Computer-Aided Design 102 (2018) 115–127

Contents lists available at ScienceDirect

Computer-Aided Design

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

Automated process planning for hybrid manufacturing

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ARTICLE INFO

Keywords:
Hybrid manufacturing
Process planning
Spatial reasoning
Additive manufacturing
Machining

ABSTRACT

Hybrid manufacturing (HM) technologies combine additive and subtractive manufacturing (AM/SM) capabilities, leveraging AM's strengths in fabricating complex geometries and SM's precision and quality to produce finished parts. We present a systematic approach to automated computer-aided process planning (CAPP) for HM that can identify non-trivial, qualitatively distinct, and cost-optimal combinations of AM/SM modalities. A multimodal HM process plan is represented by a finite Boolean expression of AM and SM manufacturing primitives, such that the expression evaluates to an 'as-manufactured' artifact. We show that primitives that respect spatial constraints such as accessibility and collision avoidance may be constructed by solving inverse configuration space problems on the 'as-designed' artifact and manufacturing instruments. The primitives generate a finite Boolean algebra (FBA) that enumerates the entire search space for planning. The FBA's canonical intersection terms (i.e., 'atoms') provide the complete domain decomposition to reframe manufacturability analysis and process planning into purely symbolic reasoning, once a subcollection of atoms is found to be interchangeable with the design target. We therefore show that geometric and spatial reasoning can be decoupled from logic and combinatorial search required to find process plans. The approach subsumes unimodal (all-AM or all-SM) process planning as special cases. We demonstrate the practical potency of our framework and its computational efficiency when applied to process planning of complex 3D parts with dramatically different AM and SM instruments.

1. Introduction

Hybrid manufacturing (HM), combining the capabilities of additive and subtractive manufacturing, is the new frontier of part fabrication. While additive manufacturing (AM) continues to enable unprecedented levels of structural complexity and customization, subtractive manufacturing (SM) remains indispensable for producing high-precision, mission-critical, and reliable mechanical components with functional interfaces. Versatile 'multi-tasking' machines with simultaneous high-axis computer numerical control (CNC) of multiple AM and SM instruments (e.g., deposition heads and cutting tools) keep emerging on the market, enabling efficient use-cases for fabrication and repair (reviewed in Section 1.1). It is only a matter of time before such processes dominate the shop floors as the unique and complementary benefits of AM and SM become vital to defense, aerospace, and consumer products.

Today, HM process planning rarely extends beyond the common "AM-then-SM" patterns. Use-case scenarios include support structure removal by CNC tooling after metal AM of near-net shapes and surface patching of corroded surfaces for repairing worn-out parts [1,2]. In some scenarios SM post-processing is inevitable due to the limitations of AM in producing overhang shapes or high-precision functional surfaces for assembly. In other scenarios it is a matter of saving production costs by optimizing material utilization – when AM/SM alone would require substantial material deposition/removal by starting from an empty platform or a large raw stock, respectively – or prolonging product lifecycles by using multiple alloys in a single part (e.g., Fig. 1(g)). Such cases are already in use for producing corrosion-resistant parts for injection molding and oil transportation industries [3].

Although the capability to simultaneously use AM and SM exists in modern fabrication, there are very few examples of designs that are *enabled* exclusively by HM. In most showcased success stories, the separation of features is trivial and the AM/SM actions come in predictable pairs that facilitate manual or semi-automatic process planning (e.g., Fig. 1(a–f)). Even when designs enabled by HM can be conceptualized, planning their fabrication remains a manual activity driven by emerging expertise in HM.

This article presents theoretical foundations and computational algorithms to enable automatic construction of valid and cost-effective HM process plans for an arbitrary collection of AM/SM capabilities, provided by the same or different machine(s), with shapes and motions of arbitrary geometric complexity.

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https://doi.org/10.1016/j.cad.2018.04.022

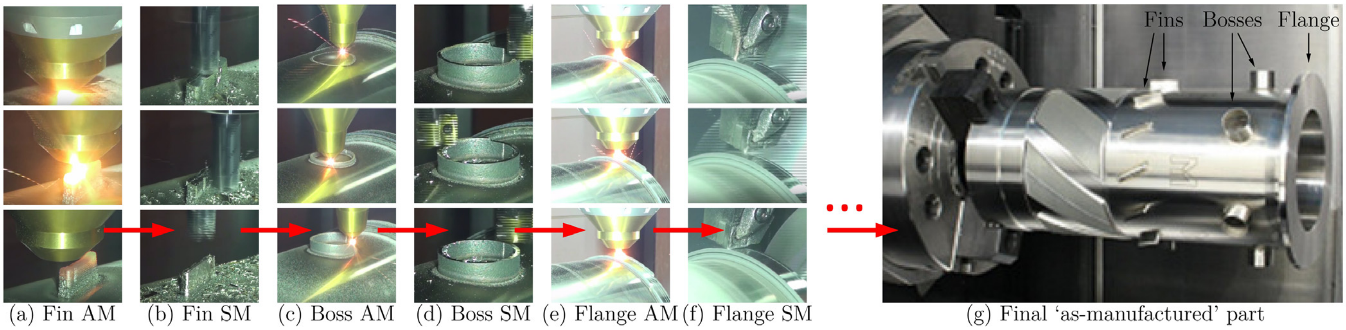

Fig. 1. A metal part manufactured by a combination of 5-axis printing, milling, and turning operations on Mazak INTEGREX i-400 AM [3]. The operations are typically planned in AM-then-SM pairs to grow features and finish them one-at-a-time.
Source: youtu.be/KbXJb4wcxnw.

