# Software-Defined Industrial Internet of Things in the Context of Industry 4.0

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***Abstract*— In recent years, there have been great advances in industrial Internet of Things (IIoT) and its related domains, such as industrial wireless networks (IWNs), big data, and cloud computing. These emerging technologies will bring great opportunities for promoting industrial upgrades and even allow the introduction of the fourth industrial revolution, namely, Industry 4.0. In the context of Industry 4.0, all kinds of intelligent equipment (e.g., industrial robots) supported by wired or wireless networks are widely adopted, and both real-time and delayed signals coexist. Therefore, based on the advancement of software-defined networks technology, we propose a new concept for industrial environments by introducing software-defined IIoT in order to make the network more flexible. In this paper, we analyze the IIoT architecture, including physical layer, IWNs, industrial cloud, and smart terminals, and describe the information interaction among different devices. Then, we propose a software-defined IIoT architecture to manage physical devices and provide an interface for information exchange. Subsequently, we discuss the prominent problems and possible solutions for software-defined IIoT. Finally, we select an intelligent manufacturing environment as an assessment test bed, and implement the basic experimental analysis. This paper will open a new research direction of IIoT and accelerate the implementation of Industry 4.0.**

***Index Terms*— Industry 4.0, industrial wireless networks, industrial Internet of Things, software-defined networks, cyber-physical systems.**

## I. INTRODUCTION

RECENTLY, the widespread deployment of wireless sensor networks, embedded systems, and inexpensive sensors has fostered the rise of Industrial Internet of Things (IIoT) [1]–[5]. IIoT is the basic premise for the implementation of Industry 4.0 [6], [7]. As it supports of all kinds of new information technologies, IIoT has the ability to continuously obtain information from various sensors and objects, securely forward sensor readings to cloud-based data centers, and seamlessly update related parameters in the form of a closed loop system. In this way, IIoT is capable of effectively detecting failures and trigger maintenance processes.

As we know, the cloud-based approaches can meet the requirements of modern industrial systems [8], [9]. It is necessary that more flexible infrastructures with the ability to carry out effective information exchange are designed to enhance the reliability and scalability of complex industrial environments.

In order to implement IIoT in modern industrial systems, we still face some prominent problems and challenges in terms of information-based interaction:

1) In the context of Industry 4.0, all kinds of equipment or devices should interact effectively in order to collaborate in accomplishing the assigned tasks. For the traditional networks, if we need to provide a new mechanism of cooperation, we should update the communication protocols of all the related devices one by one. Therefore, we should seek new methods to rapidly manage and configure all kinds of network resources.
2) Fortunately, the emerging Software-Defined Networks (SDN) technology [10]–[13], [31] is becoming viable for implementing effective information utilization. However, it is still very challenging to capture, analyze and utilize all kinds of information in a coherent manner from heterogeneous and sensor-enabled devices (e.g., industrial robots and assembly lines) owing to a lack of software-defined IIoT architectures, collection protocols, standardized APIs and assessment testbeds.

In order to promote the development of this field, we consider analyzing the IIoT architecture and information in the context of Industry 4.0. On this basis, we propose the software-defined IIoT architecture, which may facilitate the flexible network resource management for Industry 4.0. In this paper, our contributions include the following three aspects:

1) We analyze the deployment architecture of a prototype platform and present the functions and characteristics of every component layer and information exchange among all kinds of devices.

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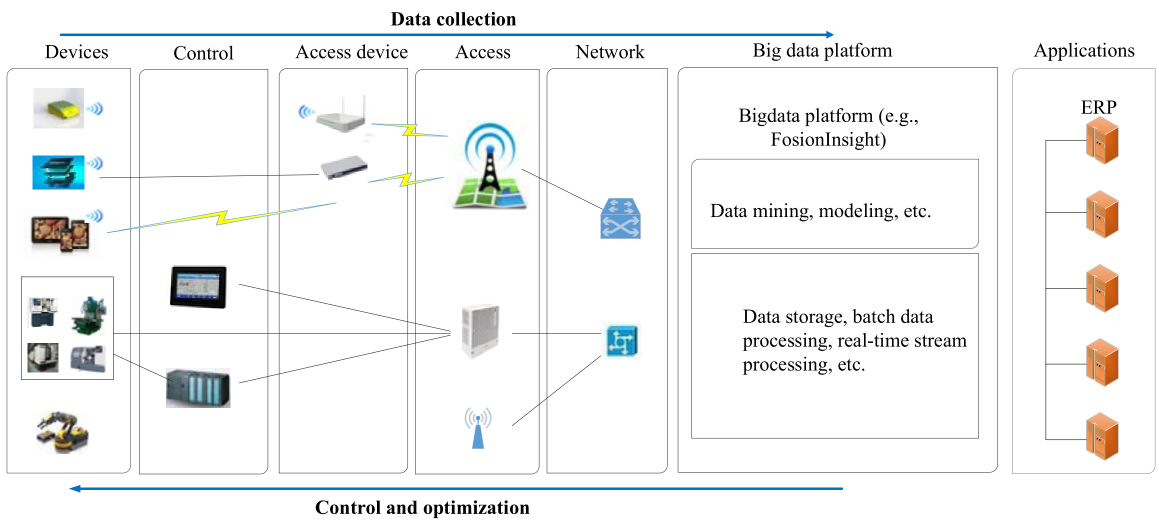


