and Yakubov 2015); f) Multiple independent heads (Frutuoso 2017; Boto 2016)

**A NEW PROPOSAL FOR MULTIPLE COLLABORATIVE PRINTING HEADS**

A different system is proposed in this paper: a new system with multiple autonomous collaborative printing heads capable of printing parts in a fraction of time compared to a single printing head.

In this modular system, each print head can superimpose partially the areas covered by others. This innovative configuration of the deposition modules allows the upper deposition module to travel along a pair of rails, while a lower deposition module travels along an adjacent pair of rails without collision between them unless, of course, the print heads were fabricating too next to each other, which is prevented by centralized planning. This characteristic allows for a virtual unlimited expansion of the number of pairs of rails and the number of deposition modules. If two or more pairs of rails are used, along a certain pair of rails there is just one type of deposition modules. If only one pair of rails is used, then upper and lower deposition modules can work along the same rails. Deposition modules are also removable and interchangeable. Not only the several machines presented above are different in their architecture, but also the process planning can be significantly different to make use of the ability of the print heads to cooperate. The process planning for multiple independent print heads is not a standard process – at least, not yet.
As expected, it shares all the steps required in the process with one print head, but it is more complex because all the process has to account for multiple print heads inside the machine. The major steps required are presented next and explained in detail below:

- Choice of the most favorable orientation, assessment of the support structure needed and slicing of both part and support.
- Part positioning and partitioning for a calculated number of print heads.
- Tool-path generation for multiple print heads, avoiding collisions among them.

Determining orientation, support structure and slicing are straightforward issues, closely related with one head machines. Nonetheless part positioning and partitioning are new challenges. Optimizing toolpaths so that idle times are minimized due to collision avoidance is also very important. Figure 3 presents the major steps concerning multiple printing heads. These issues are important for a machine to work, but after they are solved, new research is expected along various directions. First, the material properties: there will be two contour lines at each border among the several domains (areas printed by each head), this will weaken the material mechanical properties. Therefore, generating sowing paths will be very important. Another issue is the control of the machine. Usually, low cost machines are open loop controlled and systematic issues occur when the device is not well tuned. For smaller parts this might be acceptable, but for bigger parts the risk of not having a part in the end of the fabrication process is higher, thus demanding a system with closed loop control. Still another issue is the platform. In all the cases above we find one single platform where the material is deposited. Extending the concept of multiple heads to multiple platforms would be extremely beneficial in reducing support material for parts with overhangs or to initiate production with the possibly free heads while another work is being built, if there are free platforms. Each machine in Figure 2 exhibits strong valued proposals to users of additive manufacturing technologies for large parts fabrication. The Stacker system allows fabrication of multiple equal parts at the same time. The rotary system suggests that the center might not be printable, but is a solution for cylindrical parts that are hollow taking advantage of polar coordinates. Parallel systems push the X dimension for bigger parts. Our proposed concept architecture pushes the dimensions of fabrication area on both, X and Y axis, being at the same time the most complex machine to build and control.

![Diagram](image)

**Figure 3 – Process planning for multiple printing heads.**

### EXAMPLES

In this example we aim to demonstrate the relevance of printing with multiple printing heads. In these examples, simulations were performed in order to assess the potential performance of the system described above. The printing velocity was considered unitary and an infill of 35% was used. Collision distance between heads is 60 mm.
Four different parts were designed to be printed in a build area of 600x600 mm with up to nine collaborative autonomous printing heads. The best strategy for parts one to three was found to require 4 deposition heads, while for part four, all nine deposition heads were deemed necessary. Figure 4 displays the size and shape of the 4 parts.

Using part one as an example and to select the lowest process estimation time, 4 strategies were devised to decide on the best printing domains for each deposition head. This was done using a combination of fixed vs variable printing areas and using positioning and rotation with Monte Carlo simulations or with heuristics. Figure 5 exhibits the final result of each strategy.

Figure 6 shows the results of simulations for each strategy. The left side shows the fabrication time for each strategy for part one; the first 3 strategies use only four out of nine available printing heads, while the last needs 6. On the right side, the time savings for all the parts and all the strategies reveal savings from 80% to 56% of the fabrication time using only one head. These examples show that, although handicapped by some idle time, the use of multiple collaborative printing heads achieves considerable time savings.
CONCLUSIONS

In this paper the need for printing larger parts using additive manufacturing is addressed, namely in FDM. It is a huge problem and there are several attempts to solve this issue. The trilemma of time, space and quality is addressed and from the literature review, we can only have two out of three for single printing head. Several concepts from the literature were reviewed and a new concept for multiple printing heads is presented. In the proposed solution the heads being autonomous, but collaborative, means that time to build is reduced, quality can be maintained and dimensions of parts can increase significantly. With this innovative concept the size of a part can increase without the expense of quality or time. Also new possibilities for research and development are identified and discussed, especially on part positioning and partitioning.

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