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Key Technology of Network Integration for Urban Rail Transit System

Hui-bin Wang, Zheng-hai Ping, Jie Shen, Li-li Zhang
College of Computer and Information Engineering
Hohai University
Nanjing, China
E-mail: hbwang@hhu.edu.cn, hhu_pzh@163.com, jieshen_hhu@163.com, lilizhang@hhu.edu.cn

***Abstract*—Rail transit is a typical Cyber-physical Systems (CPS). The study of urban rail transit CPS was carried out with the introduction of CPS into the urban rail transit system. Based on the analysis of CPS, the fundamental architecture of urban rail transit CPS was designed and the functions of corresponding layers were explained. The system model of urban rail transit CPS was proposed. The functions of the model and the interaction between each model were explained. The issue of heterogeneous networks integration in rail transit system and train system was analyzed. Meanwhile, according to the actual demand of security monitoring and management of train running, network controller between WSN and control bus was designed and verified. The results show that the network controller can well achieve data exchange between WSN and train network.**

Keywords-rail transit; CPS; network integration; network controller

I. INTRODUCTION

CPS (Cyber-physical Systems) was proposed by the American National Foundation in 2006, and has got academic's extensive concern and research in recent years, but there's no a unified representation for its concept. Lee defined CPS as integrations of computation and physical processes [1]. Sastry believed CPS integrates computing, communication and physical entities so as to realize monitoring and control [2]. Tabuada thought that CPS comprised a network of physically distributed embedded sensors and actuators equipped with computing and communicating capabilities, through nodes to monitor and control the physical word and coordination to complete more powerful features [3]. Nevertheless, with understanding of the perspective of system, two important consensuses can be summed: (1) CPS is a complex multidimensional system deeply integrates computing, communication and control; (2) CPS is an intelligent system of collaboration and integration of information process and physical process.

Therefore, domestic and overseas academics and research institutions in the field of computer, communication, automation and many other areas have attached great importance to CPS applications. Indiana University introduced CPS to the management and monitoring of city sewer network. The COSNet system they developed can achieve autonomous scheduling management of city sewer network based on city sewer network human needs and climate change [4]. Tokyo University has carried out extensive research about applications of CPS in the development of intelligent robot. The CPRS they developed can achieve perceived intelligence, social intelligence and genetic intelligence of robot by coordinating physical robot's hardware and software and database resources. In addition, Yang et al studied the feasibility of introducing CPS technology to spacecraft control system and proposed technical approaches of control system design based on CPS [5]. Wang et al introduced CPS to design of wind power gas locking system of coal mine, built distributed hybrid system model compatible with Ethernet, device and field bus sub-station [6]. Adapting to avionics system requirements, Wang et al explored CPS application in avionics systems and proposed a reduced model of the information physical system onboard [7].

Monitoring system for urban rail transit refers to computer integrated system responsible for monitoring the status of each vehicle and all of the power devices in rail transit lines. The existing monitoring system is implemented mainly through vehicle monitoring system and ground signal monitoring system respectively. The two systems lack timely and effective information exchange. Control and decision command are mostly operated by people, unable to meet system's adaptive adjustment according to train states and real-time requirements for the timely processing of unexpected events. This paper introduced CPS technology to the monitoring system for urban rail transit, constructed architecture of train CPS and urban rail transit CPS and analyzed the problem of heterogeneous network integration. Finally, a network controller between heterogeneous networks in train system was designed and verified.

II. ARCHITECTURE OF URBAN RAIL TRANSIT CPS

A. System Architecture

The architecture of urban rail transit CPS includes physical layer, network layer and application layer. In urban rail transit system, not only does each vehicle timely communicate with ground dispatch management center, there are also real time communication between bus network and various components in each vehicle itself. Data acquisition channels, network transmission and control strategies of the

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two systems are different. Therefore, the structure of CPS contains two parts: one part is train CPS consisting of sensors, actuators, WSN, train intranets and driver control room; the other is urban rail transit CPS consisting of each train CPS, signal system, communication network and scheduling management center. The structures of trains CPS and urban rail transit CPS are shown in Fig. 1.

