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## Process planning for additive and subtractive manufacturing technologies

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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.

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## 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

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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

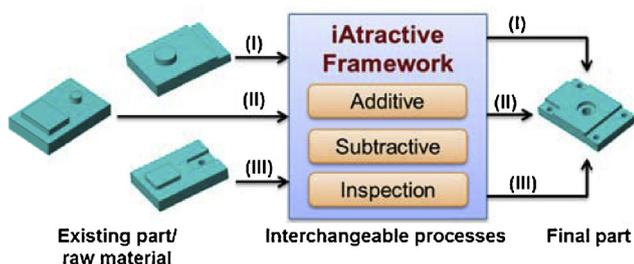


Fig. 1. Pictorial view of the iAtractive framework.

existing part (1, 2 or 3) can be further manufactured into the same final part, using a range of interchangeable processes.

#### 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.

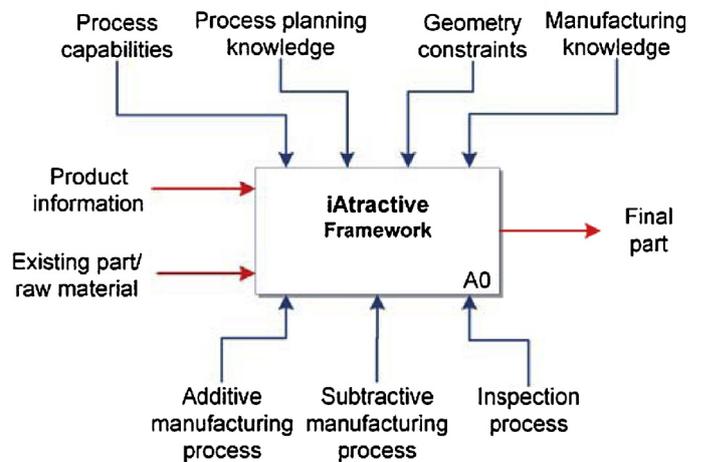


Fig. 2. IDEF-0 representation of the iAtractive framework.

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

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