Computer-Aided Design 77 (2016) 107–119

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Implicit slicing for functionally tailored additive manufacturing

John C. Steuben, Athanasios P. Iliopoulos, John G. Michopoulos *

Computational Multiphysics Systems Lab, US Naval Research Laboratory, 4555 Overlook Ave SW, Washington DC 20375, United States

ARTICLE INFO

Article history:
Received 18 November 2015
Accepted 5 April 2016

Keywords:
Additive manufacturing
Toolpath generation
Implicit slicer
Digital thread
Functionally tailored materials
g-code generator

ABSTRACT

One crucial component of the additive manufacturing software toolchain is a class of geometric algorithms known as "slicers." The purpose of the slicer is to compute a parametric toolpath and associated commands, which direct an additive manufacturing system to produce a physical realization of a three-dimensional input model. Existing slicing algorithms operate by application of geometric transformations upon the input geometry in order to produce the toolpath. In this paper we introduce a new implicit slicing algorithm based on the computation of toolpaths derived from the level sets of arbitrary heuristics-based or physics-based fields defined over the input geometry. This enables computationally efficient slicing of arbitrarily complex geometries in a straight forward fashion. Additionally, the calculation of component "infill" (as a process control parameter) is explored due to its crucial effect on functional performance fields of interest such as strain and stress distributions. Several examples of the application of the proposed implicit slicer are presented. Finally, an example demonstrating improved structural performance during physical testing is presented. We conclude with remarks regarding the strengths of the implicit approach relative to existing explicit approaches, and discuss future work required in order to extend the methodology.

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1. Introduction

Additive manufacturing, also known as layered manufacturing, rapid prototyping, or less formally as 3D printing, is an increasingly important family of fabrication techniques for the production of a wide variety of components. These fabrication techniques are characterized by successive additions of material to a domain, as opposed to the repeated subtractions that are employed by most traditional fabrication technologies [1]. Recent years have seen a surge of interest in additive manufacturing technology from a broad number of engineering and manufacturing disciplines. This interest is primarily driven by the relative freedom from geometric constraints provided by additive manufacturing methods; geometries that are difficult or impossible to produce by conventional means are often readily achievable. Additionally, the possibility of producing customized, low volume, or otherwise economically infeasible products [2] has stimulated much interest in the field.

At the present time, a variety of additive manufacturing technologies exist. Common techniques include stereolithography [3], Fused Deposition Modeling (FDM) [4], Selective Laser Sintering (SLS) [5–7], Electron Beam Melting (EBM) [8], and Direct Metal Deposition (DMD) [9,10]. The mechanical details of these processes vary considerably, but they share a common software toolchain, known as the "digital thread". A block diagram of the digital thread concept is shown in Fig. 1. Because of the highly integrated nature of modern additive manufacturing software packages, the individual components of the digital thread are not always discussed in a distinct fashion. Fig. 1 shows the major components of the digital thread individually.

As Fig. 1 shows, the digital thread is subdivided into three major domains; the design environment, a preprocessing environment, and a manufacturing environment. The digital thread begins in the design environment, and originates from a Computer-Aided Design (CAD) model produced by a designer. The ultimate goal of the additive manufacturing process is to produce this model within acceptable constraints on accuracy, time, cost, and other parameters. Within the design environment, this geometry is converted to a triangular mesh form, typical encoded as a stereolithography (STL) or similar file. It is important to note that this conversion preserves approximate [11] geometric information regarding the original model only. Any other ancillary information encoded within the original model is lost in this process, although future use of improved model representations [12] may allow some information to be retained. Moving to the preprocessing stage, the position of the resultant mesh within the build volume of the additive manufacturing process is determined by a layout optimization routine. In practice, a collection of many meshes

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* Corresponding author.

http://dx.doi.org/10.1016/j.cad.2016.04.003
0010-4485/Published by Elsevier Ltd.