1) Physical layer

In train CPS, physical layer contains sensors, actuators, WSN, is mainly responsible for information perception of train environment, operating status, etc., such as train speed, cabin temperature, humidity, pressure and other environmental parameters. Some of the information is sent directly to train network by the sensor, some is sent to network controller to process and then sent to train network.

In urban rail transit CPS, physical layer contains each train CPS, signal systems and actuators, is mainly responsible for acquiring processed and integrated information from train CPS and data of signal system. Also physical layer obtains processing results and control commands and actuators will perform system control commands to accommodate physical environment's changes.

2) Network layer

In train CPS, network layer contains network nodes, MVB, WTB (Wired Train Bus) and Ethernet, is responsible for sending sensory data from physical layer to application layer and commands from application layer to physical layer, achieves data exchange and sharing of resources.

In urban rail transit CPS, network layer contains network nodes, private networks, public networks, next generation networks, etc. Network layer sends train CPS data and signal system data from physical layer to dispatch management center, provides reliable real-time network services. Considering large amount of data, network layer must have the ability of intelligent management of mass data.

1) Application layer

Application layer is also called control layer, is the core component of CPS system. Application layer is responsible for analyzing and processing data from network layer, judging according to pre-defined semantic control rules, determining control strategies and publishing different execution orders. And then sends these orders to network layer. In train CPS, application layer mainly provides command and control, maintenance management, real-time monitoring, application software and other services. In urban rail transit CPS, application layer mainly provides scheduling management, remote control, data storage, video surveillance, expert decision, application software and other services.