Fig. 1. IIoT architecture.

2) We propose a software-defined IIoT architecture composed of three layers: the physical infrastructure, the control and the application layers, and dissect the services provided by every layer.
3) We consider the prominent problems and possible solutions from three aspects, i.e. security and reliability, standards, and specific implementation. We also present a simplified assessment testbed in the context of Industry 4.0.

The rest of this paper is organized as follows. Section II introduces the IIoT architecture and information-based interaction. Section III analyzes the software-defined IIoT architecture. Section IV examines the problems and possible solutions for software-defined IIoT. Section V presents an assessment testbed in the manufacturing environment. Finally, Section VI concludes the paper.

## II. IIoT Architecture and Information-Based Interaction

It is generally known that CPS (Cyber-Physical Systems) [14], [15] will play an important role in the implementation of Industry 4.0. In order to facilitate the discussion and analysis of information-based interaction in the context of Industry 4.0, we divide the layout of a prototype platform into four layers: the physical layer, networks, cloud, and smart terminals. Obviously, the data flow link all the layers from down to up. Therefore, in this section, we provide a brief analysis of a prototype platform, and then discuss the information exchange principles.

### A. System Architecture

In an IIoT system, many different new Information and Communication Technologies (ICTs), such as Industrial Wireless Networks (IWN) and Internet of Things (IoT) [16], [17] are incorporated into a single system. Similarly, in this prototype platform, some new ICTs are introduced. The architecture consists of four components: machines and equipment, networks, the cloud and terminals. Obviously, as shown in Figure 1, the prototype system is a closed loop for producing specific and personalized products to meet the users' needs and desires. First of all, the users design the products according to their preference or provide the key parameters for personalized products through web pages. Then, the web server submits the user information to the industrial cloud, which parses the product data and the key parameters. Meanwhile, these optimization producing data are transmitted to industrial robots, workmen, and controllers of conveyor belts via wired or wireless networks. The production system begins to create the products depending on these data. During the manufacturing process of the product, all kinds of related data are transmitted to the cloud and neighboring nodes for management and optimization.

On one hand, the plan not only provides the necessary information for managing and monitoring production, but also allows the optimization of processes and procedures for ensuring higher quality and increasing the production efficiency. On the other hand, the user can amend the design according to the manufacturing data. In the same way as before, these modifications and re-optimizations are delivered via all kinds of wired or wireless networks after being processed by the industrial cloud.

*1) Physical Layer:* The physical layer is the basic component, and directly determines the specific type implementation and production. Meanwhile, from a functional perspective, it is responsible for the specific physical activities, such as manufacturing, transportation, mobility, logistics, and obtaining sensor or other data. In this platform, all kinds of devices, such as AGVs (Automated Guided Vehicles), manipulators, flexible conveyor systems, manufacturing equipment, warehouses, and sensors, may compose the physical layer. The following setup illustrates the working processes of the physical layer in this platform.

After obtaining the working instructions from the industrial cloud, the AGV first begins to carry the raw products with RFID tags from the warehouse to the entrance of a flexible conveyor system. The RFID tags include the key manufacturing information and the data of producing progress. Then, the raw products are transported to the corresponding manipulators, where machines and workmen prepare them for the ensuing processing. After that, the products are transported to the output exit by the conveyor belts, and the AGVs carry the finished products to the warehouse. During the loop, all the sensors have the ability to record the key parameters necessary for monitoring and alerting, and save the product's information during the whole processing.

