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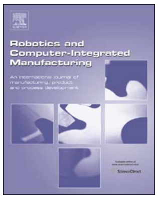

# A non-retraction path planning approach for extrusion-based additive manufacturing

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## ABSTRACT

Notwithstanding the widespread use and large number of advantages over traditional subtractive manufacturing techniques, the application of additive manufacturing technologies is currently limited by the undesirable fabricating efficiency, which has attracted attentions from a wide range of areas, such as fabrication method, material improvement, and algorithm optimization. As a critical step in the process planning of additive manufacturing, path planning plays a significant role in affecting the build time by means of determining the paths for the printing head's movement. So a novel path filling pattern for the deposition of extrusion–based additive manufacturing is developed in this paper, mainly to avoid the retraction during the deposition process, and hence the time moving along these retracting paths can be saved and the discontinuous deposition can be avoided as well. On the basis of analysis and discussion of the reason behind the occurrence of retraction in the deposition process, a path planning strategy called “go and back” is presented to avoid the retraction issue. The “go and back” strategy can be adopted to generate a continuous extruder path for simple areas with the start point being connected to the end point. So a sliced layer can be decomposed into several simple areas and the sub-paths for each area are generated based on the proposed strategy. All of these obtainable sub-paths can be connected into a continuous path with proper selection of the start point. By doing this, separated sub-paths are joined with each other to decrease the number of the startup and shutdown process for the extruder, which is beneficial for the enhancement of the deposition quality and the efficiency. Additionally, some methodologies are proposed to further optimize the generated non-retraction paths. At last, several cases are used to test and verify the developed methodology and the comparisons with conventional path filling patterns are conducted. The results show that the proposed approach can effectively reduce the retraction motions and is especially beneficial for the high efficient additive manufacturing without compromise on the part resistance.

## 1. Introduction

### 1.1. Additive manufacturing

Additive manufacturing (AM), also referred to as layered manufacturing (LM) or rapid prototyping (RP), is a fundamentally different fabrication process from conventional manufacturing methods by integrating computer aided design, material science and computer numerical control to fabricate physical prototypes from virtual CAD models layer by layer [4]. The recent decades have witnessed the rapid development of AM technologies which have been gradually employed in a wide range of applications, such as prototype fabrication, product development, biomedical engineering, electronical devices, and architecture, etc. [45]. Additionally, the capability of producing customized parts has also stimulated the interest of public in this technology. AM offers huge potential in many applications by reducing the development period and eliminating some stages of conventional fabrication methods, as well as building parts without geometric constraints. These advantages have brought in a surge of research interest in AM from many disciplines to bring its all potentialities into full play [37].

After nearly three decades of research, development, and use, a variety of AM technologies are available from the market and more potential techniques for AM are being developed by researchers with the introduction of new technologies, methods, materials, applications, and business models [44]. There are currently seven categories of AM classified by ASTM International Committee F42 based on the forming processes: material extrusion (e.g. Fused Deposition Modeling, FDM), material binding (using inkjet printing process to deposit material),

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binder jetting (using inkjet printing process to deposit liquid bonding agent), sheet lamination (e.g. Laminated Object Manufacturing, LOM), vat photopolymerization (e.g. Stereolithography Apparatus, SLA), powder bed fusion (e.g. Selective Laser Sintering, SLS) and directed energy deposition (e.g. Direct Metal Deposition, DMD). Besides, it is believable that new processes would be developed in the near future that do not fit into any categorization. Although the joining details and the forming equipments of different AM processes differ from each other considerably, they share some common aspects, such as the pre-process on virtual models before practical fabrication, the deficiencies of the fabricated parts, and the issue of long producing time.

Similarly to other manufacturing methods, AM has its own shortcomings and limitations in terms of the quality of manufactured parts and the fabrication efficiency. So far, many efforts have been devoted to improving the part performance and enhancing the fabrication efficiency. In the aspect of part quality, surface roughness and dimensional accuracy are two primary topics that have been studied and investigated. Before proposing specific approaches and methods to address the surface roughness, the surface profile of additively manufactured parts should be modeled firstly and then adopted to analyze the relation between various parameters and the surface finish [1,19,5]. The established surface models can assist in improving the surface quality by the optimization of process parameters [24,34] and post-processing strategies [28,31]. Likewise, the dimensional accuracy has also attracted many attentions from researchers; various studies have been carried out to investigate the process parameters which affect the part deviation during the whole fabrication process. Fahad et al. [11] developed a new benchmarking part to evaluate the accuracy and repeatability of AM processes by considering certain features and dimensions to ensure that the operation capabilities were fully evaluated. As the dimensional accuracy is affected by a variety of factors, some approaches were proposed and adopted to obtain the influence on the part accuracy exerted by process parameters, such as grey Taguchi method [35] and artificial neural networks [29], and finally to minimize the deviation in the fabrication process. Besides, the error compensation is an effective method to improve the dimensional accuracy. For example, Tong et al. [40,41] proposed a parametric error modeling and software error compensation method to address and evaluate the volumetric accuracy of the AM machines inspired by the techniques used for the parametric evaluation of coordinate measuring machines and machine tool systems, and the testing results of proposed strategies showed a significant improvement in dimensional accuracy of built parts. At the same time, they [39] utilized another method to compensate the error by correcting both the STL and sliced file.

