Designing a Cyber Physical System Prototype for the Leaching Process in Producing High-Purity Materials

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Abstract. Accompanied with the emerging concept of Industry 4.0, manufacturing companies in any sectors are attempting to transform their hitherto production equipment into cyber physical systems (CPSs), with the aims of improving efficiency across the whole production line and enhancing core business competitiveness. Focusing on the material manufacturing sector, this paper presents and discusses the design of a CPS prototype used in the leaching process for producing high-purity materials. This prototype contains three components/layers, namely sensor installation for data collection, wireless data transmission using ZigBee, and finally data storage and visualization. This CPS prototype design is particularly useful and practically transferrable to material manufacturing companies, especially those involving high purity material production, during their journey towards realizing Industry 4.0.

Keywords: Prototype · Cyber physical system · High purity materials · Smart factory · Data visualization

1 Introduction

The term Industry 4.0 was firstly corned and proposed at the 2012 Hannover Fair [1]. This concept has then brought the world into the trend of the new generation of industrial reform. The architecture of Industry 4.0, including sensors, Internet of Things (IoT), cyber physical systems (CPS), cloud-based data integration, standardized intelligent control, and visualized monitoring, allows human beings to communicate with physical items (both production machines and even end products) more effectively [2–4].

On the other hand, throughout the world, high-purity materials, which plays a crucial role in various fields and supports the development of a large number of high-tech industries, have penetrated into each part of social life, national economy and national defense construction. More specifically, high-purity materials have a variety of uses, from daily necessities (e.g. solar cells, non-toxic iron pots, decorative materials, etc.) to modern high-tech fields such as high-purity metals, alloys, graphite, semiconductors and insulators [5]. The largest application field for high-purity materials is the microelectronics industry [5]. With the accelerated development of science and

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technology and economic construction, the global demand for high-purity materials has been increasing substantially. And the requirements for the performance and quality of high-purity materials will also become higher and higher.

Based on the importance of high purity materials, the manufacturing industry of high purity materials should develop towards intelligent manufacturing under the impetus of industry 4.0 environment. CPS is the core of industry 4.0 and intelligent manufacturing. The main roles of CPS are to fulfill the agile and dynamic requirements of production, and to improve the effectiveness and efficiency of the entire industry [6].

Even today, there are many fields of applications for CPS, such as medical equipment, driving safety and driver assistance systems for automobiles, industrial process control and automation systems, assistance systems for controlling the power supply in terms of optimized use of renewable energies [1]. These are all applications of CPS in manufacturing: Ford Motor Company's service-oriented architecture [7]; Cloud manufacturing jointly researched between KTH and Sandvik, Sweden [8]; FESTO preindustrial system, MiniProd [9, 10]; Model-driven manufacturing systems [11]. In recent years, research and applications of CPS have been active in such areas like transportation, smart home, robotic surgery, aviation, defence, critical infrastructure, etc. [7]. However, smart manufacturing technology, especially CPS, is not widely used and discussed in the production of high-purity materials.

Therefore, this paper proposes a CPS prototype system to realize data measurement, storage and real-time monitoring of sensors installed on high-purity material mechanical equipment. All the data generated by the high-purity material production process hides huge unpredictable value. The establishment of CPS will be beneficial to optimize the production process and promote the development of high purity material industry. This paper presents and discusses the technical features and functions of this prototype, which can serve as a model to be followed by researchers and practitioners in the field.

2 CPS and High-Purity Material Production

2.1 The Importance of CPS in the Production of High-Purity Materials

In the production of most high-purity materials without intelligent transformation, although the production process in conventional laboratories and factories is controlled by mechanical equipment, it is difficult to monitor changes of all process parameters in real time. If all the data cannot be monitored synchronously, then real-time changes in the production process cannot be mastered efficiently, and the quality of high purity materials cannot be well controlled, thus resulting in the decline of output value and quality. When a problem occurs, information related to the problem is collected and an analysis will be conducted subsequently to find out the cause of the problem [12].

Because CPSs combine information and materials, decentralization and autonomy play an important role in improving the overall industrial performance [13]. CPSs are capable of increasing productivity, fostering growth, modifying the workforce performance, and producing higher-quality goods with lower costs via the collection and analysis of malicious data [14]. Therefore, it is urgent for factories to establish an innovative, reliable and easy-to-use CPS prototype system to control material leaching and other production processes. In this way, the output and quality of high purity materials can be guaranteed, and the competitiveness of enterprises can be enhanced, thus supporting the development of high technology.

