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Customising with 3D printing: The role of intelligent control

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ABSTRACT

The emergence of direct digital manufacturing creates new opportunities for the production of highly customised goods especially when it is combined with conventional manufacturing methods. Nevertheless, this combination creates a need for systems that can effectively manage and control the resulting distributed manufacturing process. In this paper, we explore three different configurations that can enable direct digital manufacturing for customisation, ranging from fully integrated to inter-organisational set up. Additionally, control requirements of such systems are developed and the suitability of intelligent control is explored. By 'intelligent control' we mean production control that is capable of assessing and interacting with the production environment and adapting production accordingly. We argue that the so called *intelligent product* paradigm provides a suitable mechanism for the development of such intelligent control systems. In this approach, the intelligent product directly co-ordinates with design agent, 3D printing agents and other conventional manufacturing system agents to schedule, assign and execute tasks independently. Via a case example of a realistic production system, we propose and implement such an intelligent control system and we analyse its feasibility in supporting 3D printing enabled customisation.

1. Introduction

Customisation in manufacturing, and especially mass customisation, remains an area of great importance almost three decades after its first appearance [1]. Recent trends in manufacturing has led customisation to attract even greater interest both from the academic community but also from practitioners [2,3]. Perhaps the most prominent trend—direct digital manufacturing—investigates the utilisation of additive manufacturing technologies, like 3D printing, for local production of customised goods [4]. Additive manufacturing technologies, and especially 3D printing, are argued to fall in the category of the advanced manufacturing technologies required for mass customisation [5,6] due to their special manufacturing capabilities like flexibility and speed [7,8].

As 3D printing enabled customisation is likely to require the combination or even integration of 3D printing technologies with conventional manufacturing systems, a key question that emerges relates to the planning and control problems associated with this combination/integration [9]. Already, since the beginning of the last decade, it has been argued that de-centralised, multi-agent systems are perhaps more suitable to manage these control problems [6] and a recent case study has shown some evidence on this [10]. In this study, we aim to further advance our understanding on how intelligent control paradigm can support 3D printing enabled customisation. We argue that intelligent control—defined as a production control that is capable of assessing and interacting with the production environment and adapting production accordingly—is a suitable mechanism for managing the order taking, coordination and fulfilment of mass customisation processes [11], while 3D printing contributes primarily on the manufacturing engineering process. Unlike similar studies found in the literature discussing this topic [9,10], we use a case example of a realistic production system to examine the role of intelligent control in introducing 3D printing resources (or 3D printed parts) in conventional manufacturing systems. The production system under consideration manufactures and assembles customised gear boxes, using a combination of customisable and non-customisable parts.

The contribution of this study is twofold: firstly, it explains and justifies the suitability of intelligent control for 3D printing enabled customisation. Secondly, by developing a realistic production system—along with the associated control system—it demonstrates evidence for the above argument and identifies technical challenges of utilising intelligent control to combine 3D

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printing with conventional types of manufacturing. The remaining of this paper is structured as follows. In Section 2 we review the role of 3D printing in mass customisation and we provide a brief review of the intelligent control paradigm. In Section 3, we identify relevant control requirements and we investigate the why and how the intelligent control paradigm addresses these requirements. Section 4 describes the case example used in this study before we conclude with a final discussion in Section 5.

2. Background

2.1. Customisation in manufacturing

2.1.1. Brief review of mass customisation enablers

Mass customisation is a generic term used to describe manufacturing customised products for a mass market [11]. It aims to achieve economies of scale and scope that enable customised products to be as affordable as mass produced products [5,11]. Since its origins, mass customisation was argued to be the answer to an increasing demand for product variety and customisation, while at the same time taking advantage of manufacturing and information technologies that could deliver higher variety at low costs [6]. It is out of the scope of this paper to provide a detailed review on mass customisation as there are numerous studies and interested readers can refer to [2] and references therein. Instead we focus on two aspects that have been recognised for their importance in successfully implementing mass customisation: flexible manufacturing systems and information management [5,6].

Firstly, flexible manufacturing systems act as a mechanism to counterbalance additional costs arising from mass customisation [2]. Utilising “advanced manufacturing technologies”, manufacturers can develop flexible and agile manufacturing systems which are required in mass customisation in order to remove barriers to product variety at low cost [6].

Secondly, as product variety increases, data becomes unmanageable using classic methods, and alternative approaches to generate Bills of Materials (BOMs) are required [2]. The role of information technologies in mass customisation is, therefore, twofold: firstly they can be used to enhance the communication between work teams (product design, manufacturing, supply chain management), thus enabling orders to be fulfilled correctly through the integration of information flows [12]. Secondly, they can improve the interaction with the customer in order to collect customer requirements, demands and preferences during the configuration process [12]. In [11], a simple model for the different stages of customisation process is introduced:

- Order taking and co-ordination.
- Product design and manufacturing engineering.
- Order fulfilment management.
- Order fulfilment realisation.

2.1.2. 3D printing facilitating mass customisation

3D printing and, more generally, additive manufacturing has been recognised as one of the key technologies enabling customisation mostly due to the high levels of flexibility it can offer [7,13,8,14]. There are also arguments found in the literature that 3D printing can significantly revolutionise manufacturing in ways that other mass customisation technologies could not [15].

One of the requirements of mass customisation is rapid product development and innovation capabilities due to typical short life cycles presented by mass customised products [6]. This can be supported by 3D printing, as the technology enables rapid manufacturing which in turn helps design customisation [16,17]. The ability of 3D printing machines to directly utilise 3D models of designed products allows the customer to design his preferences related to products directly [18].

Another key requirement of mass customisation—flexibility of manufacturing systems [2]—is also supported by 3D printing enabled manufacturing as it removes the tooling requirements and thereby allows components of any geometry to be manufactured in a single resource without too much change over time [19]. This also means that 3D printing eliminates the need for having a wide range of tooling and the associated costs. Furthermore, multiple materials can be combined to produce a part, rather than products or parts made of homogeneous materials. Additionally, 3D printing allows for small batch sizes and there is no change over of tools, thus providing flexibility to cater for various customisation requests. Similarly, 3D printing enabled manufacturing offers the possibility of reducing inventory levels of customised parts as some of them can be produced on demand based on actual customer orders.

Due to its speed and flexibility. 3D printing has therefore the potential to impact several mass customisation generic levels [6], from *design* and *fabrication* to *usage*. One could imagine for example a product produced by a manufacturer including parts printed according to specific customer requests (fabrication), which could also be further customised after delivery to satisfy new customer needs (usage). Although a very interesting topic to investigate, a further analysis on the potential impact of 3D printing on different mass customisation levels/types is out of scope of this study. We simply note here that one of the barriers of applying 3D printing in mass production processes, i.e. cost, is argued to decrease significantly over time as adoption levels increase [15].

2.2. Intelligent control, distribution and customisation

As discussed earlier, intelligent manufacturing control systems are those that are capable of varying their behaviour in response to dynamic changes, requirements and past experiences [20]. Manufacturing operations involve products and resources, and the intelligent control paradigm enables these entities to have the capability to bind the physical object with information and make decisions.

Conventional manufacturing control systems are based on centralised and hierarchical units that are not well suited for handling high product variety, support customisation and have weak response to disruptions [21]. Intelligent, distributed control systems, on the other hand, provide new pathways to overcome the challenges of centralised control systems. These systems have distributed units interacting with each other and collaboratively making control decisions [22].

These collaborative control systems are generally based on multi-agent and holonic manufacturing paradigms [23], where the individual products, manufacturing resources and other key functions are represented as units capable of decision making, information processing and communication. These systems have the ability to support small batches and high product variety due to their ability to adapt, communicate and learn.

One of the central themes behind these intelligent control systems is the ability to identify unique products and resources physically, and map these to software agents that can pass information, process them and make decisions. The developments in auto-id technologies provide capabilities for identifying products and resources [20]. This has then led to the notion of product-driven intelligent control and the intelligent-product paradigm, where a physical order or product instance can guide or govern the way it is intended to be made by negotiating with the resources [24]. Such approaches are well suited for customisation