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ADDITIVE MANUFACTURING AS A PLATFORM FOR INTRODUCING CYBER-PHYSICAL SERVICES

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ABSTRACT: Additive manufacturing (AM) is increasingly used for the production of functional components. This process is based on digital design model and can produce customized components with no additional cost (toolless process). AM is an inherently model-centric approach to manufacturing which provides a starting point for extending product-centric control and services to tasks and operations beyond manufacturing. In this paper, we investigate a method to assign a unique identification to each part using AM and the additional product-centric services enabled through it, are discussed. The use of a unique identifier in the form of ID@URI which is additively manufactured (from the design file) on the parts enables additional services throughout the parts’ lifecycle. Assembly, delivery, aftersales services, and maintenance, as well as product improvement, are the major product-centric services benefiting from identification introduced through the use of AM.

KEYWORDS: Additive manufacturing, cyber physical systems, product centric control, supply chain, customized products

INTRODUCTION

Labeling the part uniquely in the manufacturing stage provides a platform for product centric control in the future handling and use of the component (Meyer et al, 2009; Holmstöm et al, 2010; Främling et al. 2013). The benefit of product centric control is significant in complex delivery projects, after sales services, physical asset management, energy efficiency services, and more generally in improving quality and operational efficiency in demanding field settings.

There is currently very limited research on the use of additive manufacturing as a platform for introducing novel handling and control practices (Holmström et al. 2016). In this paper, we will conduct design science approach to explore the costs and benefits of using additive manufacturing as a platform for embedding downstream handling instructions in an enhanced digital design model. More specifically, we will demonstrate how additive manufacturing can be used to uniquely label components to create a platform for further product-centric handling and services.

LITERATURE REVIEW

This section reviews previous research on the control logic and handling of parts in additive manufacturing and product assembly. We review research literature and identify unique product identification as the key challenge for developing product centric solutions in the research domain of Industrial Internet of Things.
Product centric tracking and control
The product centric control concept is based on the premise that each physical object is unique and can be identified as such (Karkkainen et al., 2003). The basic schema for identifying an object can rely on the internet. The actor who initially creates the digital model of the object identifies it with a unique identifier within its own organization (ID) (Meyer et al., 2009). By adding the internet address of the actor (Unified Resource Identifier) to the individual object identifier, we have a simple scheme for uniquely identifying each object (ID@URI). This unique identification links the physical object directly with its product agent that can be an internet-based service (Främling et al., 2013).

Figure 1. Product centric control in relation to additive manufacturing process

The unique identification of physical objects opens up the possibility for shifting the management of operations from process and resource-oriented management to object-oriented management (Främling et al., 2007). The basic product centric service is tracking (Holmström et al., 2009).
More advanced services are cyber-physical, such as material kitting for supporting assembly and installation, and performance monitoring for supporting asset management and maintenance (Främling et al., 2013). Emerging standards for enabling open product centric solutions are the open message interface (OMI) and open data format (ODF) standards for object identification, communication and data exchange (Främling et al., 2007b; Dave et al., 2016). These emerging standards originate in European Framework programs (PROMISE, BIOTOPE) and are further developed in The Open Group (The Open Group, 2016; 2014). Applying the product centric concept to additive manufacturing is illustrated in the Figure 1.

Handling and control of parts in additive manufacturing

Producing the object directly from a design model controls the manufacturing process in an inherently product centric manner. This has several important implications for the handling and control of AM objects. Producing parts without tooling enables the economic production of very small batches, even individual parts (Khajavi et al., 2014; Holmström et al., 2010). The layer-wise manufacturing process enables complex geometries which using traditional manufacturing processes would require assemblies consisting of several parts (Tuck et al., 2008). Moreover, layer-wise production can reduce the amount of waste raw material specifically for metal AM and increases reuse of raw material (Frazier, 2014), enabling a shift to fewer and better performing raw materials, and simplified raw materials management.

There are many different AM technologies and materials. For details on handling and control differences for AM technology variants see Gibson et al. (2010) or Hopkinson et al. (2006).

Physical labeling

Physically labeling the manufactured object with its unique identity in the manufacturing process creates the critical cyber-physical link that enables product centric services over the life-cycle of the manufactured object. For special classes of objects, such as hydraulic hose-assemblies, labelling has been done using ink-jet printers integrated with production equipment (Lyly-Yrjänäinen et al., 2016), or for complex composite products, the computers that are part of the product have been used (Ala-Risku et al., 2010). For AM objects, printing the unique identifier as part of the build has been used by manufacturers of customized parts in complex assemblies. However, the AM produced identifiers seem only to have been used inside the factory, and not as a platform for further product centric handling and control solutions (see e.g.: Invisalign Systems, 2014; Align Technology, 2015).

According to Meyer et al., (2009), the product-centric services available for a uniquely identifiable object in manufacturing are improved production planning and control, product customization and providing a more effective method to shift amongst product variants. Moreover, they recognized the increased efficiency of goods issue and receipt, in-transit rerouting (Holmström et al., 2017), enhanced security as the services for supply chain from unique identification of parts and tracking (Holmström et al., 2010). In asset management gained values from identification are enhancements in product usage and sharing as well as in the increased efficiency of maintenance operations. Finally, product lifecycle management (PLM), gains in two main ways, improvement in future product design and manufacturing as well as end of product life management.

