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Cloud-assisted interaction and negotiation of industrial robots for the smart factory☆

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ABSTRACT

Industrial robots such as robotic arms and AGVs (Automated Guided Vehicles) are widely used in the manufacturing environment to perform various kinds of tasks. However, these industrial robots are designed for traditional production lines which need little interaction and negotiation. As a result, current robots are not suitable for the emerging smart factory in the era of industry 4.0, which features high interconnection, dynamic reconfiguration, mass data, and deep integration. In this paper, a solution using the cloud to assist inter-layer interaction and inter-robot negotiation for smart factory is presented. First, a multi-layer framework is proposed consisting of robots, cloud, and client terminals, and these components are interconnected via networks. Second, the interaction process between components across multi-layers is described. Third, intelligent negotiation mechanism for robots to implement self-organized dynamic reconfiguration is designed, especially for the hybrid production of RFID (Radio Frequency Identification) tagged products, which is a flexible and economical configuration for the production of multi-type and small-lot products. Finally, a prototype system for a candy-packing application supporting customization is presented to verify the proposed framework, interaction method, and negotiation mechanism.

1. Introduction

Human society keeps needing manufacturing industry to provide a great diversity of products. Therefore, the industry cannot stop progressing to achieve higher quality and efficiency. By now, we have experienced three industrial revolutions, enabling industry with automated machines and information systems to support rapid and innovative product design. Today, the new challenges, such as personalized consumption demands, environmental disruption, energy shortage, and population aging, ask for the fourth stage of industrialization. Technical advancement on IoT (Internet of Things) [1,2], cloud computing [3], big data [4,5], and artificial intelligence offers a huge opportunity to implement flexible, green, and human-friendly production paradigm [6]. The international community promptly seizes this opportunity. For example, in July 2010, the German government adopted a strategic initiative called “Industry 4.0” as part of the “High-Tech Strategy 2020 Action Plan” [7]. Other main industrial countries have proposed similar strategies, such as the American “Industrial Internet” [8] and the

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Chinese "Internet +" programs [9]. Moreover, clouding manufacturing [10,11] and internet of manufacturing things [12] have also been proposed and tried out.

The following three main features should be considered to implement the Industry 4.0: 1) horizontal integration via value-added networks; 2) vertical integration and networked manufacturing systems; and 3) end-to-end digital integration of engineering across the entire value chain [7]. Smart factory refers to vertical integration, and it aims to leverage the industrial IoT, cloud computing, and big data to integrate information technologies with automation deeply [13], along with the AI (Artificial Intelligence) technologies to improve the intelligence of machines and products [14]. Compared with the current production paradigm, smart production shows some distinguishing characteristics.

High interconnection. The smart factory operates in a networked environment in which both the physical entities and the information systems are involved and interact through this network. In summary, the industrial network is an essential infrastructure for the smart factory that goes beyond the traditional distributed control system in terms of the extent, performance, and QoS (Quality of Service).

Dynamic reconfiguration. Multiple types of products enter smart production system randomly making the needed set of resources and operation sequences unpredictable. Therefore, manufacturing resources must be reconfigured at run time. By contrast, the traditional production line is designed for a specific product type to achieve high efficiency with no automated reconfiguration performed.

Mass data. Many smart entities keep generating data for interaction, and most of the data are transferred to cloud for analyzing and mining. High bandwidth network and big data technology enable the transfer, storage, processing, and analysis of these mass data. By contrast, the traditional production lines rely on distributed control system and low bandwidth field buses to exchange a small amount of data, mainly for process control purpose.

Deep integration. With physical entities, information systems, and mass data existing on the same network, activities from perception, communication, and information processing, to control and physical operation take place automatically. The traditional layers including device, control, MES (Manufacturing Execution System), and ERP (Enterprise Resource Planning) break, while keeping the continuity, consistency, and integrality of data.

Although the characteristics above describe a promising manufacturing paradigm regarding high flexibility, high efficiency, and high transparency, the implementation of smart factory still faces many technical limits [15,16]. For example, the constrained computing and communication abilities limit the application of industrial robots in the smart factory [17]. This paper presents a cloud-based solution to enable interaction and negotiation for smart manufacturing. First, robots equipped with Raspberry Pi [18] controllers and ROS (Robot Operating System) [19], client terminals, and cloud are interconnected via Ethernet. Second, bidirectional interaction across the layers is described. Third, intelligent negotiation mechanism for robots to implement self-organized dynamic reconfiguration is designed. Finally, the proposed framework, interaction process, and negotiation mechanism are verified in a prototype system for a candy-packing application that supports customization.

The article is organized as follows. Framework for the smart factory is presented in Section 2, followed by the description of the cloud-assisted interaction and negotiation in Sections 3 and 4 respectively. The prototype system is presented in Section 5, and finally conclusions are drawn in Section 6.

2. Integrated framework for smart factory

Fig. 1 shows the four-layered framework for the smart factory. Various kinds of shop-floor entities including machines, robots, conveyers, and raw products form the self-organized network. A network of servers for hosting information systems and data constitute the cloud layer; people interact with the system through various kinds of client terminals. The network connects these layers establishing an integrated system. As a result, both physical entities and information systems plus data are interconnected creating the Internet of Things and Service.

According to Fig. 1, each robot is equipped with a Raspberry Pi microcontroller that expands the computing and communication abilities of the robot controller. In the presented prototype system, the Raspberry Pi controller is installed with Ubuntu OS and ROS. The ROS provides a convenient way for multiple Raspberry Pi controllers to communicate with each other through Ethernet link. The Pi controller, on behalf of its corresponding robot, is responsible for negotiating with other Raspberry Pi controllers and collecting information from its connected sensors such as a photoelectric sensor for detecting product position and a RFID reader/writer for retrieving process information stored in the tag attached to a product. Based on the results of negotiation, the sensing information, and the internal state, the Raspberry Pi controller makes decisions and instructs its robot to perform tasks.

This paper focuses on inter-layered interaction across multi-layers and inter-robot negotiation only within the shop floor layer. As to interaction, we describe how the information flows from clients to shop floor through the cloud, and how the data transmits back from the shop floor to the clients. As to negotiation, the paper explains how the shop floor entities cooperate to determine a machine and a route for each needed operation of products by negotiating with each other.

2.1. Self-organized network of smart shop-floor entities

A diversity of physical entities, such as CNC machines, robots, AGVs, conveyor belts, and automated warehouse, exist in shop floor. Such entities are called smart objects meaning they can perceive their surrounding environment, make self-decisions, and negotiate with each other, in addition to the abilities of control, computing, and communication. Through