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An ontological framework for knowledge modeling and decision support in cyber-physical systems

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ABSTRACT

Our work is concerned with the development of knowledge structures to support correct-by-design cyber-physical systems (CPS). This class of systems is defined by a tight integration of software and physical processes, the need to satisfy stringent constraints on performance and safety, and a reliance on automation for the management of system functionality and decision making. To assure correctness of functionality with respect to requirements, there is a strong need for system models to account for semantics of the domains involved. This paper introduces a new ontological-based knowledge and reasoning framework for decision support for CPS. It enables the development of determinate, provable and executable CPS models supported by sound semantics strengthening the model-driven approach to CPS design. An investigation into the structure of basic description logics (DL) has identified the needed semantic extensions to enable the web ontology language (OWL) as the ontological language for our framework. The $\mathcal{SROIQ}$ DL has been found to be the most appropriate logic-based knowledge formalism as it maps to OWL 2 and ensures its decidability. Thus, correct, stable, complete and terminating reasoning algorithms are guaranteed with this $\mathcal{SROIQ}$-backed language. The framework takes advantage of the commonality of data and information processing in the different domains involved to overcome the barrier of heterogeneity of domains and physics in CPS. Rules-based reasoning processes are employed. The framework provides interfaces for semantic extensions and computational support, including the ability to handle quantities for which dimensions and units are semantic parameters in the physical world. Together, these capabilities enable the conversion of data to knowledge and their effective use for efficient decision making and the study of system-level properties, especially safety. We exercise these concepts in a traffic light time-based reasoning system.

1. Introduction

Cyber-physical systems (CPS) are defined by the integration of physical systems with sophisticated (highly automated, autonomous, multi-agent) computation and networking. Embedded computers and networks are tasked with monitoring and controlling the physical processes, usually with feedback loops where computation affects physical processes, and vice versa [1,2]. Early applications of CPS can now be found in a variety of industries, including energy-efficient buildings, air and ground transportation, healthcare and manufacturing. The disruptive and transformative potential of these applications have led governmental entities and researchers to position CPS as the next technological revolution that will equal and possibly surpass the Internet [3,4].

The long-term expectation of CPS design is that engineers will be provided with methods and mechanisms to create systems that will always work correctly, and will operate with superior levels of performance, reliability and safety. Perhaps CPS will achieve these purposes through the use of new architectural models that redefine form and function? At this time, however, the full potential of this opportunity is hindered by the lack of a mature science to support systems engineering (i.e., definition, composition, integration) of high-confidence CPS. Capturing and analyzing CPS behaviors in formal models, even minimal ones, is cumbersome. Present-day procedures for the engineering of CPS's are weakened by the presence of non-determinate models, weak temporal semantics, coupled with the high sensitivity of CPS to timing [5]. For CPS applications that are safety critical, this is a problem because notions of design correctness will correspond to the satisfaction of physical world constraints and, in turn, their dependency on formal models of time and space.

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This paper takes a first step toward mitigating these deficiencies. We lay down the foundational building blocks to support the development of determinate CPS models, with strong temporal and domain-specific semantics strengthening model-driven approaches to CPS design. Our focus will be on the data and information processing layer of CPS modeling, with a particular attention to procedures and mechanisms for producing determinate, provable and executable CPS models. We introduce and describe an innovative ontological framework, and illustrate the structure and phases of construction for a knowledge modeling and decision support framework for CPS (CPS-KMoDS). The framework offers some flexibility in its implementation, for example, for the selection of tools and type of tasks targeted by the model. System dependability characteristics, especially safety, are viewed as multi-domain models that drive the evaluation of decision tasks and, as such, development of the ontological framework.

The paper is organized into six sections. Section 2 briefly presents CPS and semantics challenges in modeling such systems as well as key requirements for the CPS-KMoDS. Section 3, along with Appendices A–C, provides a summary background on the mathematical foundations supporting the framework with an emphasis on description logics (DL) and their central role in supporting reasoning tasks. In Section 4 the proposed framework is introduced and its construction process described. A Jena-based implementation of the framework is presented in Section 5. We exercise the framework through the development of a time-based reasoning system to support decision making for cars passing through a traffic intersection controlled by traffic lights. The paper concludes with a summary and suggestions for future work.

2. CPS knowledge modeling and ontologies

2.1. CPS: overview and key characteristics

An examination of CPS application domains (e.g., aerospace, healthcare, transportation, energy or automotive) reveals components that span multiple physics and engineering domains, operate across multiple time scales, and have dynamics that are sometimes affected by human-in-the-loop interactions. Thus, we can categorize CPS components as follows [6]:

(a) Cyber components: These are computation, control and communication platforms, each implementing some specific system function. Given their software (or cyber) nature, these components need a physical (or hardware) platform to run the corresponding program, to support communication among cyber components and with the surrounding environment.

(b) Physical components: They act as facilitators for physical interactions as well as implementation of functional specifications for the system. Generally speaking, physical component complexity increases when components cover multiple engineering domains, and when components embed computational capability. Examples of the latter include onboard computers in automobiles, unmanned aerial vehicles (UAV), smart sensors in bridges, and smart medical implants.

Fig. 1 shows the network structure and components in a prototypical CPS. The system is made of four integrated and networked platforms with a physical plant. A network (wireless in this case) allows the various platform to communicate with each others. This network could be as small as a Local Area Network (LAN) or as big as the Internet. Some of the links between the platforms are direct and would not go through the wireless network. One of the platforms (#4) is embedded in the physical plant which interacts with the cyber world through physical interfaces. Each platform is made of all or some of the following components:

1. **Computation module:** Computation modules process plant data collected by sensors and/or output from other platforms. System architectures may impose dependency relationships among computation modules, independently on their location. For our illustrative example (see Fig. 1), this capability allows physical processes occurring in the plant to affect or modify computations in platform #2 using both the embedded platform (#4) and the wireless network to communicate with platform #2.
2. **Sensors:** Sensors collect plant data (physical measurements) and pass them to the computation module for further processing. For example, sensors are illustrated on platforms #1 and #4. They usually operate as a node in a sensor network architecture.
3. **Actuators:** They intervene in the feedback control loop of the plant to control mechanisms or processes according to the system specifications. Platform #3 illustrates one of them.
4. **Interfaces:** Network interfaces allow for the flow of data between platforms directly or through a network. Physical interfaces allow for plant and platform connectivity. In Fig. 1, all platforms are equipped with both types of interfaces except for platform #2, which has only network interfaces.

2.2. Semantic challenges in CPS modeling and analysis

The design and realization of a CPS satisfying even a small subset of the architecture shown in Fig. 1 is challenging. Difficulties in development stem from a variety of sources including the need to deal with a multiplicity of physics and engineering disciplines, each requiring expertise. Lee [8] illustrates this complexity using a subset of an aircraft electrical power system (EPS). Depending on the domain-specific viewpoint, the perception of the system can range from a software to an electrical system passing by a mechanical, control or communication network. This leads to multiple domain-specific models of the CPS, with none of them covering the CPS entirely. In a slightly different take on strategies to address challenges for CPS development, Sztipanovits [6] explains this complexity through the observation that, often, the behavior of physical components in CPS is defined by interactions among multiple physics that are difficult to capture in a single model. Thus, the CPS designer will face the challenge of composition of multi-models for heterogeneous physical systems.

To complicate matters, modeling challenges seem even harder when the subject of investigation covers CPS model semantics. Doyle [9] observes that theories backing the various disciplines involved in CPS are “deep but fragmented, incoherent and incomplete.” The landscape of theories span from Turing and Von Neumann for computation to Einstein, Carnot or Newton for system physics through Nