An event-oriented real-time architecture for cyber-physical systems

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Received 1 June 2014, www.cmnt.lv

Abstract

Cyber-Physical System (CPS) is an exciting emerging cross-over research area that faces many challenges. A CPS is a distributed and deeply embedded real-time system, which involves sensing, computation, communication, and control through heterogeneous and widely distributed physical devices and computational components. This paper extends our previous proposed CPS architecture and presents an event-oriented real-time architecture (EORTA) for CPS. CPS event is defined in words and formal method respectively. A CPS event is uniformly represented by a seven-tuples. According to the methods generating CPS Events, they are divided into *Physical Event*, *Synthetized Event*, *Fused Event* and *Combined Event*. Not only is EORTA characteristic of time-space, but also it can support the real-time QoS (Quality of Service) for CPS, which will meet the intrinsic real-time requirements of CPS.

Keywords: event-oriented, real-time architecture, cyber-physical systems

1 Introduction

CPS is an exciting emerging cross-over research area that has drawn the attention of many researchers. A CPS was defined as integrations of computation with physical processes in [1]. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. In [2], a CPS is described as physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core. CPS is integrations of computation, communication, and control with the physical world [3]. In essence, CPS is a distributed and deeply embedded real-time system, which involves sensing, computation, communication, and control through heterogeneous and widely distributed physical devices and computational components. Such systems bridge the cyber-world of computing and communications with the physical world. CPS is built-in intelligent computer/communications technology, which promises to enhance efficiency while simplifying daily life. CPS will transform how we interact with the physical world just like the Internet transformed how we interact with one another. CPS has extensive application prospect. They include high confidence medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, process control, energy conservation, environmental control, avionics, instrumentation, critical infrastructure control (electric power, water resources, and communications systems for example), distributed robotics (telepresence, telemedicine), defence systems, manufacturing, and smart structures, and so on.

Although the question of "What is a CPS?" remains open, widely recognized and accepted attributes of a CPS include real-time, distributed, reliability, fault-tolerance, security, scalability, autonomous, and so on. Hereinto, "Real-time" is one of the most important properties of a CPS. For example, a deadline (i.e., a real-time QoS requirement) on a control-loop in a CPS indicates that when an event of interest occurs in the physical world: firstly, it has to be sensed and detected by certain CPS components in the cyber world. Secondly, appropriate actuation decisions should be taken by distributed system components, and lastly, an actuation task needs to be carried out by an actuator in the physical world, all within a limited time frame. Computing and networking technologies today, however, may unnecessarily impede progress towards these applications in CPS. For example, the lack of temporal semantics and adequate concurrency models in computing and today's "best effort" networking technologies make predictable and reliable real-time performance difficult.

This paper focuses on CPS architecture in terms of real-time. The main contributions of the paper are twofold. First, a unified event structure that represents CPS event instance at different layers is defined. Accordingly, a CPS event instance consists of seven components and has real-time QoS level. In addition, according to the methods generating CPS Events, they are divided into Physical Event, Synthetized Event, Fused Event and Combined Event. Second, a real-time CPS architecture is proposed, which is called EORTA and oriented event. Not only is EORTA characteristic of time-space, but also it can support the real-time QoS.

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The rest of the paper is organized as follows: In Section 2, recent work on event and architecture in CPS are reviewed. The event-oriented cyber-physical system real-time architecture and its components are described in Section 3. In Section 4, definitions of event and event types are given. We conclude the paper and point out future work in Section 5.

2 Related Work

A CPS is envisioned to be a heterogeneous system of systems, which consists of computing devices and embedded systems including distributed sensors and actuators. These components are inter-connected together in a large-scale and execute autonomous tasks to link the cyber world and the physical world. Generally, these tasks involve close-interactions between the two worlds and a certain change in one world should be reflected in the other world in a time-sensitive and/or spatial-sensitive manner. On the other hand, CPS applications and users may not be interested in every change in the physical world. Instead, certain conditions are of interest, according to which certain predefined operations are executed by the CPS. These interested changes can be called events. Naturally, the close interactions between the cyber world and the physical world can be addressed through an event-based approach, i.e., using events as the units in CPS for computation, communication, and control [4].

