Domain Model for Cyber-Physical Systems

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Abstract

Cyber Physical systems refer to new class of systems that features the integration of computation, communications and control technologies. The processing elements coordinate and communicate with sensors and actuators to monitor and affect the entities in the physical world. In this paper, we propose a domain model for CPS that tries to bring a clear terminology, by providing a common lexicon and taxonomy of the CPS domain. This model describes the most important concepts in regards to the CPS and the relationship between these concepts, in order is defining a modeling language aims at providing a means of communications between stakeholders in the engineering process.

Keywords: Cyber-physical systems, Domain model, heterogeneous systems.

1 Introduction

During the recent decades, the rapid advances in digital computing and communication technologies, has led the development of advanced sensors, data acquisition system, wireless communication devices and distributed computing solutions. Such technologies are integrated into a new system called Cyber-physical System (CPS), a harmony of physical dynamical systems with the cyberspace.

Cyber-physical systems (CPS) have gained a lot of attention in recent years and are considered as an emerging technology [Haq14]. They are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core [Raj10]. This integration of computation with physical processes in CPS is about intersection, not the union of the physical and the cyber [Lee17]. Currently, a precursor generation of CPS can be found in areas as diverse as aerospace, manufacturing, civil infrastructure, chemical processes, healthcare, energy, transportation, and automotive.

Designing cyber-physical systems is a challenge originating from the multidisciplinary and heterogeneous nature of integrated components, networks and types of processed data. In addition to the use of more advanced technologies for sensors and actuators, and wireless communication, which make CPS applications harder to model, harder to design, and harder to analyze than homogeneous systems[Lee17]. Consequently, a suitable application development abstraction is required to enable experts from various domains to specify CPS applications in their fields, and define with ease the rich interactions between the large numbers of dissimilar devices. This will be accomplished by establishing a common grounding and a common language for CPS architectures and CPS systems. The first step towards this at that point is to construct a suitable description logic that provides a common lexicon and taxonomy of the CPS domain, and also to allow scientific discourse among researchers, system programmers, as well as non- technical stakeholders.

The main purpose of this research is to propose a domain model for CPS to generate a common understanding of the components and concepts that constitute them, and to expose the CPS specific functionalities to domain experts. This model includes a definition of the main abstract concepts, their responsibilities and their relationships, on which CPS architectures can be built.

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The goal of this paper is to define a modeling language aims at providing a means of communications between stakeholders in the enginnering process.

Besides the reasons mentioned above, a domain model enables modularity in design, which the system can be divided into subsystems that can be created independently. Thus, it helps in development process, since the functions of each component are well-known.

The paper is organized as follows. Section 2 provides an overview of cyber-physical system, includes its definitions and principals' characteristics. Section 3 presents our main contribution which consists of domain model that describes the concepts relevant of cyber-physical systems. Finally, section 4 concludes this paper and provides insight for future work.

2 General Overview of CPS

This section gives an overview of CPS systems. We present key concepts and components, as well as the characteristics of CPS.

2.1 Definitions

CPS was identified as a key research area in 2008 by the National Science Foundation (NSF) of the United States and was ranked as the number one research priority by the Council of Advisers on Science and Technology [Lee14].

What is CPS? - The term cyber-physical systems (CPS) can be viewed as a new generation of systems with tight combination between computational and physical capabilities that can interact with humans through many new modalities [Bah11].

The term CPS also refers to distributed heterogeneous systems that conducts feedback control on widely distributed embedded computing systems with organic integration and in-depth collaboration of computation, communications and control technology (see Figure 1),subject to the theory and technology of existing network systems and physical systems [Liu17].

Also a complex CPSs definition was provided by Shankar Sastry from University of California, Berkeley in 2008: “A cyber-physical system (CPS) integrates computing, communication and storage capabilities with monitoring and/or control of entities in the physical world, and must do so dependably, safely, securely, efficiently and real-time”.

Some other propose that represents a congruence of technologies in embedded systems, distributed systems, dependable systems, and real-time systems with advances in energy-efficient networking, microcontrollers, sensors and actuators [Raj10].

Cyber-physical systems link between cyber and physical worlds. The cyber components coordinate and communicate to affect the physical processes usually with feedback loops where physical processes affect computations and vice versa [Lee17].

