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Combined strength of holons, agents and function blocks in cyber-physical systems

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ABSTRACT

This paper presents a novel approach to implementing cyber-physical systems (CPS) using the combined strength of holons, agents and function blocks. Within the context, a CPS is represented by a holarchy of multiple holons. Each holon possesses a logical part and a physical part, which mimic the cyber and physical entities of the CPS. During implementation, the two parts of a holon are realised by agents and function blocks for information processing and materials processing, respectively. The objective of this research is to provide a concept map and associate a CPS with holons, agents and function blocks for the ease of system implementation in decentralised or cloud environment.

1. Introduction

IT revolution has brought many practical applications of IT and Web-based systems such as those in healthcare, traffic control, and manufacturing systems. Dynamic data flow and integration of the computational entity of such systems and the physical world is of high importance to guarantee a good level of performance. Cyber-physical system (CPS) was first defined by Lee [1] as the convergence of computation and physical processes where computational entities and physical processes are connected through networks and can coordinate with each other in real-time, i.e. physical processes are monitored and controlled by the embedded computers and feedbacks loops are designed to allow both sides to affect each other. Cyber-physical systems in the area of production and manufacturing (i.e. cyber-physical production systems) are also discussed in a number of publications; see e.g. [2–4]. Cyber-physical systems can be applied as the solution to the needs of the manufacturing systems of the 21st century and are deemed to eventually lead to the 4th industrial revolution, frequently noted as Industry 4.0 [3].

New paradigms and technologies such as holons and agents have recently gained a lot of attention in the field of manufacturing control because of the upcoming challenges of the 21st century such as decentralisation, frequently shifting technologies, and various market perturbations. The trend of mass production will eventually move towards high variety of custom-made products in smaller volumes, due to the fact that the dominant role will shift from the vendors to the customers [5]. Shorter product lifecycles and rapid reconfiguration will require control systems being intelligent, flexible, extensible, fault-tolerant and re-usable [6]. To support competitiveness, manufacturing enterprises should apply new architectures for distributed manufacturing control that not only have high agility and responsiveness but also can guarantee a satisfactory quality and cost according to the customer requirements. The paradigms of agents and holons began in late 20th century [7,8] to answer the challenges of factory of the future. They were defined as autonomous and cooperative entities which were capable of decision making and negotiating with other entities to satisfy the system's goal. In the field of manufacturing, research on holonic manufacturing and multi-agent systems was motivated by stable yet flexible manufacturing tasks, intelligent decision making and distributed manufacturing structures.

Moreover, function blocks (FBs) [9,10] as machine-level execution and control standards are also considered a suitable approach to modelling distributed manufacturing systems and fit well with the concepts of holons and agents. When combined, holons, agents and function blocks can represent and model a cyber-physical system which is intelligent and adaptive, and can cope with the future challenges of the manufacturing systems.

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The aim of this paper is to address the connection of these new paradigms in the context of CPS/Industry 4.0. The rest of the paper is organised as follows. A short literature review on the evolution of control architecture as well as the notions of holons, agents and function blocks is presented in Section 2. Section 3 describes the similarities, differences and strength of holons and agents. Section 4 explains the suitability of holons, agents and function blocks for modelling CPS and presents an overview of a cyber-physical production system modelled through the combination of holons, agents and function blocks. Finally, Section 5 concludes the paper.

2. Literature review

2.1. Evolution of manufacturing control architectures

Conventional computer-integrated manufacturing (CIM) systems adopted hierarchy-based centralised architectures [11,12]. Top-down structure, fixed multi-layers of hierarchies (parent and child), and a centralised decision-making unit (scheduler) with a top-down flow of commands, are the main characteristics of such systems. The functionality of each module is strictly defined by the scheduler and their communications are only limited to their parents or children [13]. For a manufacturing plant, these layers of hierarchy are, from the bottom upwards: servo, machine axis (joint), elementary move, task, cell and job shop level [14]. Even though such control architectures can usually allow possibilities of global optimisation (thanks to a central decision-making unit) and give a good reference for defining modular systems [14], they failed to perform well during different disturbances in the system [15]. In other words, newly introduced changes to the shop floor, such as machine failure or tool breakage, might end up halting the entire system which as a result would introduce the system to some unnecessary costs. Furthermore, this rigid architecture is expensive to maintain and reconfigure, which as a result limits the system's scalability.