Other researchers have reported similar gains while being able to track a product into its lifecycle. Holmström et al., (2010) counts superior project delivery (e.g.: completion of installation work) (Ala-Risku et al., 2010), facilitation in industrial asset management and improved industrial service delivery as the benefits.
Handling and control of parts for assembly
The handling and control of the parts for assembly and delivery depends on the relationship between parts that have been produced. Bulk handling is sufficient if parts are all alike, but individual handling is needed if the produced parts are different components for an assembly, or unique customized parts.

For handling and control of parts for assembly two basic practices are available. Identical parts – stock keeping units - can be stocked in bulk to different location on an assembly-line. This practice is called line-stocking (Hanson & Medbo, 2012). The alternative is kitting. The different parts for an assembly is presented in a container, labelled and prepared, for ease of assembly (Bozer & McGinnis, 1992). Kits, in contrast to line-stocking, can easily handle and control customized and unique parts.

Kitting potentially can improve assembly efficiency and quality, work-in-progress and customization of production flow compared to the line-stocking mode (Bozer and McGinnis, 1992; Hanson and Brolin, 2013). However, despite its many advantages kitting is not widely used due to the labour intensiveness of its preparation step (Jonsson et al., 2004; Hanson and Brolin, 2013). However, if kitting can be integrated in the manufacturing process and simplified the trade-off between cost and other benefits may change (Lyyly-Yrjänäinen, 2016). While, elimination of labour intensive kit preparation steps are often not feasible with conventional manufacturing methods, it is feasible with product centric control of AM.

Additive manufacturing for kit preparation
Additive manufacturing, in contrast to conventional manufacturing can produce high volumes of single parts for assembly (Ruffo et al. 2006; Ruffo & Hague, 2007). Therefore, the labour-intensive kit preparation step (manual task of fetching parts and readying kits before feeding to the production line) is fully avoided if the kit information can be embedded into the product 3D design file (Figure 2).

![Figure 2. Example for components of a drone before and after arranged as a digital kit](image)

Invisalign, a company that produces transparent polymer braces and dental aligners for the treatment of Malocclusions is an example of combining part ID and additive manufacturing. In order to deliver their promise to each patient which is the straightening of his/her teeth, multiple braces (on average, about 55 aligners depending on the complexity of each case) should be produced and delivered in a precise sequence (Invisalign, 2016).

RESEARCH PROBLEM
Direct kitting using AM comes at a cost (Khajavi et al., 2018). In AM cost efficiency and capacity utilisation depending on the build configuration may be significant (Baumers et al., 2013). To address the utilization problem automated build volume packing approaches have been developed (Araújo et al., 2015). Introducing kitting may constrain opportunities for build volume packing and increase the cost of using AM.

We identify a gap in literature. How AM can be used to create a unique cyber-physical entity that can be effectively handled using product centric control? Earlier research by Lyly-Yrjänäinen et al., (2016) has suggested the possibility of product centric using AM. However, it falls short of explicating how such control can be achieved.

**Design theory research methodology**

The focus of the theoretical part is to articulate the purpose and scope of introducing product centric handling and control in AM. The research outlines the design principles for linking physical objects and product centric handling and control.

Studying new solutions where the theoretical concepts are not yet well defined, and the problem context and solutions are yet to be structured are cumbersome from methodology perspective. As a solution to this hurdle that makes the formulation of research method challenging, Handfield and Melnyk (1998) suggest exploratory and descriptive approach for operations management field while theory is still developing. Design science is a methodology utilized by researchers in the field of operation management (Holmström et al., 2009) as well as other management field to explore and explain novel practices and solutions.

CIMO-logic is used for design proposition in the design science methodology and provides the basis for theory development in the management field. CIMO-logic determines the Context (C) in which Interventions (I) lead to the Outcomes (O) through specific Mechanisms (M). In other words, based on the practical and empirical data, design research articulates how in a specific situation, an intervention would lead to expected results. Mean-ends proposition which is a similar logic for design proposition development has been described by Holmström et al, (2009) as a bridge between theory and practice and a method for substantive academic contributions.

A three-step approach is required to define the design proposition; exploration (for evidence), abduction (thinking) and explanation (Holmström et al, 2009; Aliseda-Llera, 1997; Magnani, 2011). In exploration step a new technology or other novel practices shall be selected as the intervention and tested in various contexts to achieve different outcomes. The purpose is to find a context for small-scale experimentation.

In second step which is abduction, innovation can take place through the adoption of similar interventions from other fields of science and trying to solve the problem in the context that we found in the first step. If intervention can become more interesting through modifications, first step needs to be revisited. Finally, explanation step utilizes the findings of previous steps to define the CIMO-logic and clarify how and through what mechanism the intervention led to the outcomes.

Goldenberg et al., (2001) though the use of empirical study illustrate, ideation through design proposition increases the chance of formulating propositions that function in practice. Overall the value of design proposition comes from the following aspects; it gives a logical structure towards solving a problem, it provides opportunities for innovation through adopting practices from other fields of science and practice, finally it provides an explanation on how the intervention causes the outcomes in a context.

In the current research, context is the increasing production of parts with additive manufacturing, while intervention is the introduction of product-centric control into the products through the generative mechanism of 3D printed identification (e.g.: ID@URI format). Amongst the outcomes are kitting during the production and aftersales services for the use phase.
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