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Resource virtualization: A core technology for developing cyber-physical production systems

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ABSTRACT

Smart factory in the context of Industry 4.0 is the next wave of smart manufacturing solution to empower companies to rapidly configure manufacturing facilities and processes to enable the fast production of individualized products at change scales. A key enabling technology for developing a smart factory is resource virtualization or creation of digital twins. The presented research fills the gap that the industry needs a practical methodology to enable themselves to easily virtualize their manufacturing assets for developing a smart factory solution. A test-driven resource virtualization framework is proposed as the recommendation for the industry to adopt to create digital twins for a smart factory. The proposed framework draws inspiration from past resource virtualization outcomes with special attention paid to the usability of the proposed framework in a business environment. It provides a straightforward process for companies to create digital twins by specifying the digital twin hierarchy, the information to be modeled, and the modeling method. To validate the proposed framework, a case study was undertaken at an international company, to create digital twins for all their manufacturing resources. The testing result showed that the proposed resource virtualization framework and developed tools are easy to use in a practical business environment to virtualize complex factory setups in the cyberspace.

1. Introduction

Today's ever-connected and decentralized business environment requires companies to be capable of quickly responding to evolving market demands to stay competitive in the market. The ability to rapidly configure manufacturing facilities and processes to enable the fast production of individualized products at change scales has become a significant focus for many manufacturing companies. This trend has been recognized at a global scale with the launch of several government initiatives aiming at delivering smart manufacturing reference models for companies to adopt to build up this capability. Industry 4.0 proposed by Germany, which is probably the most influential initiative, aims at creating smart factories where smart manufacturing systems communicate with each other and rapidly configure themselves for on-demand production [1]. A smart factory needs to:

- **Make real-time engineering decisions:** Smart factories allow in-house production processes to be radically optimized to meet personalized production needs in almost real-time conditions. This goal has been recognized by many manufacturing companies with a desire to shift to an agile production environment to support the fast production of products of diverse variants. The configuration of legacy engineering systems to support agile production is a challenge. The quality of the integration between the dominant PDM (Product Data Management), PLM (Product Lifecycle Management) and ERP (Enterprise Resource Planning) systems with a goal to support personalized production is a key component of facilitating fast and accurate engineering decision-making.
- **Monitor all manufacturing resources via industry internet:** Monitoring is an important aspect of smart production. Thanks to the ubiquity of sensors, wireless network, and cloud storage implementing sensor networks to collect key engineering information related to people, machine and processes in a factory is achievable. Analytics on manufacturing data can provide factory management team with insights on the snapshot of each machine, and the capacity of a factory so that data-driven production planning and forecast can be achieved.
- **Understand its own capabilities and self-organize production activities:** A smart factory can understand its capabilities based on gained engineering knowledge via self-learning and therefore organize production activities autonomously. Engineering knowledge learned from manufacturing data requires context and meaning. The generated knowledge graph based on collected manufacturing data will be used for decision-making at a higher level.

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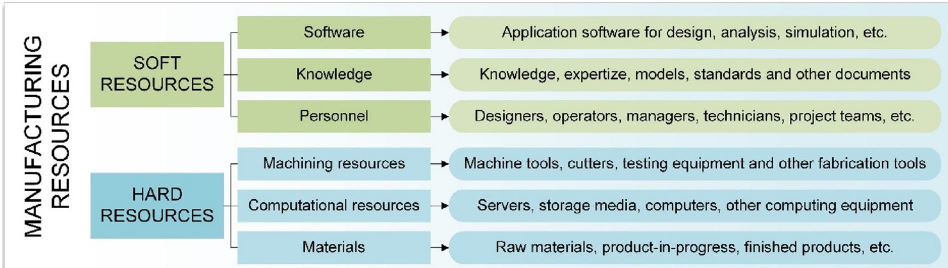

Fig. 1. Classification of manufacturing assets in cyber-physical systems.