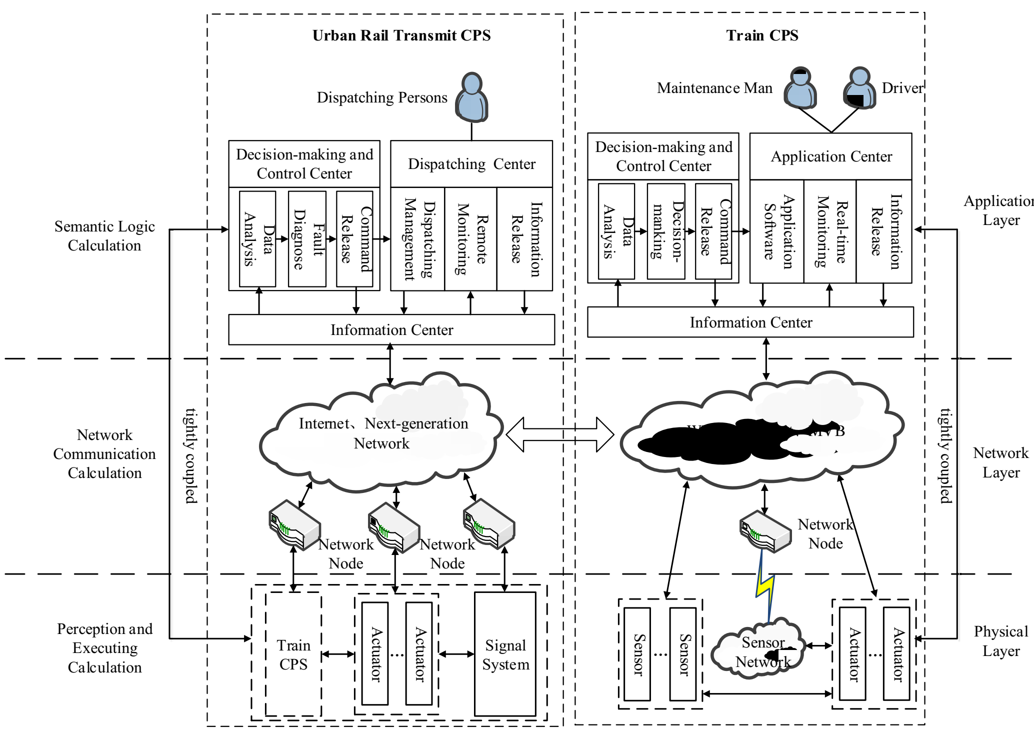

Figure 1. Urban rail transit CPS and train CPS

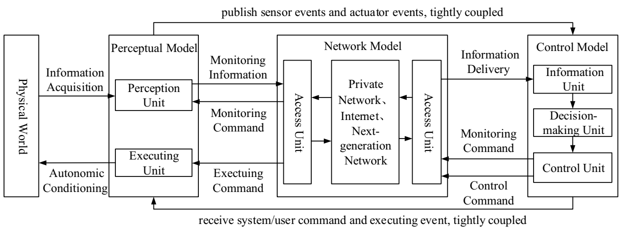

Figure 2. CPS system model

B. System Model

CPS emphasizes interaction between physical world and perception world, can realize self-perception of physical world, self-communication, self-judgment, formation of control strategies and self-regulation. Therefore, CPS can be divided into 3 components: perception, network and control, the three components coordinate to achieve interconnection, mutual inductance and high collaboration between virtual world and physical world. CPS system model is shown in Fig. 2.

1) Perception model

Perception model contains perception unit and executing unit. Sensing unit consists of various nodes with the ability of sensing and monitoring physical environment. Executing unit consists of various actuators, which are responsible for receiving decision-making and control commands. Executing unit directly controls physical world.

2) Network model

Network model contains access unit and network unit. Access unit can realize data exchange between different access networks. Network unit includes private networks, public networks and next generation communication networks, etc., completes communication tasks.

3) Control model

Control model contains information unit, decision-making unit and control unit. Information unit integrates information from network model and assists decision-making nodes in making final decision. Decision-making unit comprehensively analyzes information from information unit, makes task decision and sends to control unit. Control unit guides the work of decision-making unit, perception unit and execution unit in real time.

III. Network Integration

As mentioned above, there are two different systems in urban rail transit system, namely train CPS and urban rail transit CPS. There are two or more heterogeneous networks within the two systems. These heterogeneous networks provide not only horizontal communication within the same network, but vertical communication between different networks. This paper respectively analyzes the problem of network integration for the two systems.

A. Public Network Integration

Public network Integration evolves separate network and business, such as voice network, internet, mobile data networks and traditional data networks, into a unified integrated network to provide various services, the three networks (telecom, broadcast television, Internet) integration oriented. With the continuous development of information technology and rapid popularization of network, institutional and technical barriers to public network integration continue to decrease. Public network integration will greatly promote the development of information industry.

From technical level, public network integration must not only solve horizontal network integration of, including interconnection of core network, access networks and terminal devices, but also focus on solving vertical network integration, including mutual tolerance and penetration of different application levels, such as applications, services, transmission, control. The main work details should be focused on the micro-fusion, such as movement and immobilization integration, interface integration and standards integration, and ultimately realizes management and control integration [8].

B. Train Network Integration

TCN (Train Communication Network) is a communication network used for interconnection of programmable devices within vehicles and between vehicles to realize information interaction of the full train. TCN provides information channel for train control, device status monitoring, fault diagnosis and control. In terms of network topology, according to the distribution characteristics of communications device on the train, TCN uses bus network structure with two layers. One layer is LAN comprised of devices connected by MVB within each carriage, in order to meet communication needs of each device. Another is vehicle backbone network comprised of each carriage connected by WTB to meet communication needs of the entire vehicle. MVB communicates with WTB through gateway.

According to the actual needs of train safety monitoring, this paper introduces WSN to train network to achieve the communication between WSN and train network. Therefore, this paper focuses on the problem of network integration between WSN and MVB.

