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Process planning for additive and subtractive manufacturing technologies

Stephen T. Newman (2)*, Zicheng Zhu, Vimal Dhokia, Alborz Shokrani

Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, United Kingdom

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ABSTRACT

In recent years, techniques that combine different manufacturing processes such as additive and subtractive technologies are gaining significant attention. This is due to their ability to capitalise on consolidated advantages of combining these processes. However, there are limited process planning methods available to effectively synthesise additive and subtractive manufacturing technologies. In this paper a framework termed iAtractive is proposed to enable the strengths of additive and subtractive technologies to be combined with the inspection process. Based on iAtractive a process planning system, Re-Plan has been developed which shows the capabilities of combined process manufacture through a number of case studies.

1. Introduction

Manufacturing industry has enjoyed a rapid and continuous growth with a large number of evolutionary advances in manufacturing processes over the past 50 years [1]. Application of individual manufacturing processes is constrained by their technical limitations such as the inability to process certain materials, failure to cope with complex geometries or inhibitive production costs for use in high volume [2]. For example, additive manufacturing (AM) allows for complex geometries to be produced, but the relative quality and tolerance is poor. Machining, on the other hand, allows for precision components to be produced, but the level of complexity is limited.

In recent years, hybrid manufacturing, which combines different processes/machines together, has drawn significant attention from industry and academia [3] due to the ability to capitalise on the consolidated advantages of independent processes, whilst minimising the disadvantages. The existing hybrid processes primarily focus on enhancing an individual process rather than adopting a holistic view to effectively utilise materials, energy and resources. Adopting such a perspective whilst considering advances in different types of hybrid manufacturing approaches requires new process planning methods to be developed based on adaptable combination of process capabilities and manufacturing resource utilisation [4].

Computer Numerical Controlled (CNC) machining dominates more than 70% of manufacturing businesses in the UK and the US [5]. Subtractive technologies such as machining produce considerable material waste. This paper introduces a process planning method in conjunction with a framework entitled iAtractive that interchangeably utilises additive, subtractive and inspection technologies to allow recycled and legacy parts to be remanufactured and reincarnated into new products. In this context, reincarnation is defined as being able to generate new products directly from existing parts by enabling material to be effectively utilised resulting in reduced waste. Therefore parts can be produced with additive and subtractive processes as required at different stages within the process plan.

2. State of the art hybrid manufacture and process planning

Lauwers et al. [1] defined hybrid processes as being processes that are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools that have a significant effect on the process performance. A review of literature indicates that 'hybrid processes' are also considered as approaches that combine two or more manufacturing operations, each of which is from a different manufacturing technology, and has interactions with and influences the others [2]. Furthermore a UK government white paper on the future of manufacturing describes hybrid production as the 'integration of production technologies into systems which, while more complex, can shorten or simplify value chains and/or enable novel processing' [6]. Thus hybrid processes can be clearly identified where individual processes are used serially or in parallel and provide an increase in overall process capability.

Nassehi et al. [7] used formal methods to classify manufacturing processes into five distinct categories, namely, additive, subtractive, transformative, dividing and joining. One particular combination of these processes namely additive and subtractive is currently attracting significant interest from industry and academia [1,2]: Karunakaran et al. [3] used CNC machining to face mill each layer built by metal inert gas welding to significantly improve the dimensional accuracy of parts; Xiong et al. [8] incorporated a plasma torch into a traditional machine tool, realising plasma welding and CNC finish machining on the same platform. In industry, DMG has recently launched a hybrid additive and subtractive system named LASERTEC 65 *3D* that integrates laser

* Corresponding author.
E-mail address: s.t.newman@bath.ac.uk (S.T. Newman).

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deposition welding and 5-axis milling. This allows for direct milling of part features which are accessible as the part is being additively built but could not be milled due to lack of tool access when the part is fully complete [9]. Other popular combinations include subtractive & transformative (e.g. laser assisted machining [1,10]) and multiple transformative processes (e.g. stretch forming and incremental sheet forming [11]).