The coordination between cybernetic world and physical world by connecting with human through computation, communication and control is a key factor for future technological developments that changes future computational facilities in all areas including business, science, defense, and healthcare with unprecedented capabilities [Bah11].

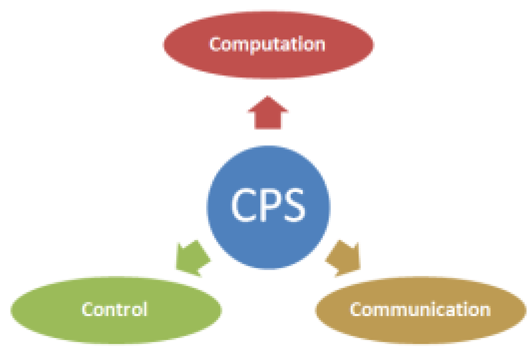

Figure 1: CPS capabilities

What is not CPS?- A CPS is not the computer in general (*PC*), traditional embedded system, and also not networked control systems (*NCS*). CPS can be regarded as networked embedded systems.

Wireless sensor network (*WSN*), internet of things (*IoT)* are different from CPS.

IoT is generally considered as interconnecting internet information sensing devices like wireless sensor and radio frequency through hierarchical communication infrastructure, while CPS stress the cooperation between physical procedures and computational elements.

WSN is a network formed by a large number of sensor nodes which collaborate together using ad hoc network technologies to achieve a well-defined purpose of supervision of some area, some physical process, etc.

Rather than focusing on the identification of entity, WSN just senses the signal, and not necessarily distinguishes the particular one from numerous entities being sensed. It underscores the perception of information using data collection, processing and routing functionalities. CPS not just has the capacity of sensing the physical world, yet in addition has solid capacity to control. Its computational capacity requirement for computing devices far exceeded that of IOT and WSN [6].

CPS forms a new type of system which deeply integrates the ability of computing, communication and control. In other terms, CPS is a method of understanding and designing real world. [Gua16]

CPS Examples- CPSs range from tiny systems such as pacemaker: which is a small electronic system that can sense physiological data to assist monitor and control the heart in maintaining regular rhythm, to large-scale systems such as power grid: an electricity supply network which includes computer intelligence and networking abilities to control the production and distribution of electricity.

2.2 Characteristics

Since CPSs are characterized by a large number of variables, many scientific papers have attempted to define the characteristics of these systems. We propose in the following a classification of their characteristics according to certain criteria, and based on the works of: [Liu17], [Raw14], [Raj10], [Kim12] and [Haq14].

•*Hybrid:* CPS collects the information of physical world (continuous variable) and transmits that information to virtual worlds (discrete event), where information is processed and sent back to the physical world. Hybrid system refers to those systems that explicitly and simultaneously involve continuous variables and discrete events and have mutual influence and interaction. Therefore the hybrid system is a foundation of CPS.

•*Heterogeneous:* The components of a cyber-physical system are of various types consisting of computing devices, interfaces, distributed sensors and actuators, and requiring interfacing and interoperability across multiple platforms and different models of computation.

•*Dynamic:* The environment of the CPS evolves continually and thus the design and operations of the system must account for such dynamic changes in the environment.

•*Networked:* cyber-physical systems components are typically networked at multiple and extreme scale. The advanced connectivity is needed for various subsystems to coordinate with each other and to ensure real-time data acquisition from the physical world and information feedback from the cyber space.

•*Autonomy:* CPS can provide high degrees of automation, and the control loops must close. Typically, CPS is a closed loop system, where sensors make measurements of physical dynamics. These measurements are processed in the cyber subsystems, which then drive actuators and applications that affect the physical processes.

3 The CPS Domain Model

The general idea of a CPS is to collect sensory data (measuring properties of the physical world) from a variety of sources, convert it to information in the cybernetic world, process it, understand it, and then notify the physical systems about the findings, and sometimes send control commands to make appropriate actions back in the physical world or reconfigure system parameters if required [Sim15] and [Ala17] (see figure 2).