1) Network structure

In train CPS, network layer is mainly responsible for receiving sensory data from physical layer and sends it to application layer. Meanwhile, network layer sends control and execution commands from application layer to physical layer. In the designed monitoring network architecture, network topology is master-slave mode, the network controller joins MVB network as a slave device and is responsible for data communication between MVB and terminal monitoring nodes. The network architecture is shown in Fig. 3.

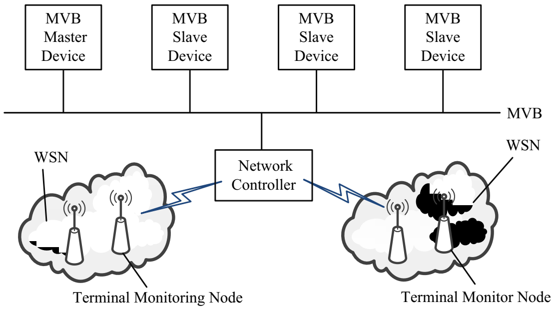

Figure 3. Train network integration

a) MVB Network

MVB network includes master devices and slave devices. Master devices send master frames to MVB according to periodic list, slave devices perform appropriate action based on port address in master frames.

b) Network Controller

Network controller is responsible for receiving master frames from MVB. When port address in the master frames and the device address is consistent, network controller sends slave frames contains corresponding environmental data to MVB. Meanwhile, network controller receives and stages environment monitoring data from terminal nodes. If needed, network controller will send commands to terminal monitoring nodes to request data. Each carriage has only one network controller.

c) WSN

WSN consists of terminal monitoring nodes and is responsible for collecting environmental data in vehicle and sending it to network controller to handle.

2) Data exchange

a) MVB Slave Devices---Network Controller

When MVB slave devices need sensor data, master device sends master frames to MVB. Network controller sends slave frames that contain corresponding sensor data to MVB after receiving the master frames. Then slave devices receive the slave frames.

b) Network Controller---Terminal Monitoring Nodes

When receiving master frames, network controller sends data request commands to terminal monitoring nodes according to the need. When collecting environmental data, terminal monitoring nodes periodically send it to network controller.

IV. DESIGN OF NETWORK CONTROLLER

From the practical application, this paper gives design of network controller for the train network integration according to communication needs of the train system.

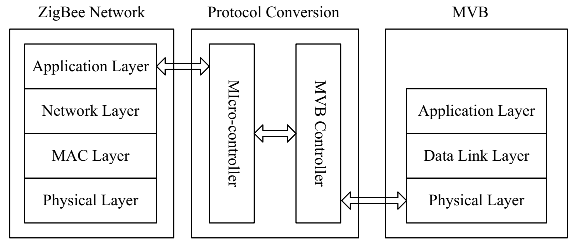

Figure 4. Schematic of protocol conversion

A. Structure of Protocol Stack

According to development status and characteristics of MVB network and WSN technology, this paper uses WSN based on ZigBee communication standard and MVB. Protocol conversion will be completed in the network controller when the two networks communicate with another one. The conversion process is shown in Fig. 4.

ZigBee protocol stack is built based on the IEEE 802.15.4 standard. The IEEE 802.15.4 standard defines the protocol standard for MAC layer and PHY layer. ZigBee protocol stack defines the standard of network layer, application layer and security services layer [9]. MVB protocol defines application layer, data link layer and physical layer for process data.

B. Data Design

1) Address mapping table

The structures of master frame and slave frame are shown in Fig. 5 and Fig. 6.

The master frames sent by master device contain 4 bits F_code and 12 bites port address. The F_code is used to define the requested data types, the 12 bits port address is requested source port address. The length of slave frames can be one of 24, 40, 72, 144 or 288. In this paper, network controller communicates with the bus as a slave device and its data is process data. At the same time, different data types can be set in periodic list depending on the different types of data monitored by sensor nodes.

According to IEC61375 standard, value of F_code [10] for process data is show in TABLE I.