According to the current literature, studies on material purification (e.g. [15–17]) and CPS development (e.g. [18–20]) are two separated fields of research. As such, there is a lack of study to bridge the gap and consider CPS development and usage in the production of high purity materials.

2.2 Using CPS in the Leaching Process of High-Purity Material Production

The production of high purity materials is the core of the development of high purity materials industry, which realizes the deep integration between information system and manufacturing process, one information system and another information system, and results an intelligent manufacturing system through CPS and intelligent manufacturing technology. The system can control the whole process of manufacturing with timely feedback information improving the competitiveness of the industry, and promote the development of high purity materials industry.

In the process of making high-purity materials, material purification is an indispensable and crucial step, which controls the purity and precision of the final high-purity materials. During the process of material purification, it not only controls the amount of material input and output, but also the time of reaction, reaction temperature etc. Those can affect the final quality of high-purity materials. And it can be said that the leaching process is the most important milestone in material purification, and the success of the leaching process also means the success of high-purity material production.

In that case, it's extremely important for us to design a CPS prototype of the leaching process to realize the control of the most important part of the high purity material manufacturing, due to the important role of leaching process. In our research, based on the requirements of material purification of high-purity material enterprises, the existing mechanical equipment is modified, and sensors needed in the process of material purification are added to collect and analyze data. Finally, the prototype system design of real-time display and monitoring of temperature, speed, environment and other changes is realized.

3 Design of the Prototype

3.1 Prototype Architecture

In order to transform the original high-purity material leaching equipment into CPS, our designed prototype contains three components/layers, namely sensor installation for data collection, wireless data transmission using ZigBee, and finally data storage and visualization.

The specific hardware frame and the flow of information transition are directly shown in Fig. 1. The collected data is obtained from two types of sensors, including temperature sensors and PH sensors, which are added into the original high-purity equipment. Subsequently, the data of each equipment will be sent to the corresponding processing terminal. Then all the processing terminals transfer the processed date to the ZigBee gateway through ZigBee communication. Finally, the whole data is obtained in PC via USB interface from the ZigBee gateway for further data processing and analysis.

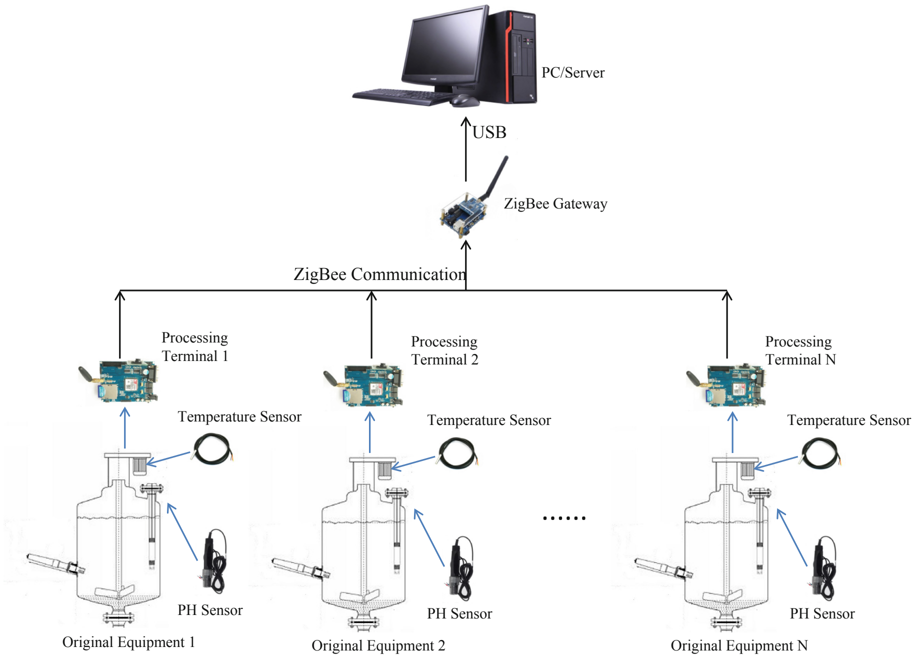

Fig. 1. Prototype hardware architecture

3.2 Sensor Deployment

To maximize the utilization of spaces of the container, all the used sensors (e.g. temperature and PH sensors) are assembled as an integral unit. The modified device is shown in Fig. 2. As the composite sensor unit is fixed inside the container, the tightness can be pursued by the less intervention during the production process. Furthermore, the data processing terminal will read the digital data automatically and send it to data base timely, instead of relying on manual measurement in traditional manner.

