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Digital twin-based smart manufacturing cell: Application Case, System Architecture and Implementation

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Digital twin-based smart manufacturing cell: Application Case, System Architecture and Implementation

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Abstract: Smart manufacturing is considered to be a universal solution for upgrading manufacturing. Currently, the manufacturing tasks are becoming more personalized and the complexity of the manufacturing environment is increasing. Therefore, the manufacturing system needs to have a high level of learning and cognitive abilities. In order to cope with changes in the manufacturing environment, this paper proposes a system architecture of a smart manufacturing cell, which can intelligently sense, analyze, and make decisions to support autonomous manufacturing. Through the implementation in the experiment, it is verified that the proposed architecture is reasonable.

1.Introduction

With the advent of the Industry 4.0 era and the development of technologies such as CPS, digital-twin, IoT, big data and cloud computing, smart manufacturing has become the research focus of manufacturing fields around the world. Nowadays, the production demand of manufacturing is changing from large-scale production to small-batch production and customization[1]. This requires that the smart manufacturing system can respond in real time to meet the continuous changes in factory conditions and customer needs. Under the requirements of Industry 4.0, the smart manufacturing system is characterized by a cyber-physical system, aiming to achieve powerful intelligence and autonomy[2]. Smart manufacturing systems need to integrate horizontally and vertically[3], such as connecting and analyzing the data from process devices[4], sensors[5], and other enterprise systems. At the same time, the smart manufacturing system is an autonomous body that can autonomously sense and process changes in the external environment without external intervention[6].

Currently, some frameworks for smart manufacturing systems have been developed. But most of them are research on theoretical frameworks[7-9] and data transmission models[10-12]. As far as we know, very few researchers focus on the development of smart manufacturing cells and specific application cases. We believe that the application of smart manufacturing technology to actual production is also beneficial to manufacturing companies, because it can provide practical help for intelligent manufacturing.

This paper analyzes the tasks of the smart manufacturing cell, based on it an architecture of digital twin-based smart manufacturing cells was prepossessed, in which the changes of the order information and the processing environment can be perceived, the machining processes can be monitored, simulated and then control decisions can be made autonomously and intelligently based on the digital twin. The rest of this article is arranged as follows: In the 2nd section, the application scenarios and tasks of the smart manufacturing cell are analyzed. Section 3 describes the abstract model and system architecture of the smart manufacturing cell. As shown in Section 4, the implementation of the proposed system is

tested on the test bed. Finally, some conclusions and future work are given in section 5.

2. Application scenarios of the smart manufacturing cell

The smart manufacturing cell is the smallest implementation unit for performing production tasks in a smart factory. It is generally a smart cyber-physical system composed of processing equipment, robot, logistics equipment, and sensors, aiming to ensure the efficient, orderly and safe processing. The application scenarios of the smart manufacturing cell are shown in Figure 1. The smart manufacturing cell is an autonomous system equipped with the cognitive capabilities such as perception, deciding and communication. It can respond flexibly according to the production order sent by MES, ERP and changes in the physical environment. On-site data can be monitored remotely in real time, and some operations such as configuration, simulation, and optimization of processing can also be performed in the digital space[13]. The following examples describe several specific tasks of the smart manufacturing cell:

1) Autonomous cleaning of the process system

The smart manufacturing cell monitors the processing areas of the process system in real time. When the system detects that there are too many chips accumulated in a certain part, which affects the processing, the system cleans the chips by controlling the robot and other related execution equipment to ensure the quality and efficiency of the processing and production.

2) Fault handling of the processing

The smart manufacturing cell autonomously perceives and handles the faults of the processing without human intervention, such as improper clamping, falling of clamped workpieces, damage of cutters, etc.

3) Quality management of the workpiece

The quality of workpiece is monitored by smart sensors for the whole life cycle of processing process. When the quality is detected to be unqualified, the execution devices directly sends the unqualified workpiece to the waste area, which improves the overall operating efficiency of the system.