As is evident from the discussions above, the traditional control systems cannot cope with the requirements of the dynamic shop floors of the future manufacturing systems (such as integratability, cooperativeness, localised decision-making authority, openness, interoperability, scalability, agility, fault tolerance, etc. [16,17]. Therefore, researchers have been studying new paradigms and new control architectures that can satisfy these requirements.

The heterarchical control architecture was proposed by Duffie [18]. In such a distributed control system, all manufacturing subsystems could be represented by a number of intelligent entities that could work independently and share information to achieve the global goal of the system. Even though the heterarchical architecture showed higher degree of autonomy and agility [19] compared to the conventional hierarchical control systems, it often failed to achieve a global optimisation and could fall into some unstable states especially in complex systems [20]. Due to these lacks of high performance and predictable behaviour, heterarchical control systems were rarely applied in industry [13] – as a result, they were modified to form a more promising architecture, namely partial hierarchical controls.

Partial hierarchical control systems are a mixture of hierarchical and heterarchical controls that apply the benefits of both systems while avoiding their shortcomings and have become the perfect solution for the upcoming challenges of the future manufacturing systems [21]. Similar to heterarchical approach, the control system consists of autonomous and cooperative units that represent the manufacturing system and can work together to achieve a goal. However, the communication path among these entities is more flexible compared to previous control architectures, and different connections (as in hierarchies or heterarchies) can be created according to the requirements of the system. Therefore, this structure can both satisfy the agility (as in heterarchical structures) and stability (as in hierarchical structures). Many research works have emphasised on the necessity of both heterarchical and hierarchical characteristics in a control system, see e.g. [13,22,23]. A general comparison of these three architectures is presented in Table 1.

2.2. Agents and multi-agent systems (MAS)

In research of alternative control architectures, the idea of autonomous and intelligent units (a.k.a. agents) eventually evolved from the Distributed Artificial Intelligent (DAI) systems research in the 90s [24]. Wooldridge [7], from the group of pioneers who investigated the agent technology, defined an agent as "a software entity situated in some environment, that is capable of autonomous action in this environment in order to meet its design objectives". One of the new definitions of agent is as follows [25]: "an agent is an autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives". In other words, an agent should be able to act without direct instruction of higher authorities or intervention of humans, but instead in negotiation with other agents if necessary. A network of agents, will create a multi-agent system (MAS) whose members are not only responsible for satisfying their local objective, but also can interact and cooperate with each other to satisfy a global objective. MAS can be best characterised as a software technology that is able to model and implement individual and social behaviour in distributed systems [5].

Some of the main characteristics of agents have been described as follows [24,26,27]:

- Reactive: agents should be able to sense their surrounding environment and react to the changes that occur;
- Proactive: agents should be capable of achieving their assigned goal;
- Autonomous: agents should have enough knowledge and authority to operate and act on their own without direct instructions or intervention from humans or other agents;
- Cooperative: agents can interact with other agents if necessary to achieve the global objective of the system;
- Adaptive: agents can learn from their previous behaviours and can apply their experiences to future scenarios; and
- Mobile: agents can move through the network.

Agent technology has shown promising applications in different areas of manufacturing such as supply chain management, process planning and scheduling, see e.g. [17,28,29].

2.3. Holons and holonic manufacturing systems (HMS)

The term "holon" was first used by Koestler [8] as he observed a dichotomy of *wholeness* and *partness* in living organisms and social organisations. In other words, he noticed that each organism is a part of a bigger *whole* while it is itself considered a whole for some other organisms if viewed from the opposite direction. The word "holon" coming from the Greek language, holds this dichotomy as "holos" means "whole" and the suffix "on" implies "part". The holonic paradigm was later proposed for controlling the manufacturing systems and the holonic manufacturing system (HMS) paradigm was born. Being closely related to the notion of multi-agent systems, an HMS is defined as a group of holons that integrate the entire range of manufacturing activities from order booking through design, production and marketing to realise the