Temperature and PH values are two very important objects for our leaching monitoring, so we must choose suitable sensors for obtaining them. Moreover, the ADC (analog-to-digital conversion) module is needed, since the terminal or PC only process and store the digital information rather than analog information.

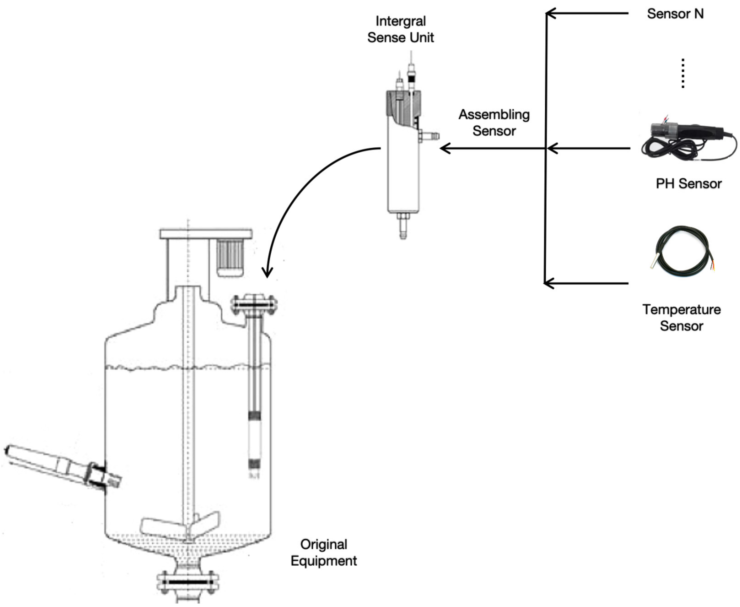

Fig. 2. Embedding sensors into high-purity material leaching equipment

For temperature measurement, DS18B20 (a contact temperature sensor with digital signal output) was selected and used. This DS18B20 sensor is not just small in size but is also very convenient to use. All sensing components and conversion circuits are integrated in a circuit which looks like a triode. The probe is directly contacted with the solution in the vessel of which temperature values can be obtained and transferred to the MCU through the DuPont line.

For the PH sensor, its working principle is closely related to the primary battery system, that is, the PH value is calculated by the voltage. Since the voltage generated by the PH sensor is small, it needs to be amplified before sending to the MCU. Here we design the ADC module on the MCU to obtain the ultimate digital PH value.

These sensors are very important direct data source for the system, just like sensing organs for people. However, these sensors as electronic measuring instruments themselves, have measurement errors caused by thermal noise, which naturally have a great influence on the accuracy of the measurement results, thereby causing trouble for analysis after data collection. Therefore, we need to make robust correction to the collected data, so that the random error can be smaller, that is to say, a filter is added after these measuring instruments.

3.3 Wireless Transmission

In order not to miss any critical data of the leaching process, we need to measure the data of the solutions in multiple chemical reaction vessels at each step. It means that each container needs to be fitted with a temperature and PH sensor accordingly. After the leaching equipment is embedded with sensors, we need to distinguish the data collected by these sensors in different containers and integrate the data for subsequent processing and analysis. To this end, we use a star network (Fig. 3) to solve the above problems. Since wired communication requires a large number of interfaces and is likely to cause wiring chaos, we choose wireless communication as the communication method between network nodes in combination with the actual production environment. This also makes it easy to add network nodes during subsequent device transitions.