*2) Networks:* Actually, for the smart factories of Industry 4.0, it is widely understood that wired or wireless networks must permeate the platform for transmitting data, commands and other information between the cloud and the equipment, including both machines and products. In all cases, networks play an important role in the implementation of Industry 4.0. In other words, networks play a role similar to the human body's nervous system. In a similar manner, in the prototype framework of Industry 4.0, several network technologies are used to support the platform. The networks are formed by inter-factory networks, including IWNs, industrial Ethernet, NFC (Near Field Communication) utilizing RFIDs, MCNs (Mobile communication networks), civilian internet, etc.

From an intra-factory aspect, there are several types of data transmission taking place. Firstly, in order to determine and verify the location of products, RFID tags are mounted on the products. The RFID tags are used to read or write information about the products. Then, the RFID Gateway (e.g. a Raspberry Pi with Linux OS) transmits the product data using wireless protocols, in this case using a USB-WiFi module (IEEE 802.11), to send the related information to the equipment and to the cloud via access points (e.g., MOXA-AWK-3121). Secondly, in this system we provide wireless communications capabilities on equipment, such as the manufacturing machines and AGVs using technologies, such com-Wi-Fi (e.g., MOXA-Nport-W2150A) or wired-Wi-Fi (e.g., MOXA-AWK-1121). Then, the equipment can communicate with other equipment, the cloud, and the products via wireless networks because of the ease of access to civilian networks, such as the internet.

Outside the factory, there are two ways of dealing with the problem of communicating with users and management. A wired network is the best option for complicated technologies such as the internet. In the platform, we use Ethernet for connecting to users and inter-factory networks. With the development of mobile communications, especially 4G and 5G, mobile networks are becoming more widespread, so in order to provide easy access to this system for the users and the management, some mobile communication technologies can be introduced into the networks.

*3) Industrial Cloud:* Based on the above discussion, it is evident that the cloud layer plays an important role in Industry 4.0, since the cloud not only performs computing for the optimization algorithms and decision making, but also stores massive data [18], [19]. Specifically, in this platform, the cloud is responsible for resolving the users' needs for products, optimizing the flexible conveyor system, fusing and storing data, and even simple data mining operations.

The prototype platform consists of hardware and software. Five servers are used to construct the cloud. The machines were identical models NF8480M3 of Inspur Cor. with 8GB memory, a hard disk capacity of 500GB and 16 CPU cores each. The cloud setup used Citrix XenServer 6.5 and Apache Hadoop. The latter is a software library which acts as a framework that allows for the distributed processing of large data sets across clusters of computers using simple programming models. For storing data from the equipment, and the users, a MySQL database system was adopted in the platform.

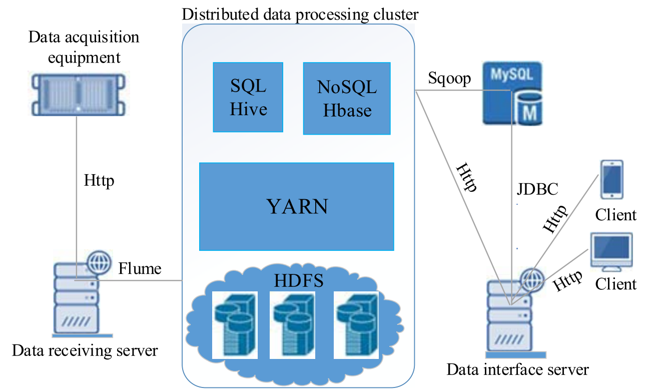


Fig. 2. Information processing of IIoT in industrial environments.

*4) Intelligent Terminals:* The intelligent terminals are directly used to display the related information and key data using web pages, messaging applications or emails. They can provide an effective, specialized, and visual way for users, workmen, and management to interact with the system. Large LCD screens, smart phones and PCs compose the terminal layers. Furthermore, the content's structure can be adapted according to different aims, goals and classes.

Using user web page as an example, the terminals can be divided into two kinds of functions: reservation of resources and monitoring of the production process. In the reservation page, users can provide key parameters according to their needs by choosing some different options or submit designs. Meanwhile, taking the words too literally, reloading web page displays can provide updated information about the products, such as procuring progress, quality, and logistics.

