Digital Twin modeling method for CNC machine tool

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***Abstract*—CNC machine tool (CNCMT) is the mother machine of industry, which plays an important role in the coming smart manufacturing. The intelligence of CNCMT has a big significance, which will enables its self-sensing, self-prediction and self-maintenance without user concerns. In order to realize the intelligence of CNCMT, a Digital Twin (DT) modeling method for CNCMT is researched, including a multi-domain unified modeling method, a mapping method and an autonomous strategy. This paper provides a demonstration of DT modeling method for CNCMT.**

Keywords—CNC machine tool (CNCMT); Digital Twin (DT); Smart manufacturing; Fault predict and diagnosis

I. INTRODUCTION

Smart manufacturing is the fourth industrial revolution driven by new technologies such as Internet of Things (IoT), big data, data mining, and machine learning[1]. Smart manufacturing and its application are essential to society, and it is the development trend of industry. CNC Machine tool (CNCMT) is the mother machine of industry [2], which plays an important role in smart manufacturing. So the intelligence of CNCMT is necessary to manufacturing.

However, in traditional modelling process of CNCMT, developers often design digital model based on design parameters in the software[3]. This redundant design pattern will cause a lot of design iterations. In maintenance stage, fault diagnosis and prediction of equipment have been drawing more and more attention[4]. Many scholars have studied fault diagnosis and prediction methods [5, 6]. Data-driven approach can obtain more effective and hidden information from the vast data, based on relevant machine-learning algorithm[7, 8]. For example, S Cho [9] proposed an intelligent tool breakage detection system which used a support vector machine (SVM) learning algorithm, JS Zhang [10]realized the CNC fault diagnoses by RBF neural network algorithm and program. But, running or faults data always rely on user's feedback or manual records, which will inevitably result in the loss of accuracy and instantaneity. That cannot realize objective and real-time design improvement according to the CNCMT application.

The important difference of smart manufacturing is interaction between cyber system and physical system. In recent years, the appearance of digital twin (DT) technology provides an effective solution to integrate the physical world and the information world. To enable the intelligence of CNCMT, a DT of it is necessary, which acts as a complete virtual prototype of an entire system and a one-to-one mapping relationship. Therefore, a multi-domain digital modeling method is needed; a consistent model between design and actual environment of machine tool should be established, which needs the real-time and accurate data mapping method; an effective machine learning algorithm to mine the data gathered from sensors and control system is also necessary.

The rest of this paper is organized as follows. In Section 2, the concept of DT and related researches are introduced. Section 3 introduces the application scenario of DT for CNCMT. Section 4 discusses the description, mapping and intelligence of DT. Section 5 concludes this paper and points out the future works.

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II. RELATED WORKS

A. Modeling and simulation

DT is a complete virtual prototype of an entire system, a new era in modeling and simulation. At present, multi-domain modeling and simulating methods consists of software interface, High Level Architecture (HLA) and UML (Unified Modeling Language).

(1) Software interface is a modeling method based on the corresponding interface of commercial software for interdisciplinary fields [11], such as ANSYS, ADAMS, MATLAB/Simulink. The above software is very mature but the interface compatibility between different software cannot be ignored.

(2) HLA is an advanced simulation structure, and has many advantages in the standardization, openness, scalability, and support for distributed simulation [12].

(3) UML method mainly focuses on the multi-physics unified modeling language Modelica [13]. Modelica is an equation modeling language put forward in 1997, based on a variety of modeling language. Modelica language has many advantages in model reusability, simple and convenient modeling [14, 15].

B. DT concept

With the development of IoT, big data, and machine learning, many companies and scholars have put forward the DT concept. The DT concept is a new idea about CPS (Cyber-physical systems) model of physical assets.

Many scholars and companies have explored the application of DT. NASA studied the health maintenance and guarantee of aerospace aircraft with the guidance of DT [16, 17]. Lee J proposed a unified 5-level architecture as a guideline

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for implementation of CPS [18]. Greyce N. Schroeder [19] proposed using AutomationML to model attributes related to DT and pointed out that this model is very useful for data exchange between different systems connected with DT. Aitor Moreno presented the process of constructing a DT for a sheet metal punching machine to support the interactive design of optimal NC machining programs [20]. TaoFei put forward the DT Workshop (Digital Twin Workshop) concept, which consists of the DT Workshop system composition, operating mechanism, and implementation method [21]. Many leading companies such as PTC, ANSYS, GE, and Siemens also explored many applications under the guidance of DT concept.