Despite the rapid development of hybrid process technologies, very little attention has been given to the importance of process planning for such approaches. Process planning is the pivotal link between design and manufacturing and has evolved from manual planning to automatic computer-aided process planning (CAPP) [12,13]. Although a plethora of research has been conducted within the CAPP domain for individual processes such as CNC machining [14] and AM [15], very limited research has been reported on process planning of combined processes, which makes their constituent capabilities underutilised. Ren et al. [16] developed a process planning method that is capable of decomposing parts and generating non-uniform layer thicknesses and toolpaths for both CNC machining and laser deposition. Zhu et al. [4] developed an algorithm for operation sequencing of additive, subtractive and inspection processes for manufacture of difficult-to-machine structures attributed to poor tool accessibility. Kerbrat et al. [17] used a design for manufacturing approach to analyse features and identify if they can benefit from being produced either by machining or AM in terms of feature complexity.

Today, the typical life cycle of a part usually follows the sequential stages including design, process planning, production, inspection, use and eventually discard or recycle [18]. Used/legacy products or parts that fail in inspection are abandoned or recycled as scrap. This has resulted in considerable material, energy and time waste and in turn, increased overall production costs. There is thus a gap in the existing research: while the capabilities of individual processes have been significantly enhanced through process combinations, little attention has been given to reincarnating recycled or legacy parts into new components.

3. The iAtractive framework

The authors propose a framework entitled iAtractive that is able to generate process plans based on different existing parts as the given raw material. This will significantly impact the way existing products are initially manufactured, re-used, remanufactured and reincarnated, giving additional lives and new uses.

3.1. Combining additive, subtractive and inspection techniques

The iAtractive framework consists of combining additive (Fused Filament Fabrication, FFF), subtractive (i.e. CNC machining) and inspection processes on a single platform. This approach is aimed at reusing and remanufacturing existing parts or even recycled and legacy parts, and reincarnating them into new parts with new features different from the original ones on the existing part. The dimensional information of an existing part can be obtained by using an inspection technique such as a touch trigger probing strategy. This enables it to be further manufactured by FFF and/or CNC machining providing new enhanced functionalities. The vision for the iAtractive process is depicted in Fig. 1, where each individual existing part (1, 2 or 3) can be further manufactured into the same final part, using a range of interchangeable processes.

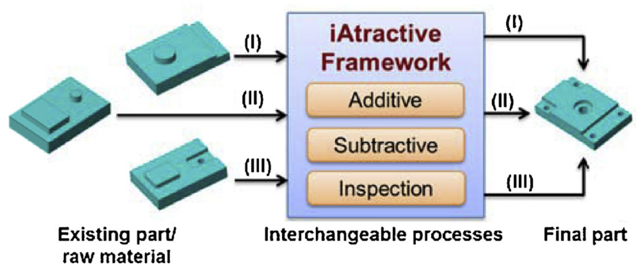

Fig. 1. Pictorial view of the iAtractive framework.

3.2. Structured representation of the iAtractive framework

An IDEF-0 representation of the iAtractive framework for combining additive, subtractive and inspection processes is shown in Fig. 2. This consists of two inputs namely: product information, directly obtained from the part design; and, existing part geometry, identified at the initial inspection stage. The core of the iAtractive process planning framework is a set of manufacturing strategies, which specifies feasible operations and sequences to produce a new part from the given existing part. The selection of appropriate manufacturing strategies depends on four decisive factors including process capabilities, process planning knowledge, geometry constraints and manufacturing knowledge. The output of the iAtractive framework is the final part to be manufactured using an interchangeable combination of additive, subtractive and inspection processes.

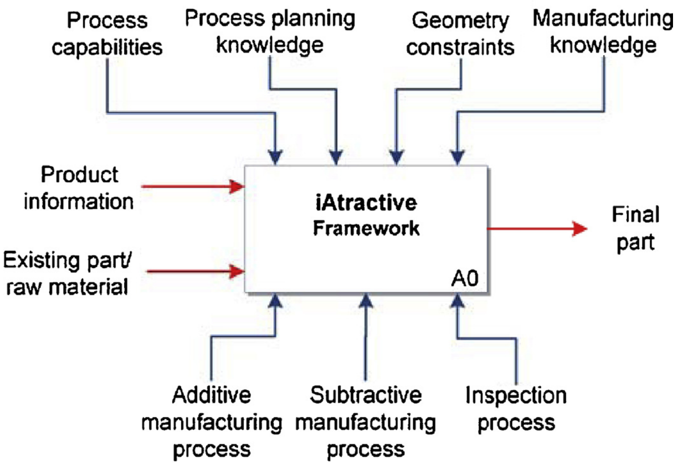

Fig. 2. IDEF-0 representation of the iAtractive framework.

