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Feature-based control and information framework for adaptive and distributed manufacturing in cyber physical systems

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ABSTRACT

Modern distributed manufacturing within Industry 4.0, supported by Cyber Physical Systems (CPSs), offers many promising capabilities regarding effective and flexible manufacturing, but there remain many challenges which may hinder its exploitation fully. One major issue is how to automatically control manufacturing equipment, e.g. industrial robots and CNC-machines, in an adaptive and effective manner. For collaborative sharing and use of distributed and networked manufacturing resources, a coherent, standardised approach for systemised planning and control at different manufacturing system levels and locations is a paramount prerequisite.

In this paper, the concept of feature-based manufacturing for adaptive equipment control and resource-task matching in distributed and collaborative CPS manufacturing environments is presented. The concept has a product perspective and builds on the combination of product manufacturing features and event-driven Function Blocks (FB) of the IEC 61499 standard. Distributed control is realised through the use of networked and smart FB decision modules, enabling the performance of collaborative run-time manufacturing activities according to actual manufacturing conditions. A feature-based information framework supporting the matching of manufacturing resources and tasks, as well as the feature-FB control concept, and a demonstration with a cyber-physical robot application, are presented.

1. Introduction

Interest is progressively growing in utilising new technological and organisational advancements, such as Cloud Manufacturing, Internet of Things (IoT), Cloud Computing (CC), Semantic Web, virtualisation, service-oriented technologies, and advanced manufacturing models, within the manufacturing shop-floor domain [1,2]. Through a closer relationship between the cyber computational space and the physical factory floor, enabling monitoring, synchronisation, decision-making and control, CPSs are transforming the manufacturing industry into its next generation, Industry 4.0 [3]. By combining many of these technologies, offering globally available information, data and services, embedded intelligence, as well as connected machine and sensory networks, the evolving CPS paradigm will move discrete manufacturing activities towards the seamless collaborative and distributed sharing of manufacturing resources [4–8]. However, the level of complexity regarding manufacturing planning and control will become significantly higher for these multi-collaborative and distributed manufacturing environments. Therefore, one of the major technological challenges within CPSs will be how to support scenarios in which dynamically configured groups of dispersed resources cooperate to complete joint manufacturing missions. Currently, many manufacturing systems are unable to reach their production goals as they are negatively influenced and restricted by a multitude of undesired variations and conditions. There are both external and internal system events contributing to this uncertainty, which result in decreased manufacturing productivity and product quality. These events often necessitate the revision of existing process plans, requiring the re-programming of manufacturing equipment, which is often both tedious and time-consuming, even for minor changes. The extent of this control code renewal depends on the effects and impact of the events, and since control programs are often created for dedicated equipment, program portability is usually very low. Most manufacturing planning tools, e.g., Computer-Aided Process Planning (CAPP), and control systems are not able to handle unforeseen changes efficiently. In addition, major limitations using traditional

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CAPP tools within distributed environments such as CPSs are: centralised decision-making, static system structure and off-line data handling [9]. This greatly limits their ability to adapt pre-made process plans to shop-floor run-time variations. In a distributed CPS environment, which may involve a disparate multitude of participating and cooperating resources and resource types, the quantity of unpredictable variations that could disrupt and cause negative impacts is significant. To cope with this uncertainty effectively, and to handle the volatile nature of manufacturing resources' conditions and availability, an adaptive and distributed planning and control approach is required, which can adapt to variations and be distributed to different resources and levels of a CPS [10]. Such a control approach would need to be able to react and respond to different kinds of uncertainties, by utilising distributed and dynamic decision-making. Effective control and execution will then require real-time monitoring of all involved manufacturing resources, in order to continually and accurately determine their dynamic availability and operational status.

An effective approach to solving many of the above mentioned manufacturing issues is to apply feature-based manufacturing. This approach, which stems from a product perspective, since it builds on the product manufacturing feature concept, is a viable and effective method for adaptive and distributed manufacturing. Feature-based manufacturing can be realised through manufacturing services. By using the concept of manufacturing services, in a similar manner to the use of services within cloud computing, manufacturing resources and capabilities can be provided in distributed environments, such as CPSs, in which device network capabilities, such as IoT, may enable access for controlling distributed manufacturing equipment. Through the use of feature-based and event-driven Function Blocks (FBs) as smart and distributable decision modules, run-time manufacturing operations in a distributed CPS environment may be planned and executed, in order to meet prevailing manufacturing conditions and requirements. Developed for distributed manufacturing equipment control, these modules can be combined to satisfy different levels of control needs, and ultimately realise the idea of Manufacturing-as-a-Service (MaaS) [11,12].