In [5], a CPS definition was given and prototype architecture was proposed. The authors in [6] extended their previous work in [5], and introduced a spatio-temporal event model to capture the close interactions between the physical and cyber worlds in CPSs. More specifically, a hierarchical CPS architecture and the hardware components were defined. Accordingly, the event model relied on a hierarchical layered structure, which extended the event spatio-temporal relations to capture the complex relationships in CPSs. A concept-lattice -based event model [7] for CPS was introduced in [8]. Under this model, a CPS event was uniformly represented by three components: event type, its internal attributes, and its external attributes. The internal and external attributes together characterized the type, spatio-temporal properties of the event as well as the components that observed it. A set of event composition rules were defined where the CPS event composition was based on a CPS concept lattice. These works were all based on event model with spatio-temporal features, but lack of enough real-time support.

The authors in [9] proposed a five-layer Web-of-Things (WoT) framework for CPS based on the requirements of distributed CPS architecture. The framework consisted of five layers: WoT Device, WoT Kernel, WoT Overlay, WoT Context, and WoT API. Underneath the WoT framework was the cyber–physical interface (e.g. sensors, actuators, cameras) that interacted with the surrounding physical environment. The cyber–physical interface was an integral part of the CPS that produced a large amount of data. The proposed WoT framework allowed the cyber world to observe, analyze, understand, and control the physical world. The authors used the WoT framework to process event streams in the CPS Fabric, and they augmented the OSGi [10] component framework to deal with real-time physical events at each CPS node. In WoT framework, an event was not an interested change of a physical object but a snapshot of the current state of a physical device in CPS. There is a corresponding event for each device’s state, which will bring about huge event data stream and event processing cost for large-scale CPS. Accordingly, this will influence on real-time performance. The OSGi-based service architecture for Cyber-Physical Home Control Systems was proposed in [11], which supported service-oriented control methods and contained three layers: the Physical Layer, the Service Layer and the Application Layer. Users could control appliances in the physical environment by intuitive operation through a virtual home on the network. However, the architecture was not based on the general event concept, and it could not provide real-time QoS support.

In short, CPS as an emerging concept introduces new challenges in system design and an event-based approach is necessary for the realization of CPS [12]. Not only is the information carried in CPS events far richer than the existing systems (e.g., the spatio-temporal information), but it must support the QoS for CPS, especially the real-time QoS.

3 CPS real-time architecture

In this section, we extend our previous work in [13] to an event-oriented real-time CPS architecture (shown in Figure 1), where the following components are considered:

Sensor network: The sensor network consists of a number of sensor nodes and some sink nodes. Sensor node is responsible to sample some properties of the monitored physical object, such as the environmental temperature and humidity, the patient’s blood pressure, sphygmus, blood oxygen content, body temperature, and so on. If the sampling of some property exceeds a certain limit, a *PE* (*physical event*, See Section 4) will be generated in the node. Multiple *PEs* can combine into one event called *CE* (*combined event*, See Section 4), if they meet the predefined conditions. If the samplings of multiple properties match the predefined conditions which are related to the application, a *SE* (*synthetized event*, See Section 4) will be generated. In the sink node, the same property or event from different sensor nodes can fuse and form a property or event *FE* (*fusion event*, See Section 4). The different events from different sensor nodes can also combine into one CE, if possible. The sink node is also responsible for publishing the received or generated events to the information centre to store as history or to the control centre to process further. In addition, sink node retransmits the sensing command from control center to sensor node.