In addition, the capabilities of additive and subtractive processes are also considered, such as cutting tool accessibility and the capability to create overhanging features. Manufacturing knowledge contains a database storing process parameters e.g. feedrate and FFF deposition strategies.

4. Re-Plan process planning system for additive and subtractive processes

The Re-Plan process planning system has been developed based on the iAtractive framework to enable existing part material to be remanufactured into a new part, as shown in Fig. 3. Existing part material is defined as a part that has already been previously produced, used, worn or scrap. In broad terms, an existing part may be of any shape and size. Existing part material is treated as raw material to be remanufactured using additive and subtractive processes in conjunction with inspection to monitor and continually gauge the part feature dimensions, by which they are transformed into final parts (new parts).

The features on the final part are termed final features. The initial-part features (IPFs) are the features on the existing part, which are not required on the final product. IPFs are further processed by adding and/or subtracting material. This essentially means that the existing part material is used within the final part and thus, the existing part is considered as being remanufactured and reincarnated to form the new final part.

The geometry constraints can be further divided into three groups, namely deposition nozzle, local and global constraints. Unlike in traditional AM methods that create physical models starting from zero material on a build platform, in the iAtractive

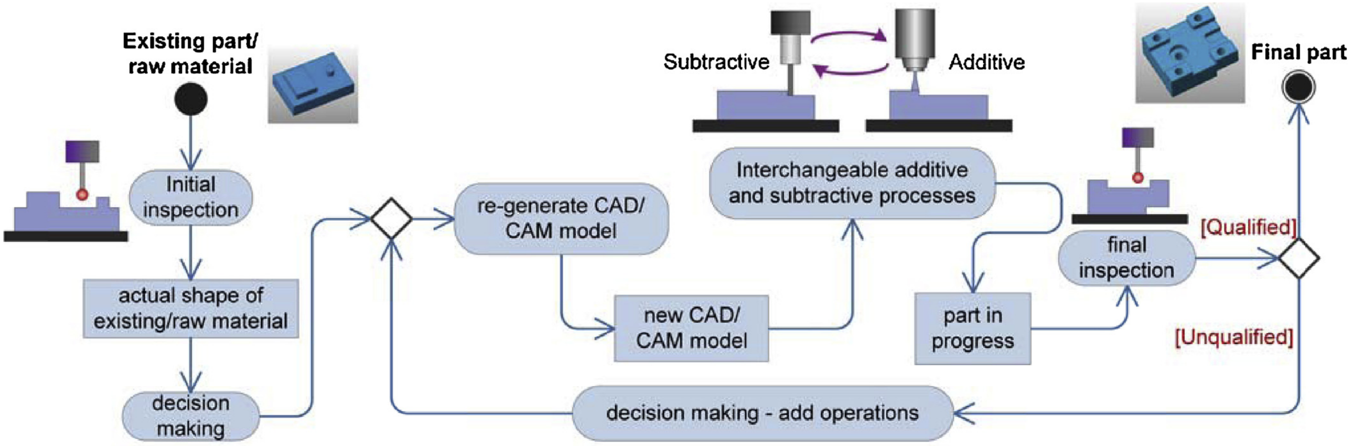

Fig. 3. Operational structure of the Re-Plan process planning system.

process, material is directly added onto the existing part. As a result, there is a risk of collision between the deposition nozzle and existing features. Local constraints only focus on feature dimensions on both existing and final parts, which determine where the material should be added or removed and the amount of material that should be added or removed. Global constraints are considered such as, production time, costs and application requirements.