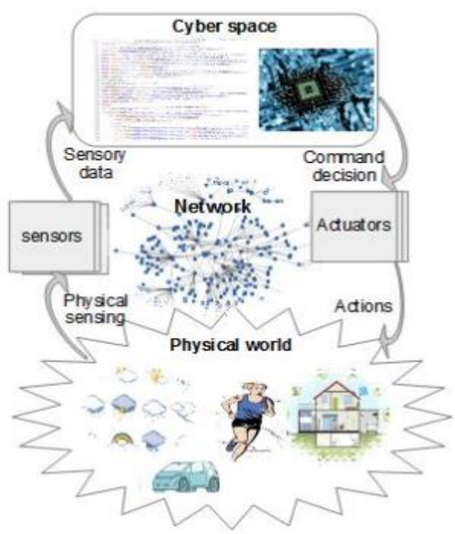

Figure 2. Structure of CPS.

Inspired by some models [Ala17] and [Pat11] that have been proposed in the closely related fields of

Internet of things, wireless sensors networks and software engineering in general, we have extracted the concepts and associations that we believe are suitable for representing applications in the field of CPS. These concepts are a refinement of the most relevant concepts found on comprehensive overviews of recently research publications and CPS applications from the real world [Ala17], [Tan08] and [Raj14].

In this section, we present our domain model for CPS as shown in figure 3. The model is described using a UML class diagram [OMG14]. This last illustrates the entities of the CPS domain model involved, as well as the interactions between domain concepts, including cardinalities of such relationships. The remainder of this section is dedicated to the description of the four main aspects of the model and the interfaces between these aspects.

3.1 The main abstract concepts and relationships

By applying separation of concerns design principal, we divide the CPS concepts into five major parts.

Physical part:

As the CPS pertains to the physical world, the characteristics of the physical world play an important role. It concerns the concepts related to the real world.

- *Physical process*- is the observable phenomenon that consists of a set of physical properties of the associated *Physical Entity*. The temperature of a room is an example of a physical process.
- *Physical Entity*- is an identifiable element of the physical environment that is of interest to the user for the completion of her goal. For instance it can be any object or environment that the CPS senses and acts on, such as rooms, cars, animals, humans, book, electronic appliances, jewellery or clothes, etc.

  The Physical Entity consists of the physical processes which represent properties that describe it. Furthermore, the entity of the physical world has a context representing the location where is situated. Locations of the entities are useful in almost every application and as a result are included as well. the Device would be modelled as an entity itself, with regard to specific application, whose principle issue is the devices and not the physical entity. For instance device management is used for managing or configuring the physical devices, ports and interfaces of a computer or server.
- *Human*- might be a part of the physical part, since the human could be considered as a physical entity that the CPS is sensing and acting on. Health monitoring is a decent case of this.

Cyber-Physical part:

From CPS domain model point of view, Cyber-Physical part includes components that provide an interface between the physical and cybernetic world. It converts data and information collected from the physical world into digital data for use in the cybernetic world. It includes transducers that can be sensor or actuator and user interfaces.

- *Sensor*- defines the set of possible sensing devices usable to sense the physical entity. Sensors provide information, knowledge, or data about the physical properties of the physical entity and generate a d igital representation of the measurement corresponding to physical process. Thermometer and accelerometer are examples of sensors.
- *Actuator*- defines the set of possible actuating devices usable to effect a change in the physical world by triggering actions (e.g. rotate, switch on /off, translate…) based on output from processing in the cybernetic world. Heating or cooling elements, speakers, lights are examples of actuators.
- *User interface*- defines a set of tasks designed to help a user to interact with physical entities by means of a given CPS application. For various purposes such as:
  - gaining information- The physical entities are observed by sensors, and then the observed information is sent; such as providing information about electricity consumption or receiving a fire notification in case of emergency to remote users.
  - Controlling actuators- A user through user interface can control an actuator by triggering a command (e.g., switch off the heater / controlling a heater according to a temperature preference).