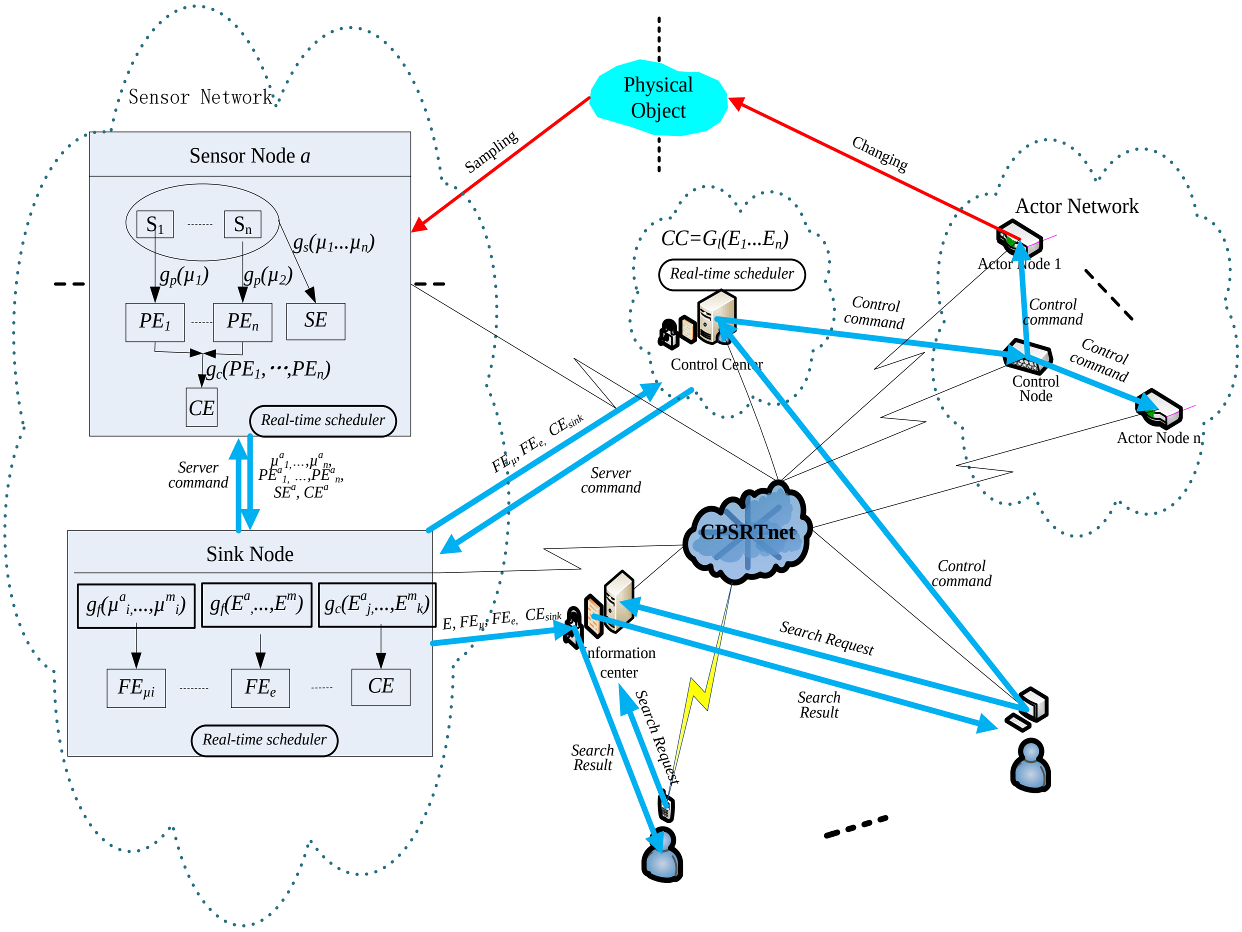

FIGURE 1 Architecture of Cyber-Physical Systems

Information centre: The information centre (i.e. the database server) is a distributed data logging service for the events and primitive sampling data which are automatically transferred from sink nodes to the center after a certain time for later retrieval.

Control centre: The control centre (i.e. the control server) is responsible to analyze and process the events from sensor network, and generate the *CC* (Control Command) according to the predefined control logic. The control commands can be directly published to the control center by the users. The control commands are transferred to actor network to execute.

Actor network: The actor network consists of control node and actor nodes. The control node is responsible to distribute the control commands from the control center to the corresponding actor node to execute for changing the property of the monitored physical object.

User terminal: The user terminals include cell phones, notebooks, desktop computers and some special terminal equipment, which are the interfaces between the user and CPS system. The user can publish query requests and control commands to CPS system through the user terminals.

CPSRTnet: The CPSTRnet is the real-time network which connects all the components of CPS. It provides the real-time transmission service for CPS and guarantees the real-time QoS in the network.

4 CPS event concept

In this section, we introduce the CPS event related concepts. In general, the term “event” has been used in two distinct contexts in the literature. The first relates to the physical world occurrences while the second involves representations of those occurrences in a computer system. However, either of the two “event”s cannot be transformed from one to another directly. In this section, the general definitions of an event are provided in word and formal method respectively. Moreover, the properties of different events and their classifications are discussed. Since temporal and spatial properties of an event are essential in CPSs, we first introduce the time and spatial models next.