In the process of bus communication, slave device judges whether its source port address and logical address in master frames are the same. If the same, this slave device encapsulates corresponding data into slave frame and sends to MVB. In this paper, network controller manages all terminal monitoring nodes in one carriage and these nodes respectively monitor various types of environmental parameters such as temperature, humidity, smoke concentration. These parameters may need multiple bytes to represent. Taking temperature value as an example, it needs 2 bytes to present. Length of slave frame data is up to 256 bits that means only 8 temperature values can be sent once. Therefore, network controller cannot send all the monitoring data once.

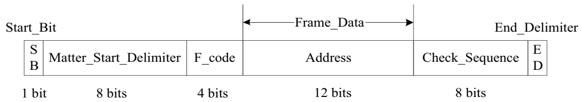

Figure 5. Structure of master frame

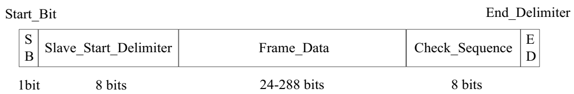

Figure 6. Structure of slave frame

TABLE I. F_CODE VALUE OF PROCESS DATA

Master Frame			Slave Frame			
F_code	address	request	source	size (bits)	response	purpose
0	logical	process data	single device subscribed as source	16	process data	all devices subscribed as sink
1				32		
2				64		
3				128		
4				256		

To solve the above problem, multiple source port addresses need to be configured for network controller. In this paper, each type of monitoring data is configured with a source port address. When receiving master frames, network controller extracts different types of data based on different source port address to improve the accuracy of data exchange.

Mapping values of port addresses and data types are shown in TABLE II.

In TABLE II, value of X is 0~E, represents 15 data types. Data type is 1~5, represents 5 types of monitoring data length. In addition, this paper also sets different priority for each type of monitoring data and short data may has high priority. Periodic list sets different polling periods for each type of data according to its priority to improve instantaneity of data access.

2) Data flow

Data flow is divided into two parts: communication between ZigBee nodes and communication between ZigBee network and MVB. The communication protocol between ZigBee nodes is application layer program developed on the basis of TI's Z-Stack protocol stack and is debugged, compiled and downloaded in the IAR platform. The following focused on the communication between ZigBee network and MVB.

The communication between ZigBee network and network controller uses the mode of serial interrupt and is processed in interrupt handler to improve real time. The network controller includes central node, micro-controller and MVB communication controller. The center node sends monitoring data to micro-controller via serial port after receiving monitoring data. When receives master frames from MVB, MVB communication controller judges whether its source port address is the same with the source port address in master frame. If the same, micro-controller fetches corresponding data and sends to MVB communication controller. MVB communication controller encapsulates the data into slave frame and sends to MVB. Program flow chart is shown in Fig. 7.

TABLE II. MAPPING TABLE OF PORT ADDRESS AND DATA TYPE

F_code	Port Address	Data Length	Data Type	Priority
0	0xFFx	16	1	A
1	0xFFx	32	2	B
2	0xFFx	64	3	C
3	0xFFx	128	4	D
4	0xFFx	256	5	E

V. EXPERIMENT AND SIMULATION

To verify the previously described network controller can complete data interaction between ZigBee network and MVB, this paper presents the hardware design of the network controller and carries out system reliability test.

The hardware structure of network controller is shown in Fig. 8. CC2430 is used as the core processing chip of center node. CC2430 is a dedicated chip for wireless communication, including a high-performance 2.4GHz DSSS radio transceiver and an efficient 8051 controller. The chip supports CSMA/CA and its operating current is 27 mA which is compliant with the feature of low power consumption of ZigBee. SSMV21CD is used as MVB communication controller. It supports 4096 process variables ports and connects with micro-controller via PC104 interface. The model of micro-controller is ATmega128 and is primarily responsible for storing monitoring data and sending data to MVB communication control. It communicates with center node via SPI interface. The system reliability test contains two parts:

A. Data Transmission from MVB Network to ZigBee Network

This part mainly tests ZigBee network receives data of MVB network via network controller, i.e., network controller receives master frames from MVB and sends data request to ZigBee nodes. The network controller is configured with 3 source ports, the addresses are 0xFF0~0xFF2 and data lengths is 16.

