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Control for Intelligent Manufacturing: A Multiscale Challenge

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ABSTRACT

The Made in China 2025 initiative will require full automation in all sectors, from customers to production. This will result in great challenges to manufacturing systems in all sectors. In the future of manufacturing, all devices and systems should have sensing and basic intelligence capabilities for control and adaptation. In this study, after discussing multiscale dynamics of the modern manufacturing system, a five-layer functional structure is proposed for uncertainties processing. Multiscale dynamics include: multi-time scale, space-time scale, and multi-level dynamics. Control action will differ at different scales, with more design being required at both fast and slow time scales. More quantitative action is required in low-level operations, while more qualitative action is needed regarding high-level supervision. Intelligent manufacturing systems should have the capabilities of flexibility, adaptability, and intelligence. These capabilities will require the control action to be distributed and integrated with different approaches, including smart sensing, optimal design, and intelligent learning. Finally, a typical jet dispensing system is taken as a real-world example for multiscale modeling and control.

1. Introduction

In Germany, Industry 4.0 is the term for the next industrial revolution [1]. In the United States, General Electric is promoting a similar idea under the name of the Industrial Internet. In China, the central government has established the Made in China 2025 initiative for future industry. All these ambitious plans indicate the beginning of the Fourth Industrial Revolution—a revolution that will merge real things with the virtual world for greater efficiency. Three other industrial revolutions have occurred in human history. The First Industrial Revolution employed mechanical production facilities; it started in the second half of the 18th century and lasted throughout the entire 19th century. Mass production using electrification led to the Second Industrial Revolution, which started around the end of the 19th century. The "digital revolution" that occurred in the 1970s can be defined as the Third Industrial Revolution, as information technology began to be used for the automation of production processes. Unlike all previous revolutions, which only released human physical power for linear changes, the Fourth Industrial Revolution will free the human thinking power that is "intelligence" and will create nonlinear changes beyond what we can imagine.

The core of Industry 4.0 is intelligent manufacturing, which can be considered as the cyber-physical system (CPS) within the manufacturing environment, in order to achieve full automation of both materials and information. The CPS is an Internet environment in which all users, hardware, and software are integrated, regardless of time and location, in order to adapt to different working conditions through good coordination and enhanced ability [2]. Examples of CPSs include smart grids, automated vehicle systems, medical monitoring, and intelligent manufacturing [3]. The differences between an embedded system and a CPS are as follows: An embedded system focuses on developing algorithms, while a CPS focuses on the connection and coordination between physical elements and computational software [4].

Over the past decades, consumable products have become increasingly advanced and intelligent, making manufacturing systems increasingly complex. From an academic point of view, the manufacturing industry is a nonlinear multiscale complex system. No single solution exists for such a complex system. Due to the human way of linear thinking, nearly all the theories and methods developed

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so far are linearly dominated, making it difficult to apply them directly to nonlinear systems. The principle of systems engineering is to decompose a complex system into simpler ones, solve them separately, and then integrate all separate solutions in order to meet a global objective. In a manufacturing plant, each product is produced through a series of complex operations, each of which can be further decomposed into multiple basic actions. Obviously, uncertainties will appear at all of these stages and affect the overall quality.

This paper briefly discusses the multiscale complexity of the manufacturing process, presents modeling and intelligence that may be required in a manufacturing environment, and examines a case study for jet dispensing control for the integrated circuit (IC) packaging industry.

2. Multiscale complexity and uncertainty processing

A whole factory or plant usually has more than one production line containing many different types of processes. Each process may integrate multiple machines or pieces of equipment. Manufacturing operations in a factory can be classified into three different levels: the machine level, the production level, and the plant-wide level. The whole manufacturing process can be considered as a hierarchical structure: from machine control at the bottom layer, through mid-level supervisory control and production scheduling, and up to business management at the highest level. Different properties are exhibited at different levels, as shown in Table 1.

The characteristics and dynamics at different levels differ such that different control actions, from continuous to discrete, are required. Different processes may have different types of dynamics and a different scale of complexity. Some typical processes may include:

- **Multi-time-scale processes.** This is the most common scenario in manufacturing, in which a single part is manufactured within a short time, whereas parts in batches are produced over a long time period. The consistency of production is hence a primary concern, and involves the integration of various methods, such as robust system design, feedback control, and statistical process control.
- **Space-time dynamic processes.** Temperature fields, pipe fluid, and flexible robotic arms belong to this space-time dynamic system. Here, the performance changes not only in time but also in spatial location, and is therefore extremely difficult to model and control.
- **Multi-level hybrid processes.** The integration of systems at different levels results in hybrid systems that may be continuous, discrete, fuzzy, probabilistic, and so forth. The modeling and control of these types of systems are difficult because no mature methods are available. In general, the lower the level, the more dynamic property is required, such that dynamic control is needed. Uncertainty exists everywhere, in all levels of the manufacturing hierarchy. The higher the level, the larger the uncertainty, such that more intelligence is required for the control system.

In terms of control engineering, several types of control can be defined, as follows:

- **Logic control.** This involves discrete action with two discrete states: on/off. No dynamics are involved.
- **Loop control.** This requires dynamic control because it entails the handling of physical dynamics. It involves continuous action at the machine level. Since machine dynamics can be expressed quantitatively, the control action can be optimized.
- **Supervisory control.** This involves nest control action, which is of a hybrid discrete/continuous nature.

All of the abovementioned low-level types of control are widely used in process control. High-level control involves a more decision-making type of action, which requires more intelligence-based methods, such as the following:

- Operation scheduling at the production level; and
- Business management of the plant-wide operation.

Regarding intelligent manufacturing, the five-level pyramid structure shown in Fig. 1 can be useful in effectively processing uncertainties and improving the overall quality [5]. The first step is to place sufficient sensors appropriately in order to collect data from the physical process. If everything can be measured and connected, physical uncertainty can be minimized. Once data is obtained, it should be converted into useful information for higher level analysis and processing. Many mature modeling and learning methods can be used to help reduce information uncertainty. Since manufacturing involves the integration of many different types of equipment and functional devices, hybrid modeling and learning is required for system-level coordination. Decision-level coordination involves human-machine interaction, which requires processing ability between human linguistic language and machine computational algorithms. In order to achieve full automation, knowledge-level decisions should be able to process unexpected events, which will continue to be a long-term challenge.

In summary, different types of processes require different control actions.

- More design is required at the fast time scale, and more control is needed at the slow time scale. The jet dispensing system for packaging is a good example that will be discussed in detail in Section 4.
- More quantitative action is required at low-level operations because machine dynamics can be expressed mathematically; in contrast, more qualitative action is needed in high-level supervision because that system cannot be described quantitatively.

Systematic work in this area should be built step by step using a bottom-up approach: from dynamic modeling, system design, process control, and intelligent supervision, up to plant-wide management control, and so forth. This is a large-scale challenge.

3. Modeling and intelligence in manufacturing

The multiscale complexity of the intelligent manufacturing process

Table 1
Multiscale properties of the manufacturing industry.

Property	Machine level	Plant-wide level
Characteristics	Local (product oriented)	Global (business oriented)
Dynamics	Fast	Slow
Complexity	Small scale (linear dominant)	Large scale (nonlinear multivariable)
Uncertainty	Small	Large
Control	Dynamics-driven (continuous, instinct)	Knowledge-driven (discrete, logic)
Evaluation	Accuracy/precision	Profit
Intelligence	Low (adaptation)	High (decision)