### *B. Information Exchange*

As mentioned above, all kinds of status data (e.g., equipment status data, product data, and measurement and control data) can be gathered by wired or wireless sensor nodes and forwarded to the industrial cloud platform. After analysis, macro-control of the devices may be realized in order to harmonize the different kinds of devices. In summation, the information exchange can be divided into three kinds: information exchange among physical layer devices, information exchange between physical layer devices and IWNs, and data processing in cloud and interaction through mobile terminals. Figure 2 shows the information exchange occurring in an industrial environment.

1) *Information exchange among physical layer devices.* The physical layer devices (e.g., AGVs, robotic arms, and conveyors) work together to process one or multiple products simultaneously. We need to develop a mechanism to support autonomous decision making and

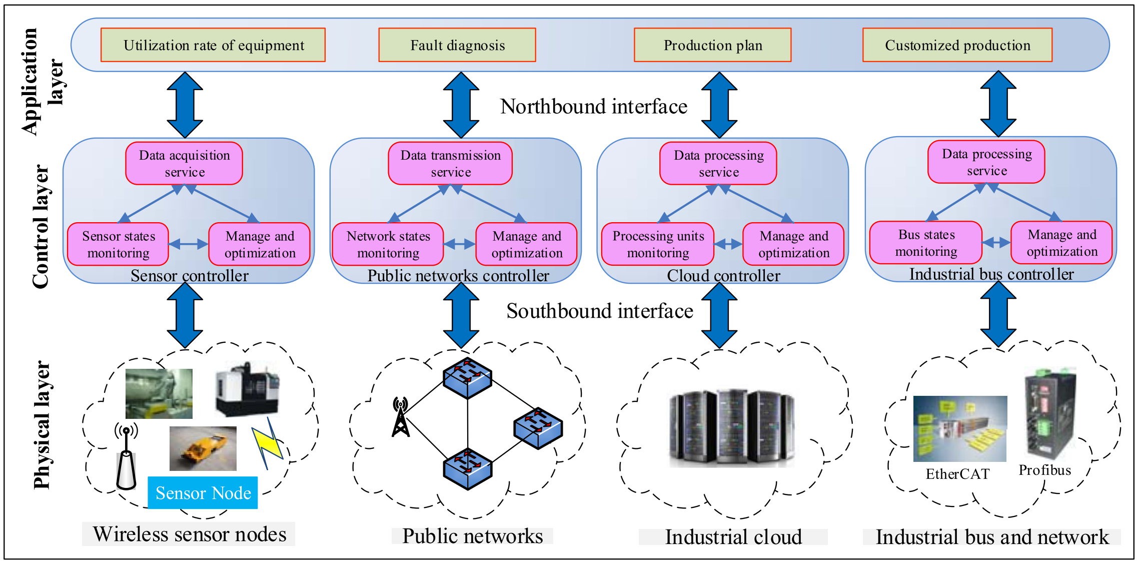


Fig. 3. Architecture of software-defined IIoT in the context of Industry 4.0.

negotiations between smart entities. For example, when we simultaneously process multiple products, more machines may be immediately scheduled to support the completion of these tasks. If the number of assignments is gradually decreasing, the number of corresponding machines engaged can be automatically reduced by the coordination mechanism. As we can see, information exchange is ubiquitous among physical layer devices.

2) *Information exchange between physical layer devices and the cloud*. All the related data, such as equipment status data, are transferred to the cloud through IWNs. For the traditional methods, we should define the data format for the interaction protocol. For example, the RFID reader obtains the information of raw products, including product ID, product type, etc. This information must be packaged according to the protocol. The cloud platform receives these data and then unpacks and extracts the information for further analysis. From the perspective of implementation, we may adopt a web service (e.g., Tomcat+Java) to receive data. When the service receives the uploaded data, we may call the Flume interface to forward the data to distributed storage systems, such as HDFS, Hive, and HBase.

3) *Data processing in the cloud and interaction with mobile terminals*. We select HDFS and Hadoop as the uniform data storage and the foundation framework of the distributed system respectively. MapReduce is selected as the data processing method. The cluster resource management system, YARN, is used to coordinate the allocation of resources between Hive and Hbase. The processed data is exported to MySQL from Hive through the Sqoop interface. The interface server provides the information for external access through the communication protocol in the format of a HTTP interface. In this way, the customer can place an order, and the administrator has access to the real time information of the enterprise through mobile terminals.

## III. Software-Defined IIoT Architecture

In this article, we propose the Software-Defined IIoT Architecture in the context of Industry 4.0, as shown in Figure 3. The architecture is composed of three layers: the physical infrastructure layer, the control layer, and the application layer.