4) Safety security of the processing environment

The environment of smart manufacturing cell is monitored for security. When foreign objects or people approach the smart manufacturing cell, the system can identify the information, and control the processing devices to decelerate, stop and other related reactions to ensure the safe operation of the system.
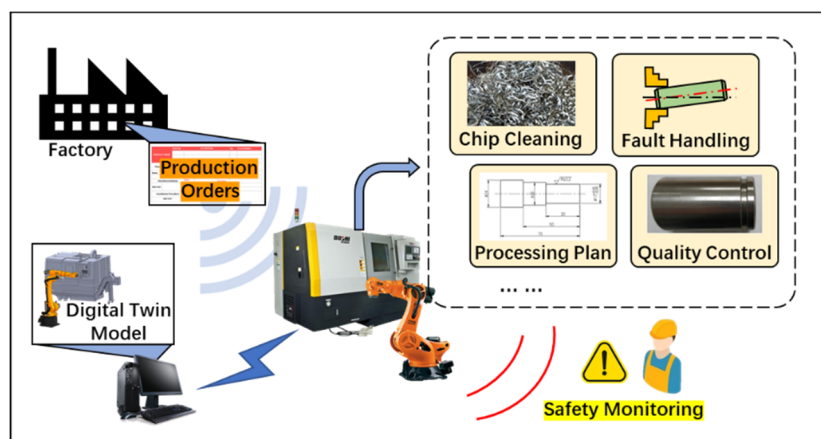

Figure 1. Application scenarios of the smart manufacturing cell

3. System Architecture of the smart manufacturing cell

According to the analysis of application scenarios of the smart manufacturing cell, this paper designs an abstract model of the smart manufacturing cell as shown in Figure 2. In this model the smart manufacturing cell is a self-organizing system, divided into physical space, cyber space, knowledge base and external communication module.

1) Physical space gathers the processing resources of the smart manufacturing cell, including processing workpieces, manufacturing devices, robots, industrial cameras, and sensors.

2) Digital space contains the control center of the smart manufacturing cell and the digital twin model. Based on the digital twin model, the processing can be monitored, simulated and optimized. The control center can collect real-time data in the physical space, perceive environmental information, make decisions, and control the devices of the smart manufacturing cell.

3) Knowledge base contains historical data of physical space's devices, robot trajectory algorithms, and machine learning cases. These historical information and intelligent algorithms improve the intelligence of control center to and make decisions.

4) External communication module integrates the communication between the smart manufacturing cell and other systems in the factory. Such as the order information and adjustment information issued in the manufacturing execution system (MES), enterprise resource planning (ERP) and other smart manufacturing cell systems.
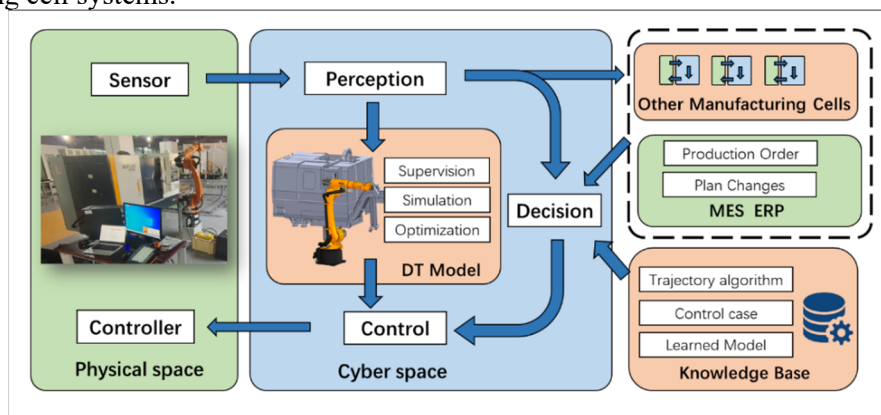

Figure 2. Abstract model of the smart manufacturing cell

Based on the abstract model mentioned above, a system architecture of the smart manufacturing cell is proposed in Figure 3. This system architecture is composed of physical equipment, system management module, function modules and smart decision module. The smart manufacturing cell completes specific processing tasks through the cooperation and mutual calling of different modules. The functions and composition of each module are described as follows:

1) Physical equipment consists of the devices connected to the communication network in physical space for perception and execution.

2) System management module is responsible for the data communication, module calling, file management and other functions of the system. It is the technical basis for the smart manufacturing cell to achieve specific tasks

3) Function modules are subsystems that achieve specific tasks. In the framework of this paper, eight function modules are defined, including digital twin model, motion control, data storage, HMI, real-time monitoring, machine vision algorithm, knowledge base and Trajectory planning.

