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CPSS: A study of Cyber Physical System as a Software-defined Service

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Abstract

The Cyber Physical System (CPS) has become a promising direction that can enrich the interaction between people and people, people and objects, objects and objects in the physical world and the virtual world. Because of the development of CPS, the number and types of smart devices connected to the Internet have rapidly increased, bringing with it the current issues of scalability and efficiency of the Internet of Things(IoT) network. These problems are caused by the key mechanism of large-scale distribution to the Internet of Things network. In this article, we propose CPSS inspired by software-defined networking (SDN) and service-oriented architecture, which is a powerful software-defined cyber physical system to solve the challenges of broader CPS adoption. To test CPSS, we develop a prototype system. Our experimental results show that CPSS can effectively control CPS, and CPSS has greatly improved latency and throughput compared to traditional controller-controlled CPS.

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Keywords: CPSS, Software-defined networking, OpenFlow

1. Introduction

According to a recent Gartner report, 8.4 billion Internet of Things(IoT) devices will be put into use worldwide in 2017, an increase of 31% from 2016, and will reach 20.4 billion by 2020. The total spending on terminals and services will reach nearly US$2 trillion in 2017, which means that IoT devices will sell US$1 million per hour and sell for US$2.5 million per minute. If the Internet of Things has a market size of a trillion dollars, then the market size of Cyber Physical System (CPS) is difficult to count, because CPS covers applications ranging from smart home networks to industrial control systems and even intelligent transportation systems, such as national and even world-wide levels.

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More importantly, this coverage does not simply link objects and things together, but it has created many devices with computing, communication, control, coordination, and autonomous capabilities. The next-generation industry will be built on top of CPS.

CPS will not only spawn new industries, but will also rearrange existing industry layouts. The CPS is a new paradigm for Network/Distributed Control Systems (NCS/DCS). It emphasizes the co-design and cooperation between a large number of IoT devices and real-world objects connected through distributed networks. At the same time, CPS can monitor and create virtual copies of real-world processes so that we can understand the status of each process, control related objects, and make the right decisions in real time. As a result, productivity will increase significantly, and costs, false rate, and waste will be significantly reduced. With the development and popularization of CPS technology, physical devices that use computers and networks to achieve functional expansion are everywhere, and will promote the upgrading of industrial products and technologies, greatly improving automotive and aviation. Competitive power in major industrial sectors such as aerospace, defense, industrial automation, health/medical equipment, and major infrastructure.

Table 1: IoT Units Installed Base by Category (Millions of Units)

Category	2016	2017	2018	2020
Consumer	3,963.0	5,244.3	7,036.3	12,863.0
Business: Cross-Industry	1,102.1	1,501.0	2,132.6	4,381.4
Business: Vertical-Specific	1,316.6	1,635.4	2,027.7	3,171.0
Grand Total	6,381.8	8,380.6	11,196.6	20,415.4

Inspired by software-defined networking (SDN)[1] and service-oriented architecture, we propose CPSS which-divide CPS into three layers: Infrastructure-as-a-Service (IAAS), Network-as-a-Service (NAAS), and Aplication-as-a-Service (AAAS). At the same time, we divide the domain of CPS, define the functions of each module of CPS, and realize the mapping between virtual and reality. This means that when an application feels that resources are not enough, you can switch to another infrastructure to serve. When the underlying infrastructure feels that there is a problem with the application logic at the top, you can switch to other functional applications to control.

2. Motivation and Problem Statement

The Cyber Physical System (CPS) revolutionizes various application areas by integrating networks, computing systems and mechanical equipment, and interoperability. Due to its size and diversity, CPS faces many challenges and raises some research issues in terms of management, fault tolerance and scalability. In this section, we first discuss the problem of CPS management in the context of traditional network. We then underline the need of right control granularity and the challenges associated with designing them.

