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Cyber Physical Systems Role in Manufacturing Technologies

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Abstract. Empowered by the recent development in single System-on-Chip, Internet of Things, and cloud computing technologies, cyber physical systems are evolving as a major controller during and post the manufacturing products process. In additional to their real physical space, cyber products nowadays have a virtual space. A product virtual space is a digital twin that is attached to it to enable manufacturers and their clients to better manufacture, monitor, maintain and operate it throughout its life time cycles, i.e. from the product manufacturing date, through operation and to the end of its lifespan. Each product is equipped with a tiny microcontroller that has a unique identification number, access code and WiFi conductivity to access it anytime and anywhere during its life cycle. This paper presents the cyber physical systems architecture and its role in manufacturing. Also, it highlights the role of Internet of Things and cloud computing in industrial manufacturing and factory automation.

INTRODUCTION

Integrating the physical, digital and biological worlds has led to the fourth industrial revolution (industry 4.0). The transition from mass and semi-customised production to mass, fully-customised and variant products manufacturing is one of the main features of industry 4.0. The fourth Industrial revolution is not going to change the way we do things only but “it will change us” [1]. New business models are emerging nowadays which will change the way things are produced, transported and consumed. The enabling computing technologies for such transformation are the system-on-chip (SoC), Internet of things (IoT) and cloud computing platforms (CCPs). At the edge level of the production lines, sensors, actuators, SoC equipped with WiFi and/or Ethernet are integrated together to transform the existing embedded systems to cyber-physical systems (CPS) [2-3]. The CPS is utilized to manufacture, operate, monitor and control cyber physical products (CPPs) remotely. The CPP consists of physical and virtual space. Physical space is the product mechanical part and the virtual space is the product digital twin that has the product data electronic sheet and dynamic data. Most products will have a unique IP address, identification number, and access code which enables it to be accessed via WiFi or Ethernet from anywhere anytime. It contains the product history from the day of manufacturing to the day of recycling as well as the product dynamic variables status [4].

CPS has many applications nowadays. It can be found in smart healthcare wearable devices, smart grid, smart water networks, smart manufacturing, smart factory, gas and oil pipelines monitoring and control, unmanned aerial and autonomous underwater vehicles, hybrid electrical vehicles and greenhouse control [5].

This review paper is an overview on the CPSs and CPPs along with a five layer conceptual model. Section 2 describes the CPS basic building blocks. Section 3 describes the conceptual model of CPS integrated with storage, process analysis and visualization, and user friendly application interface. The CPPs and digital twin concept are

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explored in section 4. The CPS generated Big Data storage and analytic techniques are highlighted in section 5 followed by conclusion in section 6.

CYBER PHYSICAL SYSTEMS

Cyber physical systems are the upgraded version of embedded systems. As the single chip microcontrollers are evolving, more built-in resources are integrated to it. In late 90's microcontrollers had limited CPU speed, limited number of digital and analog input and output ports, small size program and data memories as well as limited communication capabilities [6]. Early this century, more built-in resources have been integrated into microcontrollers. For example, Microchip Peripheral Interface (PIC) family introduced the reduced instruction sets microcontrollers that have more built in resources, higher speed CPUs, more inputs/outputs peripherals, large size split program and data memories, built-in real-time clock, DSP capabilities as well as wider data bus to handle 32-bit data [7].

These microcontrollers are utilized to build single chip embedded system platforms in smart home appliances, healthcare, factory automations, and other applications. In such systems, sensors gather information from the physical environment, the microcontroller processes the information according to embedded software algorithms and then actuate outputs according to mechanism of the process.

These embedded systems have limited built-in wired communication capabilities to interface sensors and actuators. Recently, new single chip computing platforms that integrate the functionality of a microcontroller and microcomputer on SoC are introduced to the marketplace with much more powerful CPU. These computing platforms have CPUs speed from MHz+ to GHz+, built-in memories and SD Storage from 100s to 1000s MB. In addition to that, the new chips have built-in Bluetooth, Zigbee, WiFi and Ethernet access points. The added built-in access capability allows them to be connected to the cyber space. The cyber space conductivity has transformed the existing embedded systems to cyber physical systems.

CPSs nowadays are the heart of industry 4.0. The CPSs can be defined as "the integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa" [8].

CYBER PHYSICAL SYSTEMS CONCEPTUAL MODEL

The cyber physical system conceptual model consists of five layers: physical, networks, data storage, analytic and application layers. Figure 1 shows the cyber physical system conceptual model.