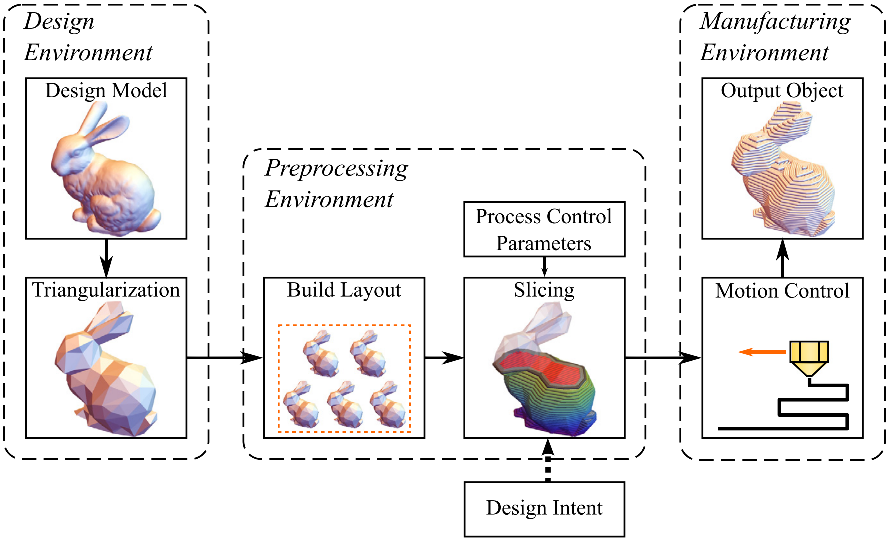

Fig. 1. An overview of the "digital thread" concept.

is packed into the build volume of the machine in order to reduce per-unit production costs, using a method such as that of [13]. The mesh (or collection of meshes) is then processed by an algorithm known as a "slicer". The purpose of the slicer is to subdivide the mesh(es) into a series of distinct layers, and to compute the numeric control (NC) commands issued to the additive manufacturing machine in order to produce the distinct toolpaths making up each layer. The build layout and slicer tools are often combined into a single commercial software product, that largely behaves as a "black box". Once the toolpath has been produced, the motion control software and hardware systems present in the manufacturing environment are used to drive the additive manufacturing machine in order to produce the output object.

The various stages of the additive manufacturing digital thread have been studied and developed for decades, and in many senses have reached a high level of development sophistication [14]. One important shortcoming of the current state of the art is the aforementioned loss of design information that occurs at the interface between the design environment and the preprocessing environment. This effectively reduces the additive manufacturing process to a purely geometric exercise. While this is acceptable for established uses of additive manufacturing such as the production of "look and feel" prototypes, there is currently a strong push towards the development of additive manufacturing technologies that imbue the components that they produce with functional properties. Examples of functional properties include yield and ultimate strengths, elastic anisotropy constants, residual strains, and thermal or electrical conductivities. Initial efforts documenting such activities can be found in [15,16].

The primary focus of this paper is on the development of a new type of slicing algorithm. The motivation for this development is to reduce the deficiency of design data in the preprocessing domain, and facilitate ongoing efforts to develop functionally imbued additively manufactured objects. In order to do so, we adopt a fundamentally different approach to the slicing problem. Unlike existing algorithms, that operate on the basis of explicit geometric transforms applied to the input geometry, we employ a novel implicit method based on the computation of level sets of field functions. We explore the use of field functions defined upon these regions in order to re-introduce design intent into the preprocessing environment. In particular, we develop a methodology by which the results of Finite Element Analyses (FEA) may be used to dictate the computation of toolpaths in order to improve functional performance fields of interest, such as strain and stress distributions, generated within additively manufactured components.

In order to provide motivation and context for the present work, Section 2 discusses both the origins and more recent development of slicing algorithms for additive manufacturing. In Section 3, we proceed to define the implicit field based slicer, discussing the mathematical details and their implementation in depth. In Section 4 we demonstrate the results of applying the implicit slicer to an escalating series of test problems. We first demonstrate the ability of the implicit slicer to compute toolpaths equivalent to those produced by explicit slicers on complex geometry. We then demonstrate the use of the slicer to compute toolpaths based on the solution to differential equations defined on the implicit layer regions. Finally, we use the results of FEA to compute toolpaths for a component intended to bear to mechanical loads. Following this, Section 5 presents the results of physical validation tests that demonstrate the use of the implicit slicer to tailor the mechanical responses of a test specimen. In Section 6 we conclude by giving remarks on the steps that must be taken to further develop the implicit slicer into a fully-fledged component of the additive manufacturing digital thread.

2. Background

Slicers are a class of algorithms in the domain of computational geometry that are used to convert input 3D geometry into a series of motion commands (a "toolpath") for an additive manufacturing machine. The slicer is required to both process the input geometry into a suitable toolpath for additive manufacturing, and export this toolpath as a series of numeric control (NC) commands that are subsequently conveyed to the additive manufacturing hardware. As the second stage of this process depends heavily on the specific additive manufacturing process and device employed, we restrict our discussion to that of toolpath generation. Fig. 2 demonstrates a hypothetical toolpath generated by a slicing algorithm.

2.1. *Origins of slicers*

The development of modern slicers was preconditioned by prior developments in the field of Computer Numeric Control (CNC) machining. Algorithms for generating cutting toolpaths from various computer-aided design (CAD) geometric representations (e.g. the work of [17,18]) are closely related to those use for