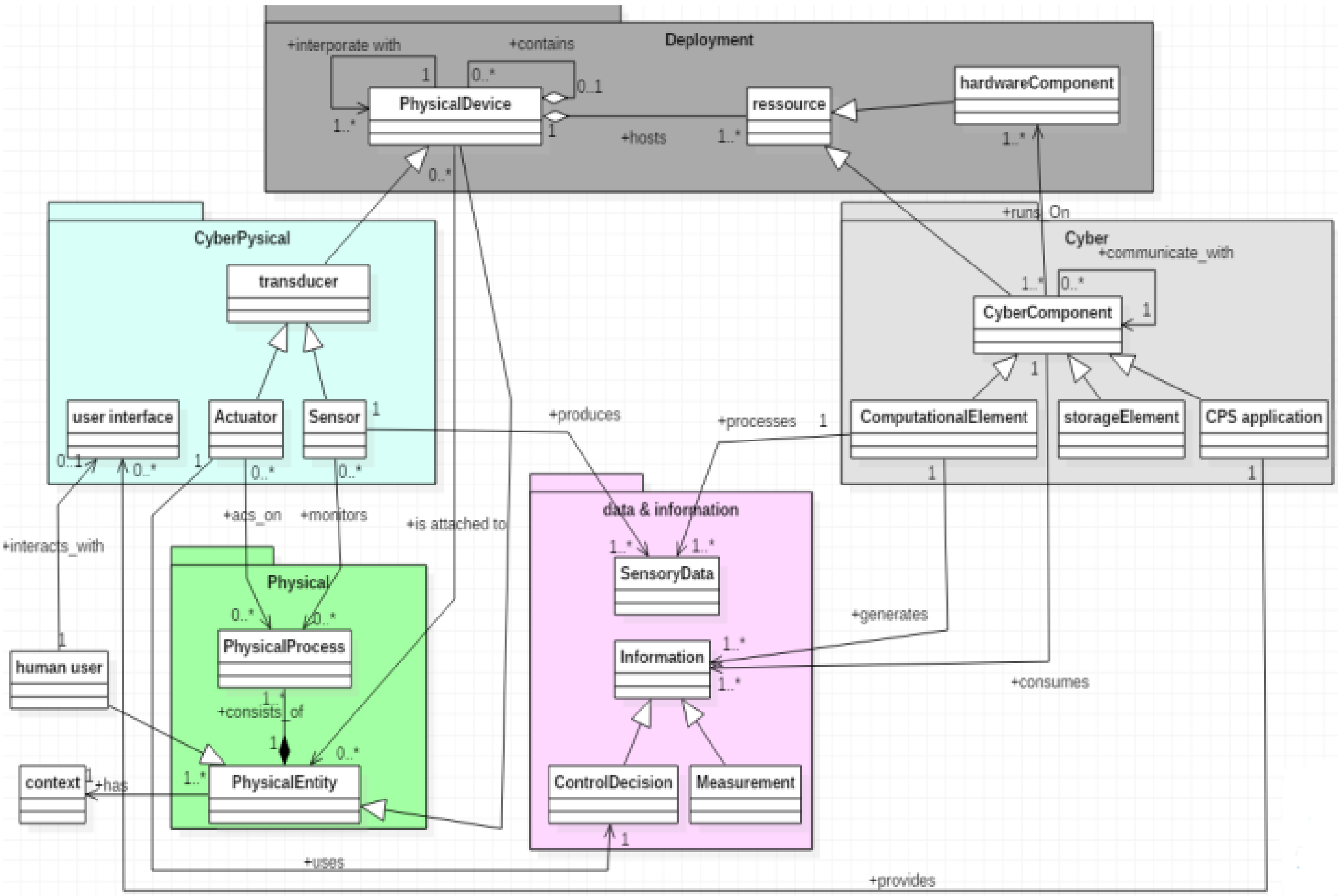

Figure 3. UML representation of the CPS Domain Model.

Cybernetic part:

The cybernetic part includes executable code for accessing, processing, and storing sensor information and produce new information, as well a code for controlling actuators. It comprises computational elements and storage elements.

- *Computational element*- takes input from sensor or non-sensor data sources (for example, other processors and datastores), and processes it according to a defined algorithm, and generates an output. An output could be information message representing the measurement corresponding to physical process that is used by others or fed directly to a data stored service or a control decision that triggers an action of an actuator.
- *Storage element*- provides access to a datastores for storing and managing a collection of data related to the monitored physical entities.
- *CPS application*- is an end-user application. It is a type of cyber component, consists of computational services that is designed to assist a user to perform tasks by interacting with other cyber components.

Cyber components communicate with each other in a well-known and consistent manner to exchange data and control to reach a common goal.