B. Data Transmission from ZigBee Network to MVB Network

This part mainly tests MVB network receives data of ZigBee network via network controller. The source port addresses of network controller are to act as the sink port address of MVB slave devices. Network controller encapsulates data from ZigBee nodes into slave frame and sends to MVB. Then MVB slave devices receive the data.

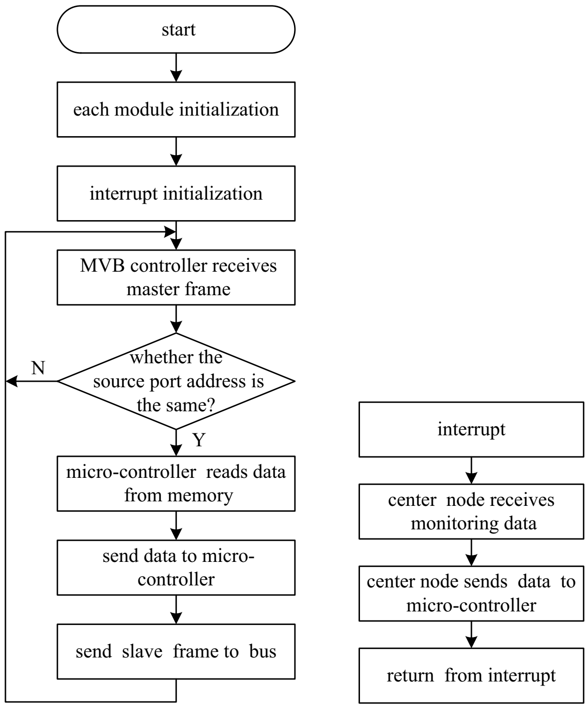

Figure 7. Program flow chart

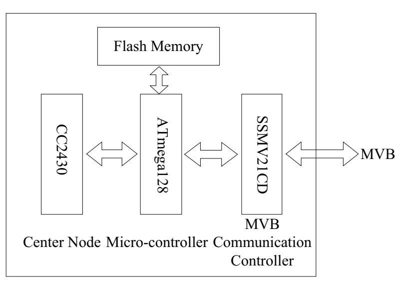

Figure 8. Hardware structure of network controller

In this paper, five groups of reliability tests are carried out and the master device send a total of 1000 master frames. The results are shown in TABLE III.

TABLE III. DATA TRANSMISSION RELIABILITY TESTS

	Number of data frames received correctly	**Accuracy (%)**
Group 1	997	99.7
Group 2	995	99.5
Group 3	993	99.3
Group 4	996	99.6
Group 5	995	99.5

As can be seen from the table above, the average accuracy of data reception is about 99.5%, indicating that the network controller can correctly receive the data request frame from MVB network and send data request information to ZigBee nodes. Meanwhile, it can correctly send data from ZigBee nodes to MVB slave devices. In addition, the network controller can be configured with 4096 source ports which can greatly improve the types of monitoring data.

VI. CONCLUSION

CPS is a new type of network system closely integrated by sensing devices, communication networks and computing devices. In many fields such as environmental monitoring, aviation heavy industry and intelligent transportation, CPS has a broad application prospect, and will bring profound influence and changes on the way of human life in the future.

This paper constructed CPS architecture of urban rail transit. On the one hand, as the basic framework of future rail transit system, urban rail transit CPS should have all important functions of the existing urban rail transit system. On the other hand, as a subsystem of widely used CPS in the future, urban rail transit CPS has many characteristics of CPS. Because urban rail transit CPS is for the actual rail transit system, its study can promote the development of CPS.

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