1.1. Related work

Recently a number of manufacturing studies have reported on "hybridizing" select AM and SM capabilities [4,5]. Among the successful concepts are hybrid layered manufacturing (HLM) [6,7] and surface patching [1,2] that combine selective laser cladding (SLC) and CNC machining for rapid prototyping (RP), repair and modification of die/mold parts, and re-tipping of high-value aerospace turbine blades [8]. Other combinations include SLC and CNC mill-turning [3] as well as direct metal laser sintering (DMLS) and precision milling [9]. For reviews of HM technologies available today, see [10–13].

As HM hardware technologies are striding ahead, computer aided process planning (CAPP) software tools to support their incredible potential are falling behind. Among the few reported efforts, Manogharan et al. [14] introduced a HM system whose software component collected a suite of existing tools used in pure AM/SM process planning such as visibility analysis, fixture design, deviation/over-growth quantification, and tool-path planning, without addressing spatial complications that are unique to commingled AM+SM. Siemens PLM Software is now offering HM computer-aided manufacturing (CAM) tools as part of its NX solutions [15], also using feature-based decomposition into pure AM/SM segments, each to be independently path planned. To the best of our knowledge, none of the existing software tools are able to systematically explore alternative HM process plans where the same 3D regions of a part – not necessarily separable as a standalone feature – can be made with both AM/SM, and make cost-driven decisions.

Automatic feature recognition comprises a large body of literature for traditional SM (reviewed in [16–19]). Notable techniques include volumetric decomposition [20,21], graph-based B-rep analysis [22,23], and rule-based pattern recognition [24,25] among others. Despite being effective when features are clearly separable, these methods do not extend to complex shapes with unclassifiable or interacting/intersecting features [26]. The notion of a "feature" – one that depends on engineering intent [16] with no consistent definition across design and manufacturing – is even more ambiguous in AM, leading to knowledge-based ontologies with their own limitations of applicability.

Recently, our group presented an alternative, *feature-free* method for CNC milling based on maximal machinable volumes in any accessible orientation [27], enabling a rapid process planning paradigm that scales to part/tool shapes and motions of arbitrary complexity (Fig. 2). The underlying mathematical foundations were later shown to be applicable to AM analysis and design correction/feedback [28] as well. There are a number of fundamental challenges in extending these ideas to HM processes with interleaved AM/SM actions that we discuss in Section 2.

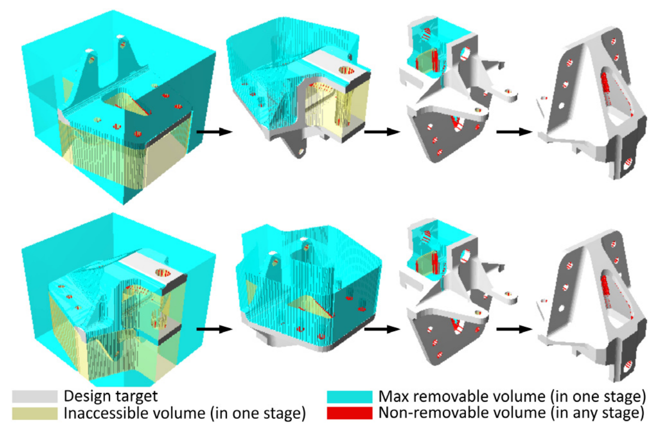

Fig. 2. Qualitatively distinct SM plans with different costs. Notice the sequence of orientations in which volumes are removed differs between the plans, despite converging to the same final shape.

The current approach subsumes our earlier work in machining process planning [27] as a special case. A major breakthrough was brought about by the ability to enumerate the entire search space using a logical (rather than geometric) representation in terms of a finite Boolean algebra (FBA), which enables *formulating and solving the planning problem in purely symbolic terms.* Rather than storing geometric representations of the evolving workpiece and the removal volumes associated with each manufacturing action (Fig. 2), we show that such information can be encoded as binary strings in terms of the atomic units of manufacturing.

1.2. Contributions & outline

This article presents a computational framework to evaluate manufacturability and find process plans for HM. It accommodates a large class of existing (and potentially future) AM/SM capabilities by an abstraction that separates geometric and spatial reasoning for accessibility analysis and collision avoidance from logical and symbolic reasoning used to search for optimal plans. We show that:

1. HM processes can be geometrically described by sequences of idempotent AM/SM actions (Section 3).
2. The AM/SM primitives characterizing the actions can be constructed independently as the *closest* shapes to the design target achievable by means of a single AM/SM capability in a particular setup (Section 4).
3. A set-theoretic notion of "closeness" is formulated with respect to minimal/maximal deposition/removal volumes, and computed using group morphological operations [29]