To achieve the above vision, there has been a good amount of scientific efforts devoted to developing smart factory models and case studies. Jay Lee et al. proposed a generic high-level cyber-physical system (CPS) architecture towards digital factory [2]. The primary use of CPS in factory floors is to lay the foundation for smart factory management by virtualizing physical assets into the cyberspace and creating resilient, intelligent, and self-aware machines. Five layers are specified in the proposed CPS architecture: 1. smart connection to physical assets via various sensors, 2. conversion of data to information for each connected asset, 3. cyber level as the central information hub where machines are interconnected into a virtual network, 4. knowledge generation of the acquired information to present to end users for making business decisions, and 5. machine self-configuration based on human decisions. The second and third layer in this architecture requires a semantic model that allows a physical asset to be abstracted to a digital twin in the cyberspace. Constructing mirrors of physical manufacturing resources in the cyberspace is a significant underlying technology for developing a cyber-physical system [3]. The research work in this paper focuses on developing a methodology to enable the development of a feasible semantic model that supports easy creation of digital twins for physical assets in a factory so that high-level factory monitoring and planning systems can rely on the generated digital twins.

Digital twin reflects two-way dynamic mapping of physical objects and virtual models [4]. The essence of a digital twin presents a middleware architecture that abstracts the shop-floor hardware for usage at high-level engineering management systems to make real-time decisions. At its technical core, the concept of a virtualized version of the physical manufacturing asset signifies a data model that encapsulates its technical specifications and information relationship with its external environment [3]. Specifically, it is the virtualization of physical entities [5]. A common practice is to develop a semantic model for encapsulating machine specifications and capabilities and relationships between the resources. There has been some research work on developing semantic models for predictive maintenance [6], machine fault diagnosis [7], digital factory [8], prognostics [9] etc. To take these research outcomes to real industry application, there is a need to develop guidelines and frameworks that empower companies to systematically develop semantic models for smart factories in Industry 4.0 environment based on their own factory setups and business needs. The research work presented in this paper proposes a systematic framework for developing smart factory semantic models and virtualizing factory assets using the development model. The framework for developing a feasible virtual smart factory using a proper modeling language with the ability to enable on-demand knowledge-based business decisions is considered as the key contribution of the presented research work. The authors understand that another key aspect of a CPS is that a digital twin is required to always stay in synchronization with the physical entity using advanced sensor technologies. This is not the focus of this research. A sample semantic model for a real factory environment is presented as a case study to show the process of virtualizing a factory using the proposed framework. The rest of the paper is organized as follows. Section 2 reviews the literature in related research areas and highlights the research gap that motivated the presented research work. The framework for virtualizing resources of a factory is presented in Section 3 with detailed discussions on the logic of the resource virtualization process and essential data to be abstracted in the digital counterpart. A case study with a global manufacturing company is presented in Section 4 to validate the proposed framework. Discussions on the testing results and industry feedback are presented in Section 5. Section 6 concludes the research work and highlights future research directions.

2. Literature review and research gaps

The role of a cyber-physical production system in a factory environment is to allow companies to quickly adapt to market changes via flexible configuration of manufacturing resources for the rapid production of one-off personalized products while maintaining required margins. It requires cyber-physical systems to be able to self-organize production activities at the configuration level using machine dynamics information from cyber level [2]. Resource virtualization is a key enabling technology for developing cyber-physical production systems [10]. This section reviews the reported research related to resource virtualization and highlights the research gap.

2.1. Literature review

Cyberspace in cyber-physical systems is an information hub that stores all the digital twins of all physical manufacturing assets. Manufacturing assets consist of diversified and distributed manufacturing resources (equipment, computational resources, materials, software, knowledge, and skills) (see Fig. 1 for further details) [11]. These resources in a factory are the key manufacturing assets to be virtualized in the cyberspace. With regard to manufacturing resource modeling, standards such as STEP-NC were recognized as playing an important role [12]. A novel STEP-NC compliant machine tool data model was developed to enable modeling of machine tools in the cyberspace for process planning and manufacturing [13]. The developed machine tool data model provides adequate information, such as machine geometry, cutter information, process information to support process planning in a smart factory. Similarly, a STEP-NC based data model was proposed to model CNC machine tools and their auxiliary devices. The focus of this developed model is to define the physical components and the kinematic chains of a machine tool in the cyberspace. Wang and Xun also investigated abstracting capabilities details from distributed manufacturing resource and utilizing these information in the cyberspace to drive decision-making in matching manufacturing facilities with production jobs [14]. More importantly, the functionality of a resource at different granularity levels needs to be modeled [15]. Before the virtualization of resources, the granularity levels, the resource categories in each granularity level and the virtual models of each kind of resource need to be defined. Another multi-granularity manufacturing resource model was also proposed to model manufacturing capabilities at different granularity levels [16].

To enhance the semantic interpretation of virtualized