2.1. Flexible control is the norm

CPS is associated with the currently popular Internet of Things (IoT), Industry 4.0, Industrial Internet, Machine-to-Machine (M2M), the Internet of Everything, TSensors (trillion sensors), and the fog (like the cloud, but closer to the ground) . All of these reflect a technological vision that deeply connects our material world with our information world. We believe that the term CPS is more fundamental and persistent than all of these terms because it does not directly refer to implementation methods (such as Internet in IoT) or specific applications (such as Industry in Industry 4.0). It focuses on the basic knowledge of the engineering tradition that combines the network and the physical world.[2]

Over the past few decades, the traditional paradigms used in industrial automation have become increasingly inadequate to meet the business needs of emerging technologies and manufacturing companies. The ever-changing conditions restrict industrial companies from conducting business because they face enormous pressures related to cost, quality and product customization in a highly flexible and responsive production system. This market and business evolution is creating a need for more flexible and scalable production systems that can handle agile fluctuations with high product variability with reasonable cost and real-time responsiveness. The collaborative automation paradigm is a major example supported by the industry, and its goal is to develop and implement tools and methods to achieve

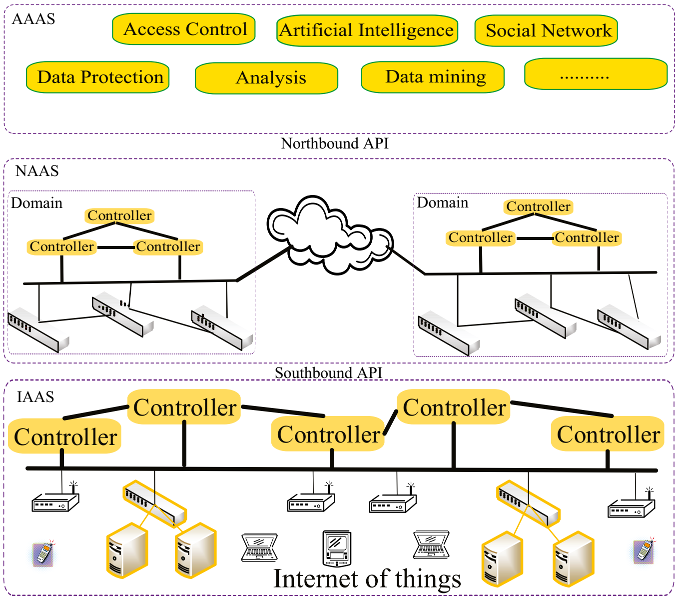

Fig. 1: CPSS architecture overview

flexibility, reconfigurability, extensibility, interoperability between distributed and embedded systems. This trend is accompanied by the evolution of technology that penetrates computing power (ie, data and information processing) into mechatronics and gradually transforms traditional workshops into ecosystems, where network systems consist of intelligent embedded devices and systems, as well as customers and businesses. Partners in business and value processes interact with physical and organizational environments and pursue clear system goals.

2.2. *Finding the right control granularity is hard*

One important trend in CPS is toward Complexity. Complexity have its advantages, hiding it from the end-users and managing it, results to grand challenges. As an example, in our cars, the complexity is hidden from the driver, as she/he just needs to handle a limited number of controls to operate the system, without being exposed to its complex networks of sensors and actuators distributed all through the mechanic infrastructure.

To achieve complexity, Mixed criticality(MC) systems are proposed that integrate application components with varying degrees of criticality onto a common hardware platform to reduce costs. MC systems have two seemingly conflicting goals: 1) Logical separation between applications with different critical levels and 2) Effective scheduling of shared resources. The key principle for balancing these conflict goals is the adoption of mode-based MC scheduling. For example, dual key systems have two key modes: High Criticality (HI) and Low Criticality (LO). In the HI system mode, it only guarantees all the requirements of the HI application. In contrast, in the LO system mode, the goal is to meet the requirements of HI and LO applications, while HI applications may be limited by some (low demand) requirements. For this reason, the MC scheduler usually adopts different scheduling behaviors in both modes. Some studies have proposed MC traffic management based on mode Controller Area Network (CAN) and Network-On-Chip(NOC)[3]. However, there is currently no solution that can implement MC traffic scheduling on switched Ethernet. Supporting mode-based scheduling on switched Ethernet is not feasible because traditional switches use only static scheduling behavior.

3. CPSS architecture

It is easy to understand how CPSS realizes a control platform if we know the features of each layer in the platform. In fact, CPSS has four layers which have very distinct roles. Compared to 3-layer platform, we represent significant principles and major challenges in designing CPSS.

AAAS. How a specific application use a network is determined by AAAS. These applications provide access control,artificial intelligence, social network, data protection, analysis, data miming network virtualization, network efficiency, advanced routing, network storage, network computing and other functions. As the operating system has a graphical user interface (GUI) desktop, CPSS also provides a GUI that allows users to more easily understand and operate the network. However, the current application of the SDN controller generally provides simple network information browsing functions, which does not provide flow entry addition and modification operations, and does not provide communication between different types of SDN controllers. To address this issue, CPSS set up a convenient and easy to use web control interface based on FLEX, which can control many different types of SDN controllers.