Physical Layer:

This layer consists of sensors, actuators, tracking devices and computing elements. Real time data collected from the product sensors by the controller, may process locally and/or transmitted to the cloud for further processing. Based on the system embedded process algorithm, an instruction to command actuators may be executed locally or remotely.

Sensors:

The sensors convert digital or analog physical phenomena from the surrounding devices, appliances, and tools into electrical signal. Sensors output signal many not be compatible with the digital and analog input of the controllers. In such case, a signal conditioning circuit must be designed to shift or/and scale the sensor output signal to the signal level that can be read by the controller. However, nowadays many sensors have built-in signal conditioning and logic circuits that convert the sensors signals into serial output. Some sensors have Universal Synchronous Receiver-Transmitter (UART) Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI), and Controller Area Network (CAN) communication protocols. These protocols provide wired communications and interfaces many sensors to the controller using 2-4 wires over a distance from few meters to 100s of meters. In addition to this, tracking devices like GPS and RFID technologies have been utilized for tracking purposes.

Single Chip Computing element (controller):

It collects information from the sensors and tracking devices. Sensors may be interfaced directly with the controller via the built-in digital and analog ports or through wired serial communication ports such RS232, RS485, USB, SPI, I2C, and CAN. The collected data from these sensors is processed locally according to the system under control algorithm. Moreover, the controller actuates the interfaced devices accordingly or transmits the data to storage and process layers in the local server system or the cloud via the network layer. Low price controller like the Raspberry Pi 3 has high speed CPU, many GPIOs, wired communication ports, wireless WiFi and Ethernet communication capabilities as well as Bluetooth. The Raspberry Pi 3 can be configured as a standalone micro server that can be accessed from anywhere and at any time as long as the Internet connectivity is available. Also, it has readymade interface ports to connect camera, LCD, and HDMI devices. Many open source functions are available for such controllers that make it easy to develop CPPs [9]. Its worth mentioning that the raspberry pi can be used as a limited addition of a standalone desktop computer with its own operating system that enable the user to browse the internet, emails, or access other desktop applications such as word processor, powerpoint, and excel .

The Photon is another recent microcontroller that has high speed CPU, many built-in I/O ports, large size of program and data memory, and WiFi for internet connectivity. Physically, it weighs just 5 grams and is the size of a post-stamp. The photon has teamed up with Google Cloud which makes it capable to access and utilize all the Google Cloud platforms for big data storage, analytic and visualization [10]. Another version of the photon is the Particle Electron. The Electron microcontroller has the same features of the Photon except that in Electron the access point to the cloud is done via the built-in GPRS SIM card instead of Wi-Fi. Other microcontrollers can be used as computing elements in the physical layer but they have to be interfaced to the cyber space using some external access points with different communication protocols.

Microchip has introduced the high-end PIC32MZEF 32-bits microcontroller with floating point unit and graphics interface. The 32-bit micro-controller features high number of digital I/O and analog channels as well as a DSP-enhanced core. Through its Ethernet connectivity, it can be utilized as a CPS edge device computing platform. The Microchip is teamed up with Amazon Web Services (AWS) which empowers the controller to access the cloud computing platform resources [11].

Giant chip manufacturer, Intel has introduced the low power consuming Intel Quark D2000 32-bits microcontroller development board. The microcontroller has many digital and analog I/Os, limited memory size, serial communication ports, and add-on Ethernet connectivity. The Intel Quark D2000 microcontroller is a cloud based platform which makes it an attractive edge computing device for CPSs and IoT applications [12].

Table 1 shows the characteristics of selected recent single chip edge computing device for CPS.

Table 1. Recent CPS Single Chip Edge Computing Device Comparison.

Controller	Raspberry Pi 3 [9]	Particle Photon [10]	Microchip DM990004 [11]	Intel Quark D2000 [12]
CPU Core	Broadcom BCM2837 64-bits	STM32F205with ARM Cortex M3	PIC32MZ2064DAH176	Quark D2000 with x86 Pentium® processor
Speed	1.2GHz	120 MHz	200 MHz	32 MHz
RAM	1GB	128 KB	32640 KB	8 KB SRAM
SD Card	Up to 32 GB	Add-On	Add-On	Add-On
Networking	Ethernet, Wireless	Ethernet Add-On, Wireless	Ethernet	Add-On
Bluetooth	Built-in	Add-On	Add-On	Add-On
GPIO	26	Up to 15	Up to 120	25
ADC	Add-On	7	Up to 45	19
Real Time Clock	Cloud-based	Cloud-based	Built-in	Built-in
Communication	RS232, I2C, SPI, CAN Add-On	RS232, I2C, SPI, CAN	RS232, I2C, SPI, CAN	RS232, I2C, SPI
Could Connectivity	Can be turned into a personal cloud	Google Cloud based	Amazon cloud based	Wind river cloud based
Price	35 USD	19 USD	99 USD	15 USD