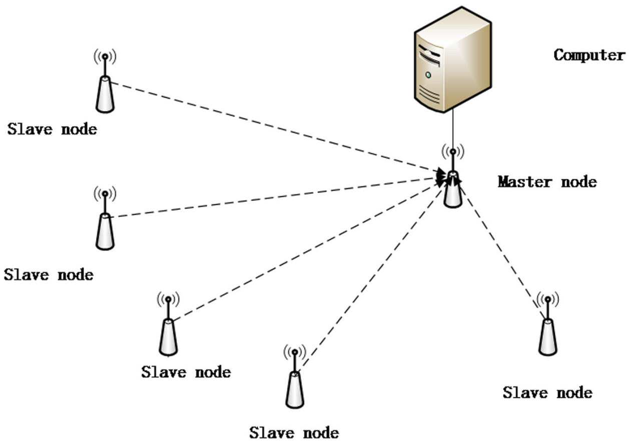

Fig. 3. Star network

ZigBee [21] is a low-power wireless communication technology based on the IEEE802.15.4 [22] standard. The development environment under Windows is IAR Embedded Workbench. There is a lot of open source code here, which greatly reduces our workload, so we can easily achieve wireless data transmission under various conditions. This is convenient for the expansion of the prototype.

Although the CC2530 [23] chip on the ZigBee development board is only a microprocessor with the weak computing power, it is enough to support the ZigBee technology. In addition, it communicate with the temperature sensor to read the temperature data, and communicate with the ADC module to obtain the converted value and convert it to PH value through the corresponding function relationship. Also it can do some mathematical calculations as the filter processing. Combined with the terminal, the raw data collected by the sensor is first transferred to the CC2530 chip for filtering. Then the filtered data is ready for wireless transmission. Finally the data collected at each slave nodes in the star network is aggregated into the master node of the star network by wireless transmission.

3.4 PC-End Software

After the data collected at each slave nodes is aggregated into the master node of the star network by wireless transmission, the next question is how to transfer the overall data to the computer. Here we took the serial communication technology for use, using the CH340G chip on the development board to connect to the USB port of the PC. The key is that the computer should know how to read the data form the MCU, so that the computer is possible to carry out storage and realize real-time data visualization.

Golang is an open source programming language that makes it easy to build simple, reliable, and efficient software [24]. So we choose Golang to achieve data transmission. Next, we use the serial tool written in Golang to read the incoming data from the device received by the computer port for further data analysis. Goserial is a simple-go package to allow users to read and write from the serial port as a stream of bytes. This allows the data in the MCU to be transferred to the computer for later processing.

After completing the data transfer from the device to the local computer, in order to facilitate the future data analysis process, we choose to transfer the data read in the computer software to the database for storage via the TCP connection. The TCP protocol is a connection-oriented, reliable, byte stream based transport layer communication protocol running on the fourth layer of the TCP/IP network model, so reliability can be guaranteed during data transmission. The data will be stored in the database of the remote computer, so that a centralized node allows departments of different functions to connect and complete their tasks, and achieve data sharing.

The above steps complete the collection, reading and storage of the data. The next step is to implement data visualization. Because the front-end interface is written by the Java language, the open source JFreeChart package is used to achieve data visualization, and the WebService interface is used to obtain the data in the database. Finally, the data is parsed into the data types available for JFreeChart through Google's gson parsing package.

To realize real-time visualization of data, we use JFreeChart's sequence diagram correlation function to create a special function to generate images based on data. When the front-end calls, an empty image instance can be generated by passing in the corresponding image name and image ordinate name. Then the data in JSON format in the database can be obtained through the WebService interface, and the JSON data can be parsed into the required data type through the gson package. Then the data can be transferred into the required time series set by calling the relevant function of the image instance, so that, the data will appear on empty images. The front-end can display the data in real time by setting the process in a thread that refreshes once a second (Fig. 4).