NAAS. The core component of CPSS is NAAS. The NAAS consists of multiple servers called decision elements that connect directly to the network. Compared to other CPS architecture, NAAS in CPSS is a newly established layer between physical devices and applications. NAAS makes all decisions driving network control, including interface configuration , security, load balancing, accessibility and access control. Instead of traditional CPSś management layer, NAAS operates in real time on a network view of the resource limitations, the capabilities, and the traffic and of the physical devices. NAAS uses algorithms to turn network-level objectives (e.g., reachable matrix, load-balancing goals, and survivability requirements) directly into the packet-handling rules (e.g., Routing rules, queuing parameters, forwarding table entries, packet filters) that must be configured into IAAS. NAAS in CPSS has three complementary modules: Network Information Collection (NIC) module, Cross-domain Management (CDM) module and Controller Selection Management(CSM) module. NIC collects network information from a different set of controllers and generates a domain-wide network view. CDM collects domain information from other domains to generate a global network view. Base on the domain-wide network view and global network view, CSM selects the most efficient controller for each network flow in the network.

IAAS. IAAS is the carrier of CPS network, includes network switches, and any other network elements that support an interface allowing NAAS to read and write the state controlling the elementś behavior (such as forwarding table entries). The function of the IAAS is mainly confined to packet forwarding and simple processing. However, it is necessary to build a flexible and easily configured IAAS in order to adapt changing demands placed on the application by the end users, the new personalized requirements of data center network and other network application scenarios.

4. Experimental Setup and Results

To test the CPSS processing performance in a real network environment, we built a partial 4-radix FatTree. A PICA8 3297 switch is divided into seven switches. Each domain has an IP Range or an IP Range set. In our test, we construct two domain: Domain A and Domain B. Domain A's IP Range is 192.168.0.1/24, and Domain B's IP Range is 192.168.1.1/24. We do this test on two PCs with same disposition: one host in Domain A and another host in domain B. Table III summarizes the parameters of the PC. Fig.2 describes the throughput of each controller connected 16 switches changes with the number of thread. Floodlight and Maestro can process 700 kilo requests per second at most. CPSS can process 900-kilo requests per second. Floodlight and Maestro do routing based on network-wide view while CPSS does routing based on simplified network wide view.

Fig. 3 describes response time (milliseconds) varying the number of switches for runs with 1 threads. At the beginning, adding more CPU beyond the number of switches improve a little latency, however serving a far larger number of switches than available CPU results in a noticeable increase in the response time.

5. Conclusions

This paper presents the first effort that CPSS inspired by software-defined networking (SDN) and service-oriented architecture, which is a powerful software-defined cyber physical system to solve the challenges of broader CPS adoption. The proposed solution, CPSS, might provoke interesting discussions on the research community and open

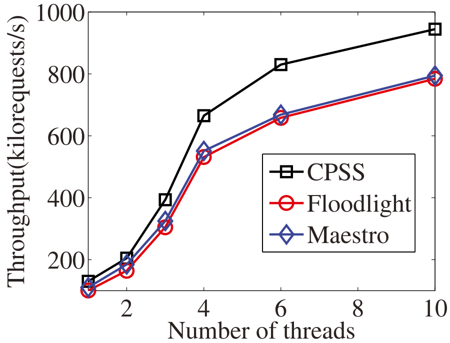

Fig. 2: The throughput of each controller connected 16 switches changes with the number of thread

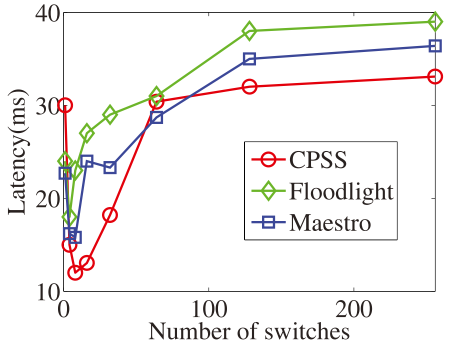

Fig. 3: Response time varying the number of switches for runs with 1 threads

the door to a range of innovation opportunities. In a word, we expect to see a new generation of SDN that is versatile, flexible, and easy to manage.

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