Actuators:

In a CPS physical layer, actuators play very important role. Based on the application process algorithm, the microcontroller commands actuators to change the status of the system under test or production. Microcontrollers provide the control signal to the actuator. The control signal could be a digital or analog output with limited voltage level up to 5 volts and driving current up to 25 mAmps. Based on the application, driver circuit such as power amplifiers and relays should be used between the microntroller output and the actuating device to provide higher voltage and current whenever required.

Network Layer:

The CPSs and CPPs can access the cyber space with different networking protocols such as WiFi, WiMAX, GPRS and 3G/4G/LTE technology. Other lightweight IoT message oriented data protocols such as MQTT, CoAP, AMQP, Websocket, and Node are used to transfer data from edge devices to the cloud for further storage and processing. Each protocol has its own advantages over others according to speed, latency, bandwidth, reliability, security, and scalability. The most common and useful CPS communication protocols are listed in table 2 based on their standard name, main characteristics, data rate, and transmission range. These protocols are utilized in many CPS applications such as medical cyber-physical systems, smart buildings, smart water networks, self-driving car, manufacturing control, hydropower plant and monitoring, wind power plant, and greenhouse efficient control. More details about these protocols can be found in reference [5].

Table 2. CPS Communication Protocols Main Characteristics, Data Rate, Transmission Range.

Protocol	Main Characteristics	Data Rate	Transmission Range
UART	Low power requirement, wired	20Kbpts-20Mbps	Up to 1000m
SPI	Low power requirement, wired	20Mbpts	Up to 100m
I2C	low power requirement	100kbps-3.4 Mbps	Few meters
CAN	Many wired devices	Up to 1Mbps	Up to 40m
Zigbee	Energy saving, very short range	20 Kbps to 250 Kbps	10 to 20m
Bluetooth	Cable replacement	1 Mbps	10 to 100m
Wireless Access Points (Routers)	Data Networking, Local Area Network	6-54 Mbps	120m outdoors
Wireless LAN	Data Networking, Local Area	1- 11 Mbps	140m outdoors
Wi-Fi	Data Networking, Local Area Network	6- 54 Mbps	140m outdoors
Antennas	Data Networking, Local Area Network	15-150 Mbps	250m outdoors
WiMAX	Metropolitan Area Network	2 to 75 Mbps)	Up to 35 miles (56 Km
Cellular 3G	Wide Area Network Connectivity. Digital, packet switched for data	144 Kbps (mobile) to 42 Mbps (stationary)	Few KMs
Cellular 4G/LTE	Same as 3G	300 Mbps to 1 Gbps	Several KMs
Satellite	Wide Area Network	10 Mbps (upload) and 1 Gbps (download)	Satellite can cover 100's of Km's to entire earth

Storage Layer:

CPS systems collect a lot of data from the objects that are located in the physical layer. This data may be stored in a local server or in the cloud. Data is stored in three slave node machines in blocks of 64 or 128MB. Utilizing some file distributed storage systems like Hadoop, data can be stored in cluster of three different slave machines for redundancy purpose.

Processing and Analytic Layer:

Processing and analytic layer is used to process the data using simulation models such as map reduce and dimensional modeling algorithms. Using SQL queries, reports, graphs and dashboard visualization can be generated for near real-time monitoring purposes. Data mining techniques such as data clustering, classification, and regression may be used to monetize the data for predictive maintenance, spot pricing and planning. In this layer, also the monitoring and control actions can be transmitted back to the physical layer in order to actuate some devices and machines.

Application Layer:

This layer is the user interface for consumers, operators, manufactures, third party suppliers, and other service providers. The applications could be in smart grid, smart factory, smart building, smart transportation, and smart healthcare. It has a user friendly interface access in which the above mentioned stakeholders can interact with the CPS layers based on privileged access and priority.

Figure 1 shows the CPS five layers conceptual model as described above.