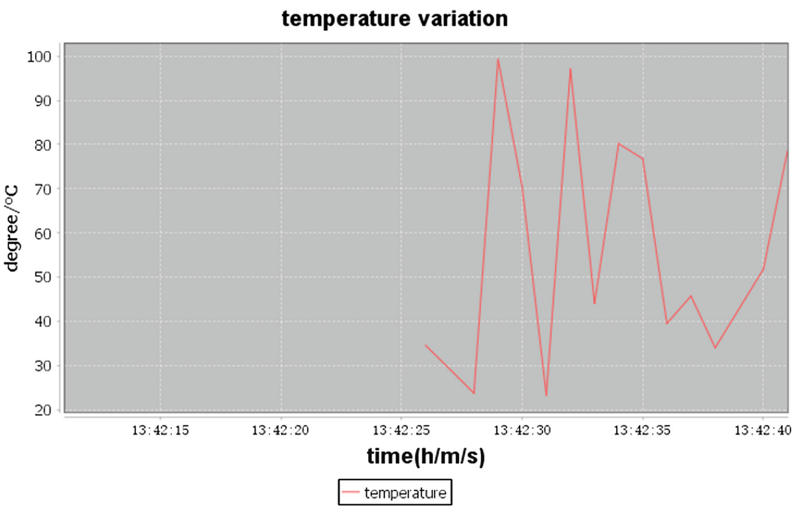

Fig. 4. Visualization interface

3.5 Summing up the Overall Design of the Prototype

Figure 5 shows the design of a complete CPS prototype. As shown in the figure, according to the direction of the data flow, the following steps are required to implement CPS. First we need to add sensors to the high purity material leaching equipment. According to the requirements of the company, we add sensors related to the data types (temperature, PH, etc.) to be measured in the actual material leaching process. After installing sensors, it is necessary to collect data of multiple sensors on the MCU, and then transmit them to another MCU through wireless, and finally transmit them to the computer through the serial port. The data transmitted to the computer is stored in the database and displayed in real time on computer and mobile phone. Finally, the leaching equipment is automatically regulated and controlled to form a cycle.

Now the prototype design of the high purity material leaching process has realized the collection, transmission, analysis and monitoring of the key data. In the future, we will continue to implement the following functions: automatic control, self-diagnosis and early warning analysis. In addition to the leaching process, the prototype of this CPS can be extended to other production processes of high purity materials, and finally realize the intelligent manufacturing of high purity materials manufacturing industry.

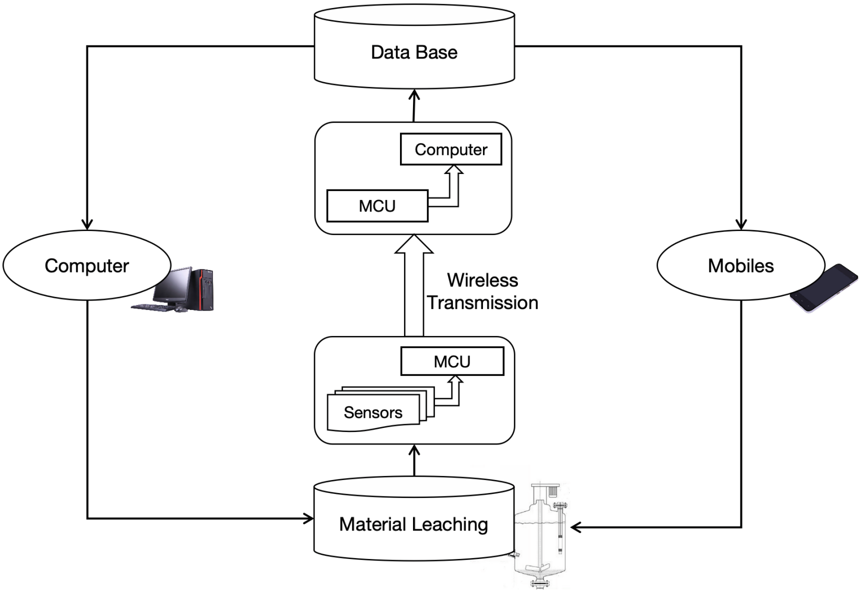

Fig. 5. Prototype design

4 Conclusions

This paper proposed a designed prototype system for the high purity material leaching process, which helped establish a complete visualization system for the high purity material leaching process, enabling the plant to observe and analyze the required data in real time. In the future project, the research will continue to realize data screening, real-time monitoring, self-diagnosis, early warning analysis and automatic regulation, and finally complete the construction of the entire CPS. The establishment of the CPS prototype based on the leaching process of high-purity materials can gradually make all the equipment in the manufacturing process become intelligent, forming a comprehensive upgrade of the high-purity material industry. It is also expected to provide ideas for the intelligent equipment transformation of other enterprises.

High purity material plays an important role in the development of national economy and is also an important indicator of national science and technology development level. In the context of industry 4.0, the only way for industry to make steady progress and finally push forward industrial reform is to master and develop core technologies like CPS.

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