Matching a wide array of available resources to requested manufacturing tasks is also a major issue within CPSs [5]. In order to express the various capabilities of manufacturing resources, and to improve the quality and efficiency of resource discovery and intelligent matching to manufacturing tasks, a unified information framework is necessary. For a description of manufacturing tasks, a feature-enriched product data model is developed, and for manufacturing resources, a feature-level capability model. These two models facilitate the discovery and matching of available resources to requested tasks to be undertaken.

The purpose of this paper is twofold: 1) to describe an adaptive FB-based control approach for distributed manufacturing resources in CPSs and 2) to present the outline of an information framework supporting this approach. The control approach and the information framework both build on the concept of feature-based manufacturing, with the use of product manufacturing features (MfgFs) as the cornerstone. Control is achieved through event-driven IEC 61499 FBs in a two-level planning and control structure for adaptive control, integrated as a service in a proposed control structure for CPS distributed manufacturing management. Examples are given for robot assembly tasks but the control approach is applicable to manufacturing equipment more generally. The information framework proposed supports the retrieval and matching of manufacturing tasks to manufacturing resources' capabilities, since it builds on a shared product MfgF perspective.

The paper is structured as follows: while Section 2 describes the concept of product manufacturing features, Section 3 presents adaptive manufacturing equipment control through a combination of event-driven FBs and MfgFs. How the control approach can be implemented in a distributed CPS environment, and how the control system's integration into the CPS management functionality can be achieved, is described in Section 4. This is followed in Section 5 by an outline of a supporting feature information framework for the discovery and matching of manufacturing resources to manufacturing tasks. Section 6 presents a description of a system implementation for the MfgF-FB control approach in a CPS, while Section 7 specifies the authors' concluding remarks.

2. Product manufacturing features

Feature-based descriptors, and the concept of manufacturing features (MfgFs) have been used in both product design and manufacturing for many years to identify the relationships between product features and the manufacturing operations required for their creation. The feature technology "Design by Features" [13], involves the definition of product designs through combining the necessary manufacturing features to realise the product. The opposite process is performed in "Feature Recognition" [14], in which existing product designs are examined and evaluated, in order to identify the manufacturing features and operations required to create the product.

Different categories of MfgFs can be realised by identifying, classifying and mapping discrete low-level or atomic manufacturing operations required for the creation of unique product features. Different manufacturing domains require different features, e.g., machining features (MFs) for machining tasks and the creation of unique product designs, and assembly features (AFs) for product assembly tasks. A higher-level manufacturing task is made up of a sequence of different lower-level basic manufacturing operations, e.g., *Side*, *Face*, *Step* in machining [15,16] and *Place*, *Insert*, *Move* in assembly [17], which can all be defined as separate MfgFs.

Manufacturing resources may provide one or more MfgFs and a specific MfgF may be available from different resources and be used in different manufacturing tasks. Another important advantage is that the MfgF representation is independent of both the implementation scenario and manufacturing equipment. Consequently, portability and transferability is good since the functionality mapped into the FB will be performed equally well by different manufacturing resources. The use of MfgFs has many advantages in manufacturing, as they can be applied for different, and cooperative, purposes. Central in this work is a combined approach for the use of MfgFs, established from a product perspective. This provides great flexibility since MfgFs are used: to detail the product model and the manufacturing task, describe generic capabilities of manufacturing resources as well as support and simplify the planning, control, programming and run-time generation of control instructions for manufacturing resources (Section 3). Using MfgFs to describe both products and resources is an important property for discovering and matching manufacturing task requests to available manufacturing resources (Section 5). With regard to resources, MfgFs for different manufacturing domains are used to describe the resource's ability to complete unique manufacturing operations as product features, through combining and aggregating the functional capabilities and properties of manufacturing resources. With regard to products, MfgFs are used to describe how they are to be manufactured.

2.1. Product assembly features

For a more specific and detailed description of the use of MfgFs, a robotic assembly task is selected and the concept of AFs is described in more detail. Here, robotic assembly relates to the manipulation of components (parts and sub-assemblies) for the creation of