1) *Physical Infrastructure Layer:* This layer is made up of all kinds of devices, including IWNs (e.g., sensor platforms), a fieldbus control network (e.g., EtherCAT), robot networks, the core network (e.g., the gateway, the base stations, and switches or routers), the cloud's network, etc. The information of these devices can be transmitted from one node to the other node in real time. Also, the network bandwidth and requirements for real-time performance may change depending on the different applications; this may be dynamically determined by the control layer.

2) *Control Layer:* The control layer realizes the interaction between the application layer and the physical infrastructure layer. The control layer manages the physical equipment (e.g., the robot network and the fieldbus control network) through southbound interfaces and adapts their different functions according to performance requirements. At the same time, the control layer may provide information (e.g., equipment utilization rate) to the application layer through the northbound interface and API. In the context of Industry 4.0, the control layer may customize the services provided according to the application requirements by data collection, transmission and processing.

3) *Application Layer:* In this layer, the provided APIs can be used to design various innovative applications (e.g., equipment fault monitoring, equipment utilization rate monitoring, and product processing status monitoring). Also, the developers can accelerate the design of new applications by customizing the data collection, transmission and processing. In this way, hardware

resources can easily be shared, system performance can be optimized, and project costs can be reduced.

In an industrial environment, the software-defined IIoT architecture may provide three kinds of services, i.e. data collection, data transmission, and data processing, as follows:

1) *Data Collection Service:* In this layer, the applications are designed according to the provided API, and the data format (e.g., data type, and data attributes) may be re-customized, thus allowing adaptation to different application requirements. For example, for the same equipment, different users may focus on different parameters, which may be accomplished by dynamically configuring the data format.
2) *Data Transmission Service:* Wireless or wired networks are used to forward the perception data to the industrial cloud or transmit data from one control node to other control nodes. The interaction among these devices forms the foundation of a new intelligence design approach, which allows, for example, designs of interactive mechanisms for avoiding deadlocks, or deployment the system resources according to real-time requirements of different applications. All these problems may be approached from the perspective of configuring the data transmission service.
3) *Data Processing Service:* Figure 2 shows the data transmission and data processing. For software defined data processing, we should consider the data attributes and application requirements to determine how to deal with the data [20], [21]. For example, an industrial robot with laser navigation carries out the path planning, which involves a large amount of data processing. If we upload these data to the cloud, and then compute the path information, considerable computing resources may be saved and hardware costs can be correspondingly reduced. Therefore, software-defined data processing may provide more flexibility.

## IV. Problems and Possible Solutions

In Sections II and III, we analyzed the information processing of IIoT and the architecture of software-defined IIoT. However, many problems and challenges for software-defined IIoT need to be addressed. In this section, we focus on existing problems and possible solutions.

The widespread acceptance of IoT has changed the manual mode of data collection used in traditional information technology. In particular, IIoT can record various parameters of the production process automatically, accurately and in a timely manner. Traditional industrial production only realizes inter-machine communication through M2M technology, but IIoT can achieve seamless connections among people, machines and physical objects. However, in the environment of IIoT, the function and performance of the communication devices are very different. For example, some applications require high real-time performance while others do not, whereas some application tasks are performed periodically and others are triggered by events. These characteristics increase the difficulty of the practical application of IIoT. When SDN is combined with IIoT, we can modify the network devices directly, and can also reroute traffic and access rules through software virtualization technology [22], [23]. Nevertheless, SDN and IoT are both at their preliminary stage, which means that the complexity of IIoT applications will result in unpredictable scenarios. In the following, we will discuss existing problems and possible solutions for software-defined IIoT from three aspects, as shown in Figure 4.

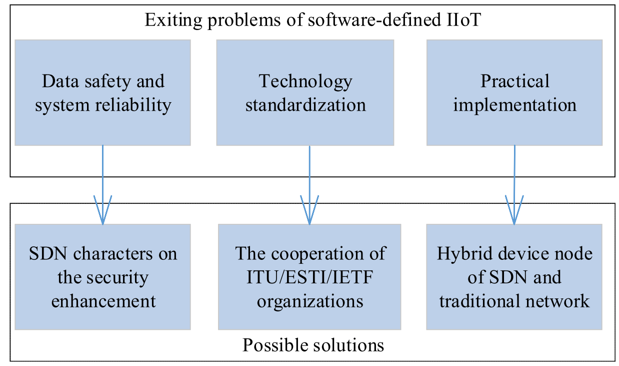


Fig. 4. Existing problems and possible solutions of software-defined IIoT.