Time Model: In a digital system, the notation of time is always discrete and has limited precision. Therefore, time is also considered as discrete collection of time points in our time model.

Spatial Model: Because the real world is in a 3-dimensional space and CPS is closely related to the real world. The spatial model we use in this paper is a standard 3-dimensional Cartesian coordinate system, in which a rectangular coordinates (x, y, z) indicates a specific location point and a function z = f(x, y) indicates a specific location field in three-dimensional space.

4.1 CPS EVENT DEFINITION

Definition 1 CPS Event $\boldsymbol{\delta}_{cps}$: it is a phenomenon that one or more properties of the monitored physical object exceed the certain limit.

Definition 2 CPS Real-time Event: it is a CPS event with real-time QoS requirement. That is to say, when a CPS real-time event is detected, it must be processed within the limited time, and the monitored object must be controlled efficiently in time. "Real-time" is an essential feature of CPS, so the CPS event refers to the CPS real-time event in this paper.

4.2 CPS EVENT MODEL

A CPS event is uniformly represented by a seven-tuples, which is as follows:

$\boldsymbol{\delta}_{cps}(\rho, \tau, \ell, \text{finder}, \text{sn}, \text{category}, QoS^{\varepsilon}_{rt})$,

where ρ is a set of properties which belong to the monitored physical object and are related to the event. τ is the event occurrence time. ℓ denotes the event occurrence location, finder is the monitor node which finds the event. sn denotes the event serial number which is generated by the finder, category represents the event type, for example, in intelligent medical CPS, low fever, medium fever, high fever, super high fever, and so on. The category has physical significance and can reflect the event's intrinsic conditions. Given a CPS and an application, the available types of sensors and the associated events that can be generated by these sensors can be determined, so the category of CPS event can be determined. QoS^{ε}_{rt} is the event's real-time QoS level which contains the time-critical information, such as priority and the deadline, etc.

According to the occurrence time, an event can be further classified as a *Punctual Event* or *Interval Event*. The event occurrence time τ is expressed as $[t_1, t_2]$, if $t_1= t_2$, the event is a *Punctual Event*, if $t_1< t_2$, the event is an *Interval Event*.

According to the occurrence location, an event can be further classified as a *Point Event* or *Field Event*. The event occurrence location ℓ is expressed as $[point_1, point_2]$, if $point_1= point_2$, the event is a *Point Event*, if $point_1 \neq point_2$, the event is a *Field Event*.

4.3 EVENT CLASSIFICATION

According to the methods generating CPS Events, they are divided into *Physical Event*, *Synthetized Event*, *Fused Event* and *Combined Event*.

Definition 3 *Physical Event*: is the CPS event which is caused by a single property. This type event is generated only by sensor node.

Definition 4 *Synthetized Event*: is the CPS event which is caused by multiple properties of the monitored object. This type event is also generated only by sensor node.

Definition 5 *Fused Event*: is further classified as property fused event and event fused event. The former is the CPS event which is caused by fusing the samplings of the same property from multiple sensor nodes. The latter is caused by fusing the same events generated by multiple sensor nodes. This type event is generated only by sink node.

Definition 6 *Combined Event*: is the CPS event which is caused by combining multiple different CPS events. This type event can be generated by sensor node or sink node.

5 Conclusions

This paper extends our previous research and presents an event-oriented real-time architecture for CPS. The definition of CPS event is given in words and formal method respectively. A CPS event is uniformly represented by a seven-tuples. According to the methods generating CPS Events, they are classified into *Physical Event*, *Synthetized Event*, *Fused Event* and *Combined Event*. Not only is the architecture characteristic of time-space, but also it can support the real-time QoS for CPS, which will meet the intrinsic real-time requirements of CPS. The proposed real-time architecture lays the foundations for further research and development in CPS. However, in this paper, we have not abstracted the CPS event conditions and their generation functions which are important for realization of CPS and closely related to the special application. In the future, we will model the CPS event conditions and their generation functions, and test and verify the whole CPS model through the case study: Intelligent Medical Systems.

Acknowledgments

This work was supported in part by NSFC under Grant No. 61364023 and No. 61162002, Aeronautical Science Foundation of China under Grant No. 2013ZD56008 and Science and Technology Project in Jiangxi Province Department of Education under Grant No. GJJ13516.

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