氏　　　名	GHOSH ANGKUSH KUMAR
授 与 学 位	博士（工学）
学 位 記 番 号	博甲第 198 号
学位授与年月日	令和 4 年 3 月 18 日
学位授与の要件	学位規則第 4 条第 1 項
学 位 論 文 題 目	Developing a System for Constructing Digital Twins of Machining Phenomena Based on Semantic Annotation and Time-Delayed Sensor Signals（セマンティックアノテーションおよび時間遅れ型センサー信号を規範とする機械加工現象のデジタルツイン作成システムの開発）
論 文 審 査 委 員	主査　教　授　裡　　しゃりふ
	教　授　星　野　洋　平
	准教授　髙　井　和　紀
	教　授　林　田　和　宏
	教　授　升　井　洋　志

学位論文内容の要旨

Manufacturing has rapidly been transforming under the umbrella of the fourth industrial revolution, known as Industry 4.0 or smart manufacturing, which diligently utilizes information and communication technology. In smart manufacturing, cyber-physical systems host Internet-of-Things (IoT)-based networks and digital twins. The networks integrate manufacturing enablers such as computer numerical control machine tools, robots, numerous process and resource planning systems, and human resources. Digital twins are computable virtual abstractions of real-world entities exhibiting real-time responsive capacities. The twins work as the brains of the enablers; that is, the twins supply the required knowledge and help enablers solve problems autonomously, responding to various sensor signals in real-time.

Remarkably, three types of digital twins (object, process, and phenomenon twins) must populate the cyber-physical systems. Compared to other twins, phenomena twins have not yet been researched elaborately. This thesis fills this gap. The issues underlying semantic annotation and time latency (or delay) are significant for a phenomenon twin. Time latency or delay occurs when sensor signals are exchanged through the above-mentioned embedded systems. As a result, the signal at its origin (e.g., machine tools) and signal received at the receiver end (e.g., digital twin) differ. Moreover, many datasets of heterogeneous sensor signals are exchanged through IoT-based networks. Hence, acquiring the right signals for a twin is difficult and time-consuming. Semantic annotation-based representation of sensor signals can solve this problem.

Thus, a phenomenon twin must machine-learn the required knowledge to emulate the phenomenon from the relevant historical sensor signal datasets, seamlessly interact with the real-time sensor signals, handle the semantically annotated datasets stored in clouds, and accommodate the transmission delay or latency.

Accordingly, this thesis presents two systems denoted as Digital Twin Construction System (DTCS) and Digital Twin Adaptation System (DTAS). The first system constructs a phenomenon twin, and the other adapts the constructed twin into a cyber-physical system. Both systems are developed using a Java™-based platform. The modular architectures of the systems are presented in detail. In addition, real-life machining torque signals are used to demonstrate the efficacy of DTCS and DTAS.

DTCS consists of five modules denoted as Input, Modeling, Simulation, Validation, and Output Modules. The Input Module can make sense of the semantically annotated datasets and helps users select the right ones. It ensures fast and effective data mining using a human-machine-comprehensible semantic annotation mechanism (concept map and Extensible Markup Language (XML) driven). The Modeling Module can extract the required knowledge to emulate a phenomenon from the information supplied by the Input Module. This module uses a Markov chain-based machine learning method and accommodates data transmission delay-related arrangements. The Simulation Module can operate on the knowledge extracted by the Modeling Module and simulate the signals of the phenomenon using a discrete event-based stochastic simulation method. The Validation Module can validate the simulated signals of the phenomenon against the real signals using quantitative measures (e.g., fuzzy numbers). Finally, the Output Module transfers the selected Modules of DTCS to DTAS. DTAS, in turn, can adapt the constructed phenomenon twin into the cyber-physical system for monitoring and troubleshooting.

The thesis is organized as follows. Chapter 1 presents the introduction of this study. Chapter 2 provides a literature review on the role of cyber-physical systems and digital twins in smart manufacturing or Industry 4.0. Chapter 3 describes a semantic annotation-based representation mechanism of data and knowledge. Chapter 4 describes the role of the delay domain in mitigating the effect of time delay or latency of signal transmission. Chapter 5 presents the proposed DTCS and DTAS. Chapter 6 demonstrates the efficacy of DTCS and DTAS using a real-life case of intelligent monitoring of machining (milling). Chapter 7 discusses the implications of this study and highlights future research directions. Finally, Chapter 8 provides the concluding remarks of this thesis.

Since the digital twins of the machining phenomena are needed to make the machine tools and other programable devices more intelligent and autonomous, the presented DTCS and DTAS contribute to the befitting advancement of Industry 4.0 or smart manufacturing.

論文審査結果の要旨

本論文はセマンティックアノテーションおよび時間遅れ型センサー信号を規範とする機械加工現象のデジタルツイン作成システムの開発について述べ，次のように構成する。第1章では，第4次産業革命および関連研究分野の概要を説明する。第2章では，インダストリー4.0におけるサイバーフィジカルシステムやデジタルツインの役割に関する文献をレビューする。第3章では，セマンティックアノテーションに関するメカニズムを述べる。第4章では，時間遅れとそのセンサー信号の性質への影響および時間遅れドメイン型信号処理の有効性について述べる。第5章では，Java™プラットフォームによってデジタルツイン構築システム（DTCS）およびデジタルツイン適応システム（DTAS）の開発について述べる。第6章では，DTCSならびにDTASの有効性を実例によって示す。 第7章では，本論文の含意および今後の研究課題について述べる。最後に第8章では，本論文の結論を述べる。機械加工現象のデジタルツインは，工作機械の知能化および自律化に有用であるため本論文で示したシステムはスマートマニュファクチャリングに欠かせない。また工作機械以外のデバイスにおいても同様のことが言える。従って，本論文で示したDTCSおよびDTASはインダストリー4.0またはスマートマニュファクチャリングの進歩に貢献することが期待できる。

よって，申請者は，北見工業大学博士（工学）の学位を授与される資格があるものと認める。