4) Smart decision module is the decision center of the smart manufacturing cell. According to the collected status information, the smart decision module calls several function modules and eventually controls the corresponding execution equipment to complete the task operation.
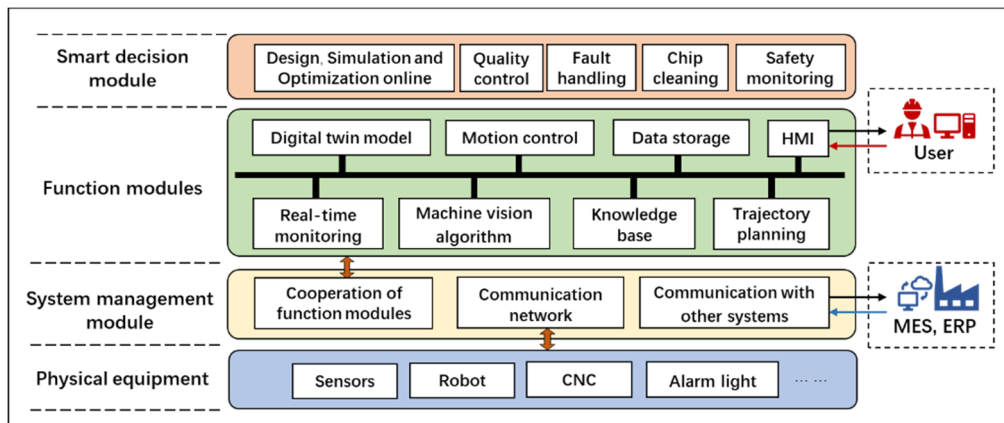
Figure 3. System Architecture of a smart manufacturing cell system

4. System implementation of the smart manufacturing cell

The experiment platform designed in this paper is shown in Figure 4. This experiment platform connects heterogeneous devices into a real-time communication network, analyzes the data of each device and controls the robot to execute.
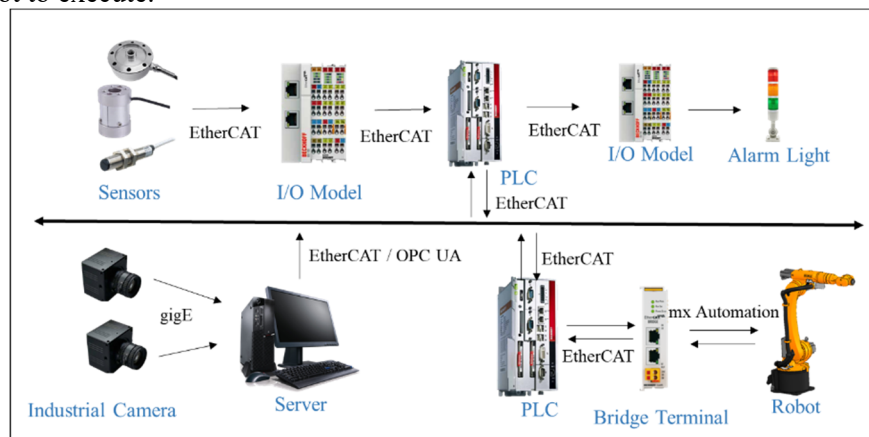

Figure 4. experiment platform of a smart manufacturing cell

Considering the real-time performance and transmission speed of the control of industrial device, most of the communication of this experimental platform uses EtherCAT fieldbus. In order to balance the computing load of the equipment, this experimental platform uses a distributed system. The input and output devices with high real-time requirements like photoelectric sensors, force sensors, alarm lights and etc. are connected to the system through I/O modules of PLC. The devices with low real-time requirements, such as industrial cameras, are connected to the system through OPC UA or EtherCAT. The main execution equipment of this experimental platform is a KUKA six-axis robot. Through a bridge module and KUKA's mxAutomation function library, the PLC can directly control the robot and realize the real-time communication between the PLC and the robot.

Based on the above platform, an implementation of the main equipment in the platform is developed in Figure 5. In this implementation PLC is embedded in PC in the form of software, and data transmission is completed through the EtherCAT network interface on PC.
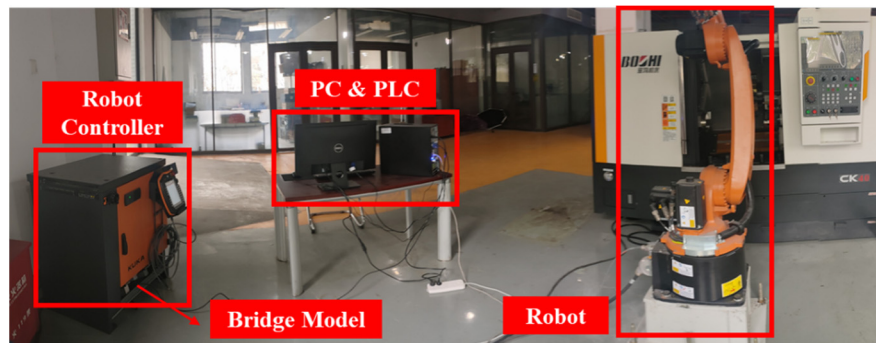
Figure 5. The practical implementation of the smart manufacturing cell