### A. Data Safety and System Reliability

The data generated by IIoT has great commercial value, and therefore the secure management of the devices deployed in the IIoT and prevention of theft of the generated data is a great challenge. Firstly, RFID technology is widely used in the sensor layer of IoT. The main safety problems of RFID tags include: a) illegal access. For example, any user (authorized and unauthorized) can read RFID tags using legal reader devices and the information contained in the tag can be rewritten. b) Vulnerabilities caused by the mobility of RFIDs. Secondly, the sensor nodes of IoT are deployed in wireless and mobile environments, in which the network topology changes frequently, so the transmission of data among these nodes can be intercepted by attackers easily and traditional security mechanisms are insufficient for protecting the sensor networks. Finally, the number of the nodes may be enormous and it is almost impossible to manage so many nodes using traditional network management modes.

Traditional network security policies are designed based on different network layers. For example, the authentication mechanism of the network layer is designed based on the identification of a network address, and the authentication mechanism of the application layer is designed based on the identification of business types. These mechanisms exist and operate in the network independently at the same time. However, in most cases, the nodes of the IoT are designed for specific purposes, in which application operations and network communication are tightly coupled. One possible solution to this problem is to design IoT management modes based on SDN. SDN can help IoT withstand many security attacks better, because SDN can provide visibility of all the traffic in the network, which makes it easier to detect suspicious traffic using automated policies and analyze such occurrences further [24]. By simplifying network management, SDN can perform distributed access control, and provide dynamic, intelligent, and self-learning layered security modes. The security advantages of SDN are more effective than those provided by traditional network firewalls, because the attackers are usually inside the firewall [25], [26], [32]. In addition, SDN can also make automatic real-time decisions by re-programming the network when an attack has been detected.

### *B. Technology Standardization*

Technology itself is not the main barrier for the widespread application of IIoT; it is the interoperability interfaces of systems belonging to different vendors that inhibit adoption. In order to achieve good interoperability, the key is to develop a unified standardization of interaction interfaces between different components owned by different vendors. IIoT is the combination of computer, communication and microelectronic technologies, so there exist many interfaces between hardware, software and network components. A lack of unified standard interfaces will greatly restrict the large-scale deployment and application of IIoT [27].

As previously mentioned, IIoT based on SDN has many advantages, but SDN is also an emerging technology, which is still in the stage of initial development, and the standardization of SDN is still ongoing. Therefore, the technology standardization for IIoT is a very complex task, the main problems of which include [28]: a) coordination between the various standardization organizations is not sufficient, and there are different versions of standards, which are incompatible with each other; b) the progress of standardization is insufficient to keep up with market changes and the requirements of industry; and c) no unified standardization can be accepted widely, especially accepted and practiced by small and medium-sized enterprises.

Currently, both academia and industry have made a lot of efforts for the standardization of software-defined IIoT, and relevant standardization organizations have been established. For example, the International Telecommunication Union (ITU) and Internet Engineering Task Force (IETF) are conducting SDN standardization research from the perspective of next generation Internet. The European Telecommunication Standards Institute (ETSI) is a standardization organization that is composed of major telecom operators and vendors in Europe and the United States, which is working on network virtualization standards. Their goal is to replace proprietary network elements by standard devices through virtualization technology, and particularly standard IoT nodes.

### *C. Practical Implementation*

Compared with the traditional networks, the scale of IoT networks is greatly increased. In order to apply SDN technology on IIoT, network systems will face the following problems during practical implementation [29]: a) the design of a forwarding plane for software-defined IIoT is a challenge. With the continuous improvement of OpenFlow, the flow table of switches has evolved from the original single table structure to a multiple table structure, where the matching fields of the flow tables are constantly increasing. For example, IPv6 and MPLS fields have been added in OpenFlow 1.3. Therefore, the design of SDN forwarding has become more complicated [30]. b) Extensibility of control plane. The number of network nodes of IIoT is enormous, and multiple distributed controllers are necessary. The coordination and interaction between these controllers is a challenge in practice. c) Forwarding plane delay. Software defined IIoT is a centralized control system, with new data constantly forwarded to the controllers, which may result in forwarding delays and even packet loss. d) The software architecture of the controllers is very complex and system stability is difficult to guarantee. For example, in order to achieve the programmability of the network, system control applications must be allowed to have many access privileges for system control, which increases the probability of system crashes.