III. Application Scenario of DT for CNCMT

A. Characteristics of CNCMT

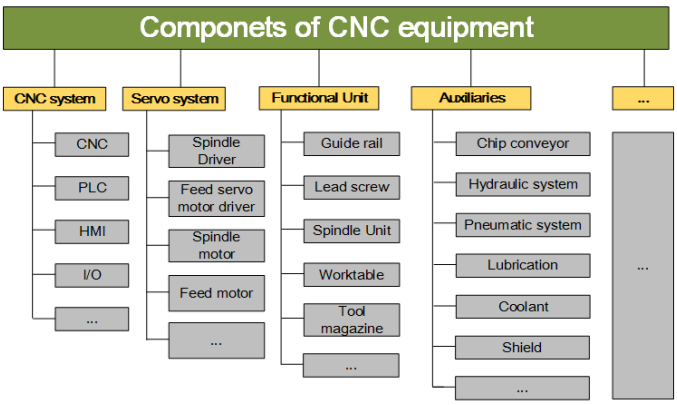

Fig.1 System composition of CNCMT

CNCMT is a set of machine tool equipped with computer numerical control system, which can be considered as a typical mechatronic equipment composed of mechanical, electrical and hydraulic components. The basic components of CNCMT are CNC system, servo system, functional unit, and the auxiliaries, as shown in Fig.1. It consists of many interacting parts such as a spindle, cutting tools, a servo feed system, a hydraulic system, an electrical control system, a control panel and the like. Therefore, a multi-domain digital model build method is needed. By using model-based diagnosis and prediction , error will be found in one component or in other parts which influences that component if a measured or computed value is outside an interval.

B. DT modeling and application framework

To realize the self-sensing, self-prediction and self-maintenance of CNCMT, a DT framework is proposed. As shown in the Fig.2, the DT framework contains the physical space, the digital space and the connection between them.

- In the physical space, the device's running status are gathered to control system by different type of sensors such as temperature sensor, pressure sensor, velocity sensor and so on.
- In the digital space, the DT consists of DT descriptive model and DT intelligent model. The main function of descriptive model is to describe the geometric, physical and electrical character of CNCMT. The DT intelligent model stores and analyzes the running status data, then makes decision using machine learning algorithm.
- The connection layer is a DT mapping model, which consists of a mapping model server, a mapping model client, and a data-mapping dictionary. The DT mapping model makes the DT interact with physical CNCMT real-timely. The DT mapping model is designed as interface to communication drivers, allowing a standardized read and written access to data in CNCMT.

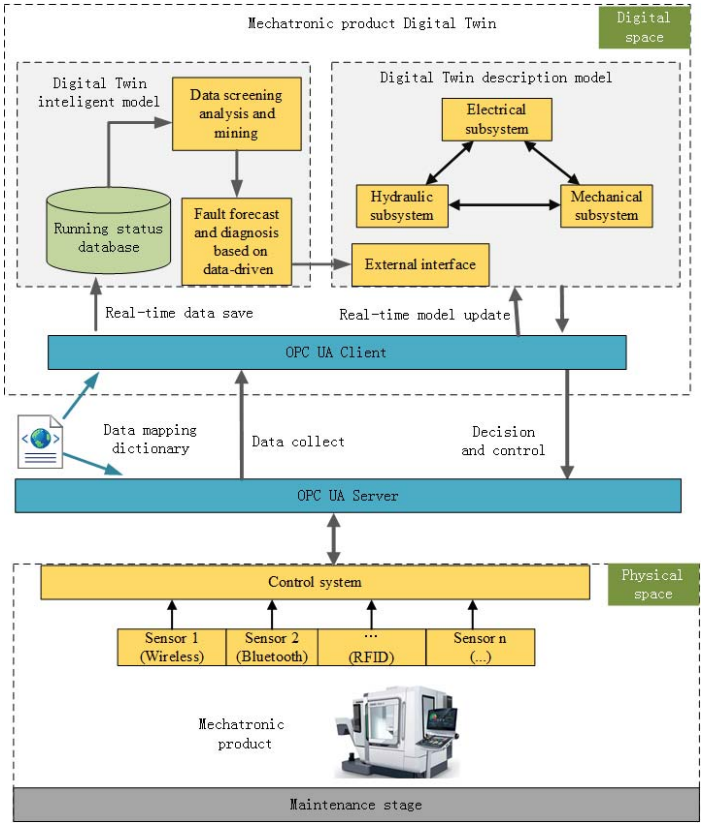

Fig.2 DT modeling and application framework

IV. Modeling of DT

DT framework contains the physical space, the digital space and the connection between them. This paper proposed a building method of DT, which contains DT descriptive model, DT mapping model and DT intelligent model.

