Automatic assembly planning based on digital product descriptions

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This paper proposes a new concept in which a digital twin derived from a digital product description will automatically perform assembly planning and orchestrate the production resources in a manufacturing cell. Thus, the manufacturing cell has generic services with minimal assumptions about what kind of product will be assembled, while the digital product description is designed collaboratively between the designer at an OEM and automated services at potential manufacturers. This has several advantages. Firstly, the resulting versatile manufacturing facility can handle a broad variety of products with minimal or no reconfiguration effort, so it can cost-effectively offer its services to a large number of OEMs. Secondly, a solution is presented to the problem of performing concurrent product design and assembly planning over the organizational boundary. Thirdly, the product design at the OEM is not constrained to the capabilities of specific manufacturing facilities. The concept is presented in general terms in UML and an implementation is provided in a 3D simulation environment using Automation Markup Language for digital product descriptions. Finally, two case studies are presented and applications in a real industrial context are discussed.

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1. Introduction

In the last few years, a growing volume of research has emerged on business networks involving manufacturers pursuing efficiency through agility and thus providing a new form of competition to manufacturers with low labor costs (e.g. [6,8,16]). The need for agile manufacturing arises not only from rapidly changing market demand but also from novel design approaches exploring larger parts of the design space [1]. A potential manufacturing concept to address the need for agility is product-centric control, in which the digital counterpart of the product requests its own manufacturing services [3]. However, the research is specific to an industrial partner’s business case of a single manufacturer serving several OEMs producing similar but customized products, and the focus is on the logistics level without investigating how the product-centric control can be applied to assembly planning.

Our goal is to address these limitations by proposing a product-centric control concept that enables an OEM to flexibly contact potential manufacturers and involve them already in the product design phase. Such manufacturers will have the ability to support the designers at the OEM to perform virtual manufacturing of their design automatically and promptly according to a digital product description provided by the designer. Our proposed means to achieve this goal is through a new concept of agility illustrated in Fig. 1, in which digital twin objects generated from the digital product descriptions drive the product-centric control. The digital twin will have the intelligence to perform assembly planning and to orchestrate the production resources in the manufacturing cell. Thus, these resources only need to provide generic services, resulting in great versatility to handle diverse digital product descriptions without a need to reconfigure the cell.

The following contributions are made. Firstly, a general framework is presented to realize the concept in shown Fig. 1, independent of a particular product description technology. Secondly, an application to the AutomationML product description technology [38,42] is provided. Thirdly, an implementation in a 3D simulation environment is described and demonstrated with two case studies.

2. Previous work

Previously the trend in manufacturing industries was to outsource manufacturing operations to low labor cost countries [7]. The more recent trend of Industry 4.0 targets the goal of making manufacturing sustainable in higher labor cost countries. Toward this goal, a number of recent publications on CPS (Cyber-Physical Systems), CPPS (Cyber-Physical Production Systems),
Smart Manufacturing and Industrial Internet show a trend towards business networks of companies into which potential participants can offer their specialized services [16,8,16]. One unresolved challenge for such networks is how they could be performing assembly planning already during the product design phase as this is significant for the efficiency of the eventual manufacturing [18,2], and existing approaches require considerable manual effort, such as using real operators in a virtual assembly environment [19]. To realize the potential of agile business networks, this article investigates how a designer could submit a digital product description to several potential manufacturers with the capability to perform fully automatic virtual assembly planning. Such a capability has not yet been proposed despite numerous manufacturing applications of CPS, Internet of Things (IoT), multi-agent systems, holonic systems and flexible manufacturing systems (e.g. [12,14,15,47]). Our proposal differs from approaches such as product configuration systems [10] and product family architectures [17], whose agility is limited by detailed a priori specifications about the range of product to be manufactured.

One specific aspect of CPPS and Industry 4.0 is data from virtual models of products and production resources is available for optimizing manufacturing operations [9]. In the Industry 4.0 age, approaches for exploiting this data to plan manufacturing operations can be grouped into the more conservative approach of extending MES systems [4,5,47] and to the radical approach of product-centric control. In the latter case, a digital counterpart of the product keeps track of its status and is able to participate in the planning of operations from supply chain management and logistics to routing on the factory floor [26–31] exploiting the flexibility from additive manufacturing (AM) [3]. In addition to product-centric control, a similar concept under the name of digital twin has shown active research in 2016–2017 in a number of diverse communities such as CPS, IoT, Industry 4.0 and model-based systems engineering [25,32–36]. Both concepts are similar in the sense that a digital counterpart of the product maintains up to date information and can participate in operations involving some part of the lifecycle of the product. However, the research on digital twins opens new opportunities in the product design phase, in bridging design and operation and especially in 3D simulation of the assembly process [37]. Our proposal is thus extending the product-centric control to the lower level task of assembly planning as well as exploiting the digital twin concept in 3D simulation. Bridging the gap between these bodies of knowledge may lead to the various researches cited above finding broader application in more holistic concepts of agility in manufacturing, spanning supply chain management and product design. Our goal is to define the concept rather than to focus on protocols, service discovery mechanisms and ontologies for which a number of specific works exist [11,13,47,48].

A discussion on agile manufacturing would not be complete without addressing the potential of AM to shorten time to market [24]. As discussed in Section 5, after virtual assembly has been performed satisfactorily, a physical assembly validation could be performed using AM to obtain the parts from CAD models provided by the designer. Thus the proposed concept would be poised to integrate with anticipated disruptive developments from AM including decentralized supply chain management [20] and hybrid approaches combining AM and conventional technology for reduced time to market and investment risk [21]. Although current costs for AM limit its application [22], decreasing costs and increasing market demand for customization result in conventional manufacturers facing increasing competition from entrants with AM technology [23].

Assembly planning is the process of creating a sequence of assembly motions to craft a product from separate parts considering the final product geometry and the production environment including resources and obstacles. Assembly planning can be divided into Assembly Sequence Planning (ASP), which considers the parts as free flying, and Assembly Path Planning (APP) that considers the trajectories those parts move along and the relevant manipulators. Automatic methods for ASP have been
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