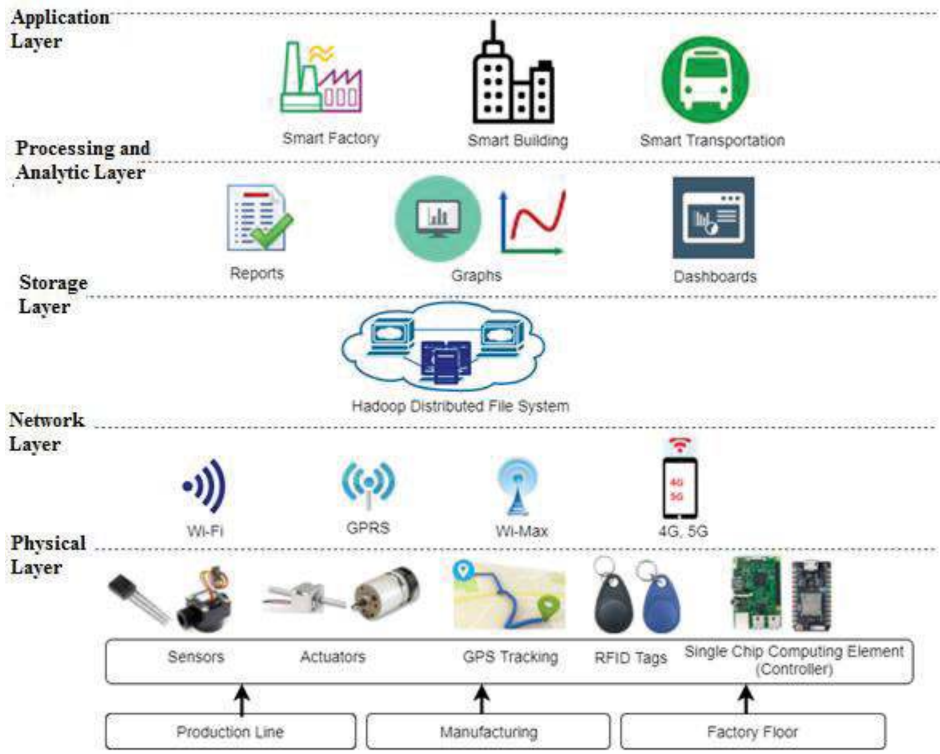

Figure 1. Cyber Physical System Conceptual Model

CYBER PHYSICAL PRODUCT AND DIGITAL TWIN CONCEPT

The cyber physical product (CPP) has two parts namely; the mechanical part and the virtual part. The mechanical part is the actual physical system that is manufactured to perform a function such as automobile transmission, airbag, ABS system, smart energy meter, and traffic light controller. The products are equipped with single chip microcontroller that is embedded within the product. The controller has some sensors, actuators, unique address and access code. It can be accessed remotely from anywhere any time to monitor, control, and track the product from the day of manufacturing to the day of recycling [4]. The virtual part is the digital twin. It is a tiny microcontroller that is attached to the product. It collects the location and the dynamic status of the product to enable the manufacturers to track products location and their health status for better performance and productive maintenance.

ROLE OF IOT, BIG DATA, AND CLOUD COMPUTING IN CPS

A holistic development of a CPS can be achieved by integrating it with other complementary technologies such as Internet of Things, cloud computing, and big data techniques to build a more efficient and robust CPS. The concept of IoT ensures interoperability between CPS units to provide a large ubiquitous platform for industrial automation. Each CPS in a IoT platform is functioned to control and monitor real-world physical infrastructures. Thus, the data generated from CPS is very large in its volume with high frequency and multiple varieties. This data called, Big Data, has distinct 3V characteristics; Volume, Velocity, and Variety. Volume refers to the large amount of data in Petabyets and Terrabytes. Velocity corresponds to the data rate or frequency at which data is generated and collected in real time. Variety of the Big Data is the different formats in which the data is generated. Big data techniques can provide large scale data analytics for data monitoring and visualization in near real time. Cloud computing offers storage of large volume of data and processing it with complex computational algorithms in cloud with lower latency [13].

CONCLUSION

The paper presented an overview of the cyber physical systems, cyber physical products, and digital twins. The conceptual model of a cyber-physical system was presented. Digital twins' concept were introduced along with their role in the cyber physical product. The role of cyber physical systems and digital twin were introduced along with some applications. It is worth mentioning that the cyber security issues of the CPS and CPP is a major concern and it was not discussed in this paper. The authors are in the process of reviewing and developing security solutions for such new evolving technology.

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