With regard to the fabrication efficiency, although AM has long been labeled as a technique that can shorten the production period, it is not always true and the fabrication process is not as rapid as desired actually. The fact that the time for fabricating **n** objects is **n** times as much as that for one object in AM brings in that the current AM systems are becoming unacceptably slow with the increasing size and complexity of parts being fabricated [6]. So, the drawbacks of AM in fabrication efficiency becomes much more prominent when the objects to be produced turn from small cubic inches or thin wall features to parts with large sliced cross-sections. The fundamental reason is that the methodology of building a part in AM essentially consists of a sequence of steps which are necessary and cannot be neglected. The layer-based forming method leads to a mutually contradictory relationship between the surface quality and the build time. Specifically, a large layer thickness can reduce the number of the sliced layers, and hence shorten the fabrication time, but the surface quality would be deteriorated due to stair-step effect; though a smaller layer thickness can improve the surface finish, the fabrication efficiency would be affected inevitably. This problem becomes more serious when it comes to the extrusion-based additive manufacturing, where the semi-solid filament is deposited line by line to form a layer.

Some works have been done to fasten the fabrication process based on the aforementioned reasons. Besides the development and modification of the forming process to decrease the time consumed on one layer, like the continuous liquid interface production (CLIP) technique developed by Tumbleston et al. [42], another feasible methodology applied in the optimization during the process planning, such as build orientation selection [48], support reduction [2] and path optimization [17], is very effective and important. As the time traveling along a path is the basic component of the whole fabrication time, minimization of the traveling time for each layer by path optimization is thus essential to minimize the time needed for completing the fabrication of a part. The aim of this paper is to minimize the fabrication time by decreasing the number of the start-stop processes appearing in retracting paths, mainly for but not limit to, extrusion-based additive manufacturing.

### 1.2. Extrusion-based additive manufacturing

Among the most widely used and rapidly developing AM technologies, a typical and well-known technique is the extrusion-based additive manufacturing [43]. In this process, the material is fed into an extruder by the motor driving force or the pneumatic force, and melted (no need in some cases) in a liquefier to be extruded from a nozzle, which is controlled by a moving platform in the horizontal plane when the extruded material is squeezed and deposited on the build plate line by line based on the pre-designed paths to form a surface. The deposited surface would solidify rapidly when the material leaves the extruder and exposes to the atmosphere with much lower temperature and moisture. At the same time, the nozzle and build platform can be moved in the vertical direction relatively to enable the nozzle to be lifted by the distance of layer thickness to deposit upper layers, and finally to produce complex 3D objects.

The extrusion-based additive manufacturing technology has achieved great improvements in respect of model data processing, material property, part performance, and fabrication efficiency after a lot of works have been exerted. In the aspect of data processing, Kai et al. [20,21] presented an improved interface between 3D models and AM systems based on the analysis and investigations of existing file formats for AM. The proposed new file format support the STL format by removing redundant information in the original STL file and adding topological information to balance storage and processing costs. Starly et al. [36] pointed out that direct slicing from CAD models may overcome inherent disadvantages of using STL format in terms of the process accuracy, ease of file management, and incorporation of multiple materials. So they developed a direct slicing algorithm for the STEP-formatted NURBS geometric representation. Koc et al. [23] presented a method of biarc curve fitting technique to improve the accuracy of STL files, as well as to reduce the file size for AM. In the fabrication technique and employed material, Lee et al. [25] installed a spindle and a low-cost FDM extruder on each end of a rotary axis in a five-axis machine tool to fully realize the advantages of AM and conventional subtractive manufacturing and to improve the part accuracy which is usually uncertain in AM due to the uneven shrinkage and residual stresses. The materials for extrusion-based AM have been extended from the early thermoplastics to many types of functional materials, such as liquid metals, foods, drugs, and biocompatible materials. The adoption of these materials in extrusion-based AM enables this technology to be used in many new areas, like soft components as flexible sensors for electronical devices [3] and biological soft tissues [30]. With regard to part performance and fabrication efficiency, the related studies and researches have been mentioned in the last section.

### 1.3. Process planning

Process planning of additive manufacturing technology is a bridge between virtual 3D models and AM machines by transferring the digital