A. DT descriptive model

After analyzing the structure and function of CNCMT, it is divided into different subsystems, components and parts. Using object-oriented method, as shown in Fig.3, subsystem engineers can determine the structure and mathematics equations of CNCMT according to existing experience and parameters.

Different parts connect through interface between them and different subsystems connect through energy convertor. Using this method, a parameterized, modular and mathematical DT

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descriptive model can be built in the multi-physics modeling and simulation environment.

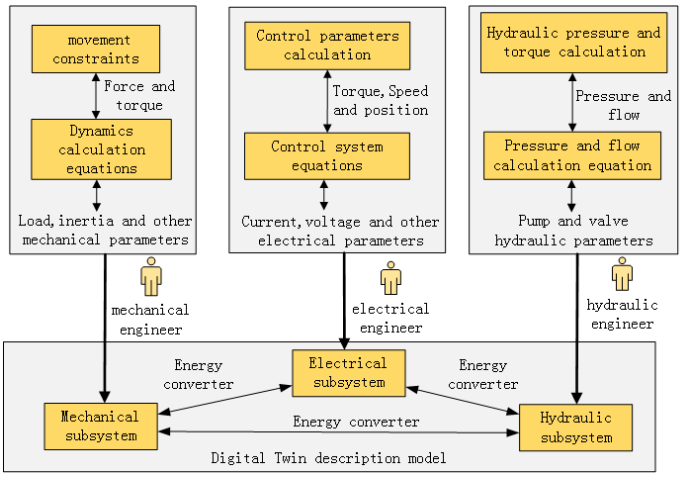

Fig.3 Multi-physical modeling of CNCMT based on UML modelica

B. *DT mapping model*

Working conditions of CNCMT comprise kinematics, dynamics, and thermodynamics parameters according to different subjects. To make the DT descriptive model be alive, the running data from various sensors and CNC controller should be uploaded to DT digital space real-timely.

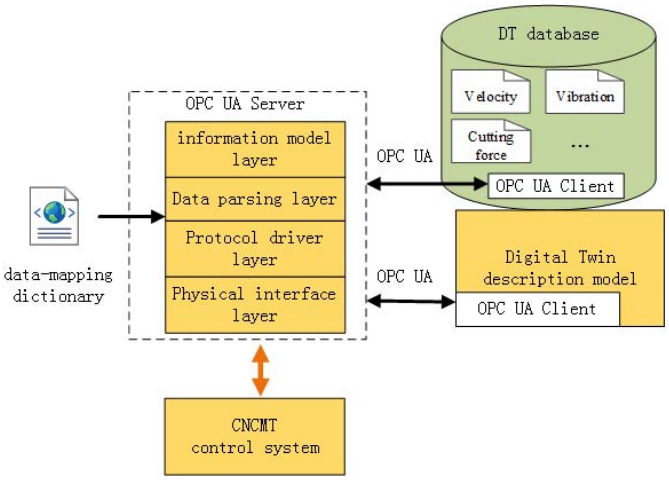

Fig.4 DT mapping strategy

OPC (OLE for Process Control) is used today as standardized interface between automation systems. Recently, OPC foundation proposed OPC UA (Unified Architecture) as a replacement for all existing COM-based specifications. OPC UA enables a platform-independent interoperability standard for moving data between the factory floor and the enterprise.

Mapping method is designed according to the OPC UA standards in this research. Referring to the OPC UA unified architecture, mapping model server is design to collect data from different sensors, and the data-mapping dictionary is designed after analyzing data type and physical meaning. The sensors on the CNCMT connect with the DT model after parsing and transformation of the protocol by mapping model server, as shown in Fig.4. The solver and post-processor of DT descriptive model can conduct the working condition loading and system simulation of DT. Through statistical analysis of running status data, the design parameter and working condition can be verified and simulated.