Typically, the generation of the Re-Plan process plan consists of three stages.

(i) The deposition nozzle and local constraints are applied, by which various manufacturing strategies are selected.
(ii) Global constraints are applied to the generated strategies to decide on the final strategy to be used. For example, when there are two or more applicable manufacturing strategies and the priority is production time, the one where the least amount of production time required, would be chosen.
(iii) Finally, the appropriate process parameters for each operation are determined.

4.1. Workflow of the Re-Plan process planning system

The workflow of the Re-Plan system is outlined as follows:

- Raw material is first measured to obtain its actual geometrical attributes, which becomes the basis of the process planning approach for determining subsequent operations.
- A new CAD model is generated, which shows the shape of the rest of the material required to produce the new part. Based on the features' geometries of the existing part and the new required part, a feasible manufacturing strategy is selected. Additive, subtractive and inspection processes are utilised interchangeably in a serial manner, by which the final part will be manufactured.
- The part is further inspected identifying which dimensions are out of tolerance and identified as an unqualified part. If this is the case then further decisions can be made on whether to add more manufacturing operations until the dimensions are in tolerance.

4.2. Operational structure of the Re-Plan process planning system

Upon obtaining the actual geometrical attributes of the existing part, the geometries of the existing and final parts are compared and the relevant features are adapted or modified if necessary. For remanufacturing a part there are three typical scenarios. The ideal scenario is adding material directly onto the existing part and/or finish machining the existing features or adding features to produce the final features. This scenario is normally applied to worn or unqualified parts that are identified in an inspection operation. These parts can be remanufactured back into their original shapes (i.e. new, before use) or reincarnated into a new part.

The strategy that can be applied to any existing part regardless of what the features and dimensions they exhibit is to first obtain a planar face on the existing part by machining, then add and subtract material interchangeably until the final part is produced. However, this is not time-efficient since a large quantity of material must be removed, subsequently added back and then finish machined. Therefore, this strategy should only be used in the worst-case scenario where deposition nozzle collisions are unavoidable, whilst directly depositing material onto the existing part.

The intention of developing the Re-Plan process planning system is to effectively utilise existing part geometries as opposed to removing features by machining and adding new features onto the machined part. For certain application requirements where, for example, solid parts are not necessary and the parts are not load bearing, the unique characteristic of the additive process in building overhanging features without support is utilised. In Fig. 4a, an existing part is shown and the product to be manufactured is shown in Fig. 4b. The newly deposited part 1 and 2 are first added onto the existing part (see Fig. 4c). Part 1 and 2 in conjunction with the existing feature enables further material (i.e. part 3 and 4) to be built, creating the rough shapes of the desired final features for finish machining (see Fig. 4d). The features on part 4 are derived from the product information as described earlier in Fig. 3. The geometries of part 1 and 2 depend on the actual shape of the existing part and the deposition nozzle as well as the additive process capability in producing overhangs. It is realised that the manufacturing strategy depicted in Fig. 4 is not the only feasible strategy. After selecting a strategy, the global constraints will be applied, evaluating critical factors including production time and cost.

5. Test part case studies

The Re-Plan system has been initially tested through using three existing parts made from polylactic acid (PLA) as shown in Fig. 5, namely, a part with an IPF pocket, a part with an IPF boss, and an unqualified finished part. These three different shaped existing parts were remanufactured and reincarnated into three identical new parts using the strategies described below. The blue PLA material in Fig. 5 is the given existing parts and the white PLA material is the new material added onto the existing part.

