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Reduction of support structures and building time by optimized path planning algorithms in multi-axis additive manufacturing

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Abstract

Additive manufacturing is an emerging technology that enables new product design. However, major inhibitors are long building times and a fixed build direction of the workpieces. In this article, new optimization and path planning methods for multi-axis additive manufacturing are presented going beyond conventional three-axis systems. This includes an adaptation of the building direction and an algorithm for the special case of cylindrical axes. These methods can reduce the production time drastically by avoiding support structures and by using the integration of predefined building blocks to substitute the infill. We present both, the new manufacturing process and the necessary computation methods for optimal process and path planning. Decreasing the building time and the amount of support structures paves the way for new application domains of additive manufacturing in the future.

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Keywords: Additive manufacturing; Multi-axis; Path planning; Trajectory; Support structures

1. Introduction

In recent years, additive manufacturing (AM) has become an emerging technology of the production industry. The potentials of AM are free forming of individual parts in an economic process, functional integration, multi-material workpiece fabrication and topology optimization [1]. This manufacturing method enlarges the possible variety of workpieces by overcoming limitations of conventional subtractive manufacturing and forming technologies, as shown exemplarily in previous work of the authors for biomimetic workpieces and processes [2,3]. There is a great variety of additive processes that can be grouped in powder bed, liquid based and freeform processes [4].

This paper focuses on fused deposition modelling (FDM) since it is a freeform process that allows the extension to more than three axes by adaptation of the kinematics, printing head and trajectory planning [5,6]. FDM is limited to thermoplastic materials, however, the developed algorithms and strategies can be applied to other processes using different materials, e.g. wire and arc additive manufacturing (WAAM) for metal workpieces [7].

State-of-the-art FDM printers are limited to three-axis movements with a fixed building direction in Z. Consequently, the slicing software splits the workpiece description, usually STL format [1], into single slices with a constant layer thickness limited by the nozzle diameter. For each horizontal layer, a two-dimensional path is calculated based on the nozzle diameter while focusing on the outer geometry. One constant infill pattern is chosen for the complete internal workpiece structure (e.g. diagonal infill) [8]. The resulting G-code is interpreted and executed by the machine control. The main drawback of this approach is the limitation to one fixed building direction, causing a possible lack of strength [9–11], a stair-step effect on the surface [12,13] and the need of support material for overhanging structures [12]. Toolpath calculation for five-axis subtractive machining (e.g. milling) is state-of-the-art and already embedded in commercial CAM software. Concerning multi-axis AM, recent developments deal with multi-directional slicing algorithms by dividing the workpiece in piecewise building directions [14]. Within each building direction, the conventional slicing strategies are applied yielding the same drawbacks as before.

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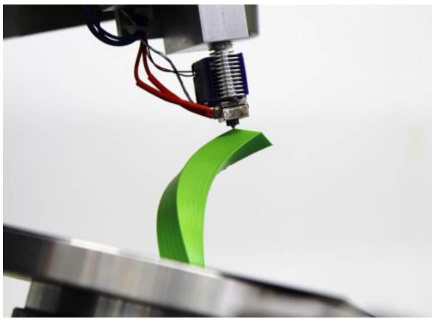

Fig. 1. Multi-axis printing on a seven-axis FDM machine developed at the University of Stuttgart.

The main advantage of multi-directional slicing is the reduction of support material by tilting the building table to avoid overhanging structures (Fig. 1). The shown prototype is a seven-axis FDM machine developed by the authors at the University of Stuttgart. The approach of using tilting and rotating tables can also be transferred to laser metal deposition [15]. Another research work provides an extension from conventional three-axis systems to three-dimensional path generation for strength-optimized curved layers of the FDM process [16]. This formulation is suitable for thin-section, slightly curved surface parts but it cannot be applied to solid parts and does not consider printing head rotations.

The main drawback of the algorithms in research and industry is that the full potential of multi-axis movements is not explored. Therefore, we propose a generic method for trajectory planning of multi-axis systems by adapting the building direction, demonstrated on a seven axis machine tool with FDM printing head. Then, we present a path planning strategy for a machine using a rotatory axis instead of a planar building bed to demonstrate the new possibilities compared to a conventional three-axis system.

This paper is structured as follows. Section 2 describes basic workpiece features that are relevant for workpieces manufactured by AM, especially freeform processes like FDM. In Section 3, the algorithms for creating three-dimensional trajectories for multi-axis FDM are described. Section 4 presents preliminary experimental results in a laboratory on an industrial machine tool equipped with a FDM printing head. The last section provides a summary and outlook towards possible future research topics.

2. Workpiece features

In order to explore the design freedom given by the multi-axis FDM process, it is necessary to define workpiece features. For conventional AM using three axes, geometrical features such as islands and overhangs are described in literature [17,18]. Islands are elements which are separated at the beginning of the process (Fig. 2 a)), and are then connected during the building process (Fig. 2 b)). Parts that are solid and stable when completed can therefore be unstable during the process.

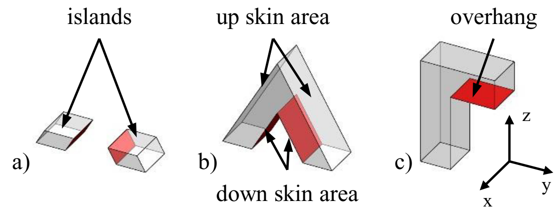

Fig. 2. a) Islands during the building process, b) completed workpiece and c) overhang in building direction Z (adapted from [18]).

Overhangs may need support structures, depending on the down skin angle (Fig. 2 c)). Different down skin angles are recommended varying from 40° up to 60°, where 45° are most common [19]. The down skin angle is the angle between a downwards facing surface (down skin area Fig. 2 b)) and the build platform plane [18]. Upwards facing surfaces (Fig. 2 b)) are called up skin areas with the up skin angle between the surface and the build platform plane [18].

In FDM, the workpiece geometry is mostly stored in STL files, which describe only the outer geometry [20]. The infill pattern and density is chosen manually by the operator and remains constant throughout the whole building process [21]. Therefore, workpieces with high volume consist mainly of infill material depending on the shape and size. Consequently, the highest production effort in terms of time and material is spent to produce infill patterns that are not described by the STL files and are just used as internal workpiece support. One approach to reduce material and time consumption is to decrease the infill density. However, infill is necessary in order to enable the fabrication of the outer layer, especially on the top of the workpiece, and it influences the surface quality.

Therefore, we propose to replace the printed infill pattern by pre-manufactured thermoplastic insertions (Fig. 3). Before the FDM process starts, the inner workpiece volume is assembled by using the available infill elements from a module kit. Those elements can be produced faster and cheaper by injection molding and can be provided by specialized suppliers.

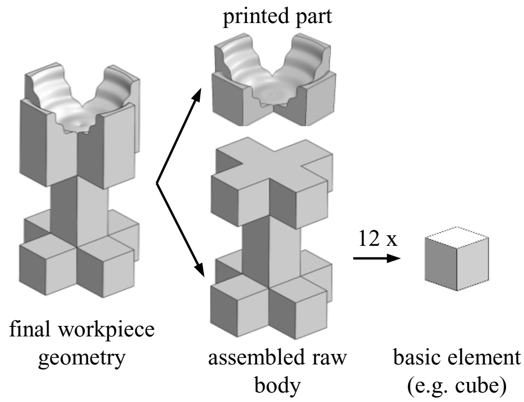

Fig. 3. Decomposition of a workpiece in basic elements (e.g. cubes) in order to replace the infill.