C. *DT intelligent model*

CNCMT will incur different faults irregularly. It will cause bad precision and affect the production if the troubleshooting is not timely. Traditional fault diagnosis method mainly depends on expert's experience but it is very expensive and unstable.

In this research, a DT intelligent model is built. It mainly contains expert system for DT with input from history maintenance data and fault information as well as fault solutions output. Expert system contains a knowledge base and an inference engine. To acquire knowledge autonomously and simulate people's thinking method, artificial neural network is used to build expert system. Artificial neural network generates a number of rules with relevant algorithm, and provides an effective method to acquire knowledge, which is very difficult in traditional method. When the CNCMT incurs failure, diagnosis results can get from output of neural networks after inputting failure phenomenon，as shown in Fig.5.

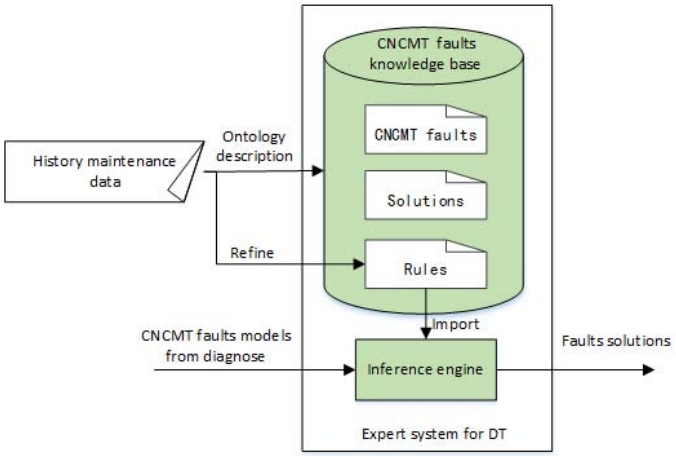

Fig.5 DT intelligent model

The DT intelligent model acts as a brain of CNCMT comprises fault monitoring, fault analysis and decision-making functions. Fault monitoring mainly monitors the important parameters of system; fault analysis is aimed to locate the source of fault and decision-making gives out prediction and fault solution.

D. *Case study*

CNC milling machine (CNCMM) is an important kind of CNCMT and has a wide application. Since the component failures seriously affect the production task, DT is necessary for CNCMM to predict and diagnose the fault.

Ball screw is an important component of CNCMM, which transforms the force from motor and guarantees machining accuracy. The lead screw and bearing of feed system always encounter failure, so it is worth studying the intelligent fault

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prediction and diagnosis of them. In order to descript the essence of it, a multi-domain model is built using modelica in MWorks software.

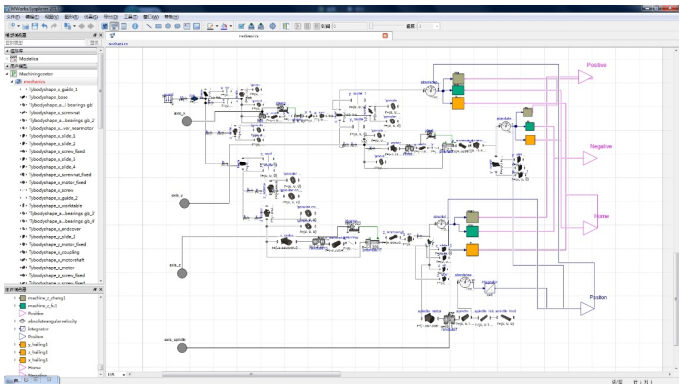

Fig.6 multi-domain model of x-axis

The mapping model is developed based on XML schema. In this paper, B-splines neural network is used for the fault predict model. Vibration sensors are installed on the two sides of ball screw and temperature sensors are installed on the supporting base. They are used to monitor components of ball screw real-timely. The residual lifetime of ball screw can get after analyzing the temperature and vibration values. Through the application of DT, it gives out alarm and resolution timely, the fault is recognized and troubleshot before serious failure occurred.

V. CONCLUSION AND FUTURE WORKS

In this paper, a modelling method of DT for CNCMT is proposed. This paper gives a demonstration of DT application scenario in CNC machine tool era. However, the research still needs many works to fulfill the entire DT application. For future work, we intend to continue works, which conclude: (1) applying the TensorFlow to construct the machine-learning algorithm; (2) improving modelling consistency and accuracy according to experiment; (3) studying the smart thinking ability, analysis and decision-making ability of modelica.

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