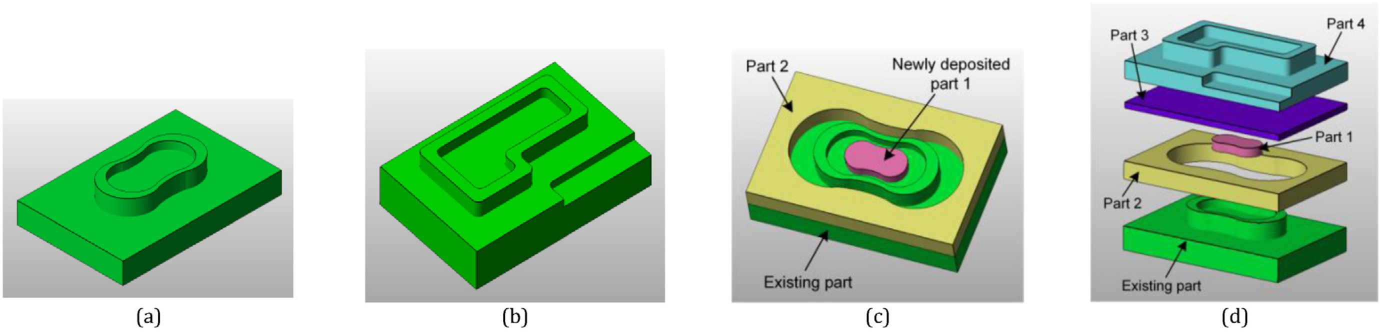

Fig. 4. Reincarnation of an existing part into a new part: (a) existing part; (b) final part; (c) adding newly deposited part 1 and 2; (d) overview of adding material onto the existing part.

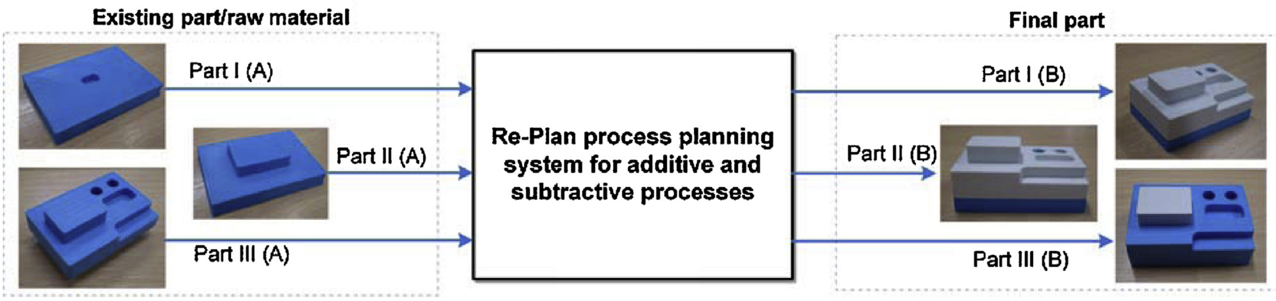

Fig. 5. Identical PLA test parts produced by the Re-Plan process planning system.

- *Part I* (*B*) was produced from *part I* (*A*), which was an existing part with an IPF pocket. As the pocket width was less than the maximum overhang length that the additive process can feasibly produce without support, additive layers were directly deposited on top of the existing part until the near-net shape of the new part was obtained. The part was finish machined and finally inspected to assure dimensional tolerance.
- *Part II* (*B*) was produced from *part II* (*A*). Based on the measurement results, new material was deposited around the existing IPF boss, which was similar to part 2 in Fig. 4. More material was continuously added to build the rough shape of the new part for finish machining.
- *Part III* (*A*) was identified as an unqualified part in the final inspection process (see Fig. 2) due to the dimensions of the boss being out of tolerance (nominal dimensions: 20 mm × 18 mm × 8 mm; actual dimensions: 19.5 mm × 17.8 mm × 8.3 mm). Therefore, three independent operations were added in the process plan, where the original boss was removed and a new boss was added and subsequently finish machined.

6. Conclusions

In this paper, the authors introduce the concept of the iAtractive framework for process planning using the combination of additive and subtractive technologies. The devised Re-Plan process planning system has shown that parts can be generated from existing part material to be effectively reused, remanufactured and reincarnated into new parts with new identities. The reincarnation of parts is realised primarily by appropriately sequencing the use of additive and subtractive processes. Based on the geometrical information of the existing part obtained in the initial inspection operation, material is added and/or removed in a serial manner according to the generated process plan. The Re-Plan process planning system can be further extended by a knowledge base that contains capability information for other additive processes. Thus, further manufacturing strategies can be used, resulting in increased process capability for generation and remanufacture of complex structures e.g. precision internal features with free-form surfaces.

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