Data & Information part:

Information services allow querying, changing and adding information about the physical entity in question. There are two types of information:

- *Sensory Data*- Sensors collects the *data* of physical world which cyber components consume as inputs. They are described by a set of attributes as well as equations and constraints between the attributes (called invariants) to define the laws of physics describing the inputs,
- *Information*- They are the physical outputs which are generated by the computational elements in order to provide a meaningful representation of the Physical Entity. These outputs could be the *Measurement* which is characterized by a set of attributes to measure the physical process corresponding to the physical entity or the *control decision* used by the actuator to trigger an action so as to affect the physical entity. The *information* also can be *used* by other cyber components to perform other tasks or to be stored.

Deployment part:

The concepts that fall into this part describe information about devices.

- *Physical Device*- is a technical component which is a combination of hardware and software forming a usable computing system that performs some kind of computation and exposes some intelligence. It provides the ability of interacting with other devices and with the external environment. Mobile phones and smart watch are examples of devices. A physical device hosts a number of *resources* and is connected to a network of other computer controlled physical devices. It can be aggregations of several Devices of different types.

The devices can be attached to or embedded in the entities themselves – thus creating smart things. A good example for that is healthcare monitoring. *Resource*- It is any digital or hardware components connected to a physical device. It comprises cyber components that offer information about the things (identifier, sensed, data), and they may provide actuation capabilities as well, and hardware elements which must have at any rate some level of communication, computation and storage abilities for the purposes of the CPS.

4 Disccussions

Based on the definition of cyber-physical systems we extracted commonalities and created a CPS Domain model applicable to cyber-physical systems. We cite the following benefits of our domain model:

Generality: The CPS Domain Model is independent of specific technologies. It defines the language, the concepts, and the entities of the CPS world and how they are related to each other, which do not change from one application to other and thus, introduced the foundation of CPS which often serves as a base of knowledge about a specific application in this broad domain.

Modularity: Development of CPS is a sophisticated activity which requires a multidisciplined approach where knowledge from multiple concerns intersects, since varied set of skills are required during the process. By applying separation of concerns design principle we have divided the concepts and the associations among them into different parts each part addresses a separate concern, which is matched with a precise stakeholder according to skills. The special value of this separation is to allow stakeholders to developed and updated independently.

In order to support the development of CPS based on CPS domain model a development methodology can be proposed. It comprises three steps. At first, the System Requirements must be gathered, analyzed, and afterward used to instantiate the CPS Domain Model, along these lines getting CPS Domain Model of the particular system that has to be implemented. In the conceptual high-level model a representation of the high-level features, at cyber, physical, cyber-physical, deployment and information concern, are acquired. . Each concern is matched with a precise stakeholder according to skills and abilities. The obtained model can be iteratively refined in order to move from a conceptual high-level model to a more detailed one.

5 Conclusion

A cyber-physical system is a system in which computational elements work together to control and command physical entities.

This type of system will certainly transform the way humans interact with and control the physical world, and w ill play an important role in the design of future engineering systems with more powerful capabilities than today's counterpart. However, much research remains to be done to address complexity and productivity issues in the design and development of CPSs.

Inspired by closed domains (Internet of Things and wireless sensor networks) and comprehensive overviews of recently research publications and CPS applications from the real world, we have provided a domain model for CPSs through an UML class diagram. The use of such standard language makes the domain model understandable to a large audience.

Indeed, we have highlighted some concepts and relationships that seem relevant for these systems. These abstractions are independent from any particular technologies, thus the concepts and relationships do not vary from one application to other.

Our work will serve as a common basis and common language for CPS architectures and systems, and will reduce some barriers in scientific discourse regarding these systems by providing a means of communications between stakeholders in the enginnering process.

By applying separation of concerns, we have divided CPS domain model into four aspects. The major advantage of this separation is that, it enables modularity in design, since the capabilities of each aspect are well- known. This can also be seen as a first step towards developing a suitable programming abstraction.

Our future work intends to finalize the model by adding more details, such as attributes and behaviors, and including information about runtime platform components (such as processor and memory). In addition, our model can be improved by extending it with more features related to the validation of the system such as the introduction of requirements and risks that could affect the design, which will be followed by case studies for recent CPS applications, as well as the development of a high-level programming model for CPS.

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