For the above problems, we can find possible solutions from the following aspects. a) SDN is not suitable for all scenarios of IIoT; its applicability will depend on the network scale and application complexity. Only when the network scale is very big, or the security policy and traffic scheduling strategy are very complex, should SDN technology be considered. b) Designing hybrid devices that support both SDN and the traditional network architectures. When a packet enters into a specific port, the hybrid device can recognize whether it is an SDN packet or a traditional network packet, which can solve the interoperability problem between SDN and traditional networks. c) In cases where single controllers are responsible for performance bottlenecks, we can consider the adoption of a distributed control plane, which distributes multiple computing tasks to different controllers. Thus, distributed controllers can not only alleviate the performance pressure on single controllers, but also improve the reliability of the whole network through redundant controller availability.

## V. Assessment Testbed

In this section, we present a brief case study to further explain the benefits of software-defined IIoT in the context of Industry 4.0. Figure 5 shows a prototype platform of software-defined IIoT, and this platform includes a variety of physical equipment, such as a cloud data center, an industrial robot, an AGV, an IWN, a RFID reader, a conveyor, workpiece, etc.

In order assess the characteristics of software-defined IIoT, we carried out a comparison between the software-defined IIoT and other traditional schemes. With the support of software-defined IIoT, more intelligent services can be provided due to effective interaction between components. In the traditional schemes, the lack of interaction among equipment will result in reduced autonomous decision making capabilities of the devices. For example, only one kind of product will be placed on the conveyor at any time.

Since the data available from the workpieces, the conveyor and the industrial robot can be gathered in real time, intelligent operation of the equipment may be achieved through a negotiation mechanism [1]. Under the framework of software-defined IIoT, we can have two kinds of workpieces processed at the same time. However, the traditional schemes usually do not

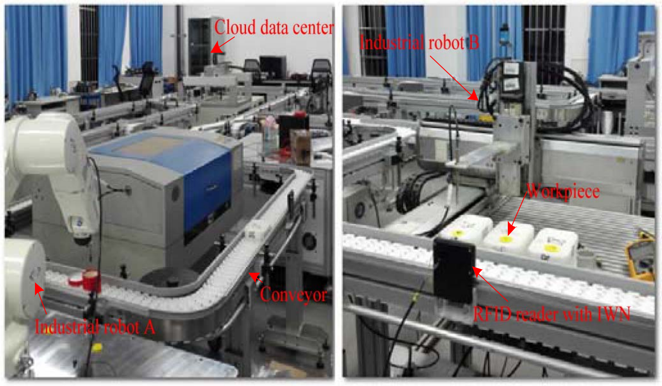


Fig. 5. The prototype platform of software-defined IIoT.

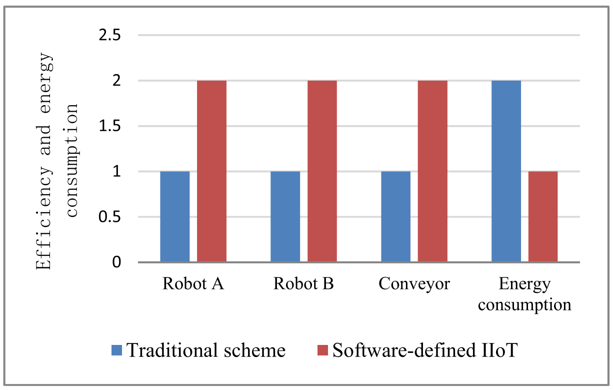


Fig. 6. Illustration of the performance of equipment.

support personalized customization. Figure 6 is an illustration of the performance assessment of the equipment. We can see that the equipment utilization rate is improved, and at the same time the energy consumption is obviously reduced. Obviously, the software-defined IIoT will accelerate the implementation of Industry 4.0.

## VI. Conclusions

In this paper, we focused on the IIoT architecture and information-based interaction for the industrial environments in Industry 4.0. In particular, we analyzed a software-defined IIoT architecture to determine network resource allocation and accelerate information exchange mechanisms through an easily customizable networking protocol. We also discussed the existing problems and possible solutions for software-defined IIoT. With the support of this architecture, some innovative industrial applications can be realized through well-defined APIs. Also, the increased intelligence of the equipment will improve the system's efficiency and at the same time allow the provision of a wider range of services. The software-defined IIoT will facilitate the evolution of Industry 4.0.

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