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Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination

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ABSTRACT

The proliferation of cyber-physical systems introduces the fourth stage of industrialization, commonly known as Industry 4.0. The vertical integration of various components inside a factory to implement a flexible and reconfigurable manufacturing system, i.e., smart factory, is one of the key features of Industry 4.0. In this paper, we present a smart factory framework that incorporates industrial network, cloud, and supervisory control terminals with smart shop-floor objects such as machines, conveyers, and products. Then, we provide a classification of the smart objects into various types of agents and define a coordinator in the cloud. The autonomous decision and distributed cooperation between agents lead to high flexibility. Moreover, this kind of self-organized system leverages the feedback and coordination by the central coordinator in order to achieve high efficiency. Thus, the smart factory is characterized by a self-organized multi-agent system assisted with big data based feedback and coordination. Based on this model, we propose an intelligent negotiation mechanism for agents to cooperate with each other. Furthermore, the study illustrates that complementary strategies can be designed to prevent deadlocks by improving the agents' decision making and the coordinator's behavior. The simulation results assess the effectiveness of the proposed negotiation mechanism and deadlock prevention strategies.

1. Introduction

The application of automation and information systems such as enterprise resource planning (ERP) and manufacturing execution system (MES), significantly improves factory productivity. However, the current industrial production faces many critical challenges. The end users continuously require highly customized products in small batches. Moreover, the current production paradigm is not sustainable [1]. On one hand, the impact of industrial production on environment in terms of global climate warming and environmental pollution is severe. On the other hand, the consumption of non-renewable resources such as petroleum and coal increases and the industry suffers an ever-shrinking workforce supply because of population aging. Therefore, industrial processes need to achieve high flexibility and efficiency as well as low energy consumption and cost. Many advanced manufacturing schemes have already been proposed aiming to overcome the drawbacks of the current production lines, e.g., the flexible manufacturing system (FMS) and the agile manufacturing system (AMS). Among these schemes,

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the multi-agent system (MAS) is the most representative one [2], where the manufacturing resources are defined as intelligent agents that negotiate with each other to implement dynamic reconfiguration to achieve flexibility. However, due to the lack of some global coordination, the proposed MAS schemes could not handle complex manufacturing systems in an efficient way [3].

Nowadays, the emerging cyber-physical system (CPS) presents a significant opportunity to implement smart manufacturing. The CPS can arm the MAS with the emerging technologies (e.g., Internet of Things (IoT) [4–6], wireless sensor networks (WSN) [7,8], big data [9], cloud computing [10–12], embedded systems [13], and mobile Internet [14]). Consequently, a strategic initiative called “Industrie 4.0” (Industry 4.0) has been proposed and adopted by the German government as part of the “High-Tech Strategy 2020 Action Plan” [15]. Similar strategies have also been proposed by other main industrial countries, e.g., “Industrial Internet” [16] by USA and “Internet +” [17] by China. The Industry 4.0 describes a CPS oriented production system [18–20] that integrates production facilities, warehousing systems, logistics, and even social requirements to establish the global value creation networks [21].

The smart factory is an important feature of Industry 4.0 that addresses the vertical integration and networked manufacturing systems for smart production [15]. For smart factory to be implemented, it should combine the smart objects with big data analytics. The smart objects can dynamically reconfigure to achieve high flexibility whereas the big data analytics can provide global feedback and coordination to achieve high efficiency. Therefore, the smart factory might be able to produce customized and small-lot products efficiently and profitably. Considering that FMS tries to allocate manufacturing resources to a family of product types with a kind of central computerized controller [22], and MAS relies on autonomous agents to reconfigure dynamically [23], the smart production enabled by smart factory features high interconnection, mass data, and deep integration.

In this article, based on a novel smart factory framework that integrates the autonomous agents with big data based feedback and coordination [24], we focus on the key algorithms that can operate the smart factory. The contributions of this study mainly include two aspects. First, we model the smart shop-floor objects such as machines, conveyers, and products as agents, and propose an intelligent negotiation mechanism for them to cooperate with each other. Second, we identify the conditions that enable deadlocks, and design four complementary strategies to prevent the deadlocks by improving agents’ decision making and the coordinator’s behavior. Finally, we test and validate the proposed negotiation mechanism and deadlock prevention strategies through numerical simulation.

The article is organized as follows. Section 2 introduces the framework and operational mechanism of smart factory. Section 3 proposes an intelligent negotiation mechanism to enable self-organization of agents. Section 4 describes four deadlock prevention strategies. Section 5 reports the main simulation results. Finally, Section 6 concludes the work.

2. System architecture and operational mechanism

The smart factory is a manufacturing cyber-physical system that integrates physical objects such as machines, conveyers, and products with information systems such as MES and ERP to implement flexible and agile production. In this section, a framework for smart factory is proposed and its operational mechanism is investigated.

2.1. System architecture

Figure 1 summarizes the smart factory framework consisting of four tangible layers, namely physical resource layer, industrial network layer, cloud layer, and supervisory control terminal layer. The physical resources are implemented as smart things which communicate with each other through the industrial network. The integrated information system exists in the cloud which collects massive data from the physical resource layer and interacts with people through supervisory control terminals [14]. Thus, the tangible framework enables a networked world for intangible information to flow freely. This actually forms a CPS where physical objects and informational entities are deeply integrated.

2.2. Operational mechanism

From the perspective of the control engineer, the smart factory can be viewed as a dual closed-loop system, as shown in Fig. 1. One loop consists of physical resources and cloud, while the other loop consists of supervisory control terminals and cloud.

The smart shop-floor object has 3C’s capabilities and it is autonomous and social. The term autonomous means that the smart object makes decisions by itself and no other entities can directly control its behavior. The term social means that the smart objects understand and share a common set of knowledge and negotiate according to a common set of rules. Therefore, a society of smart objects can yield a highly flexible manufacturing system, i.e. a self-organized and reconfigurable system that seems to be humanoid or smart.

Through cooperation, the smart objects try to align their behaviors to approach a system-wide goal. However, the system performance is generally not the optimum. This is because the smart objects make decisions based on local information. Thus, as to manufacturing, for example, load may not be balanced, efficiency may not be the highest, or deadlocks may occur. One of the big data analytics blocks (the coordinator) can solve this issue. The smart machines communicate their state and process information to the block, and the distributed sensors transfer their sensed data to the block as well. Therefore, the global state of the smart factory can be extracted from the massive real-time system information. Based on the powerful computing ability, the block processes these big data in time to coordinate the behaviors of the distributed smart objects, and to feedback performance indicators to the self-organized network. Therefore, this global optimization can assist the autonomous agents to achieve a better performance.