In this implementation, several function modules have been developed, such as communication module, digital twin model, motion control and HMI. Currently the real-time monitoring and real-time control of the robot have been realized. In terms of data transmission, PLC reads variables and writes control commands to the KUKA robot controller through the mxAutomation function library. The PLC binds the handle of the PLC variable to the variable defined by the C# program through TwinCAT ADS communication. After calculation the variables are displayed to the user. At the same time, the variables related to the pose of the robot are transmitted to the CATIA model through the CATIA automation function module, so that the pose of the CATIA model is synchronized with the pose of the robot in the physical world. The specific data transmission method is shown in Figure 6.
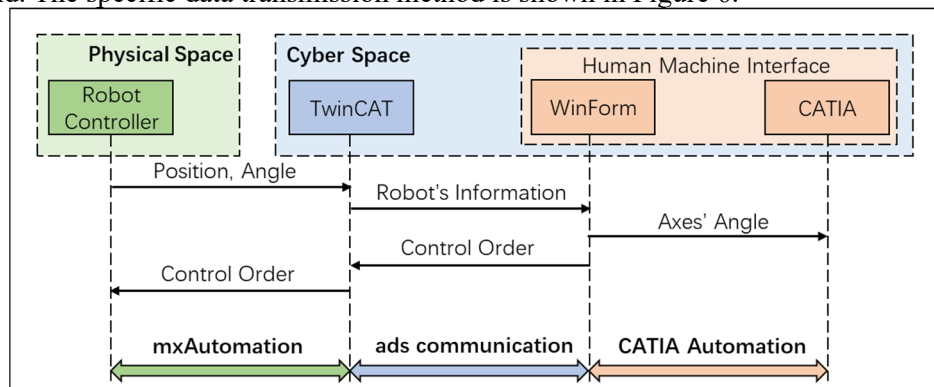

Figure 6. data transmission of the system implementation

As shown in Figure 7, through experiments, the information such as the angle of each axis of the robot and Cartesian coordinates can be reflected in the user interface in real time. Besides, the digital twin model can respond in real time with the robot, and the user can control the robot through the button in control interface.
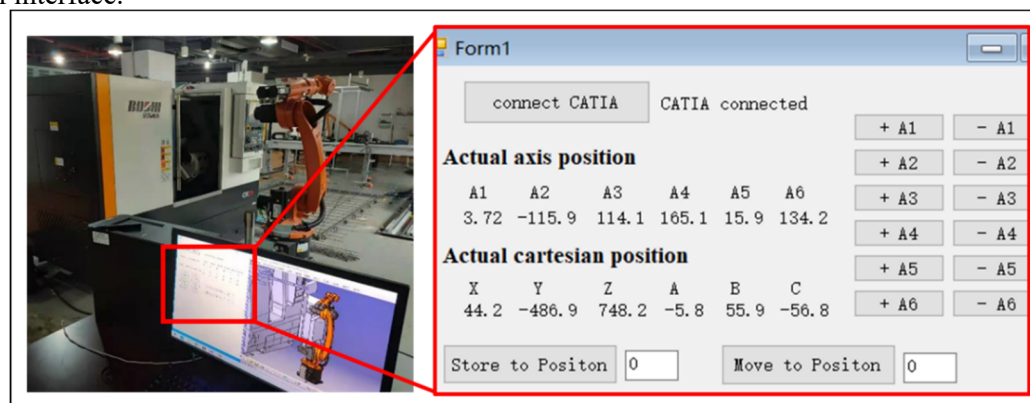

Figure 7. user interface of the experiment

5. Conclusions and future work

In this paper the application scenarios and framework of the smart manufacturing cell are proposed. By introducing the technology of digital twin and CPS, an autonomous model has been developed. In the proposed model, the situation and faults of the processing site can be intelligently sensed, analyzed and processed by the smart manufacturing cell. In the system implementation, the development of the smart control module realized the two-way connection between physical space and digital space and proved the rationality of the proposed system structure.

In future research, more devices and communication methods will be integrated to the system. Besides, the other function modules will be developed to realize more functions of the smart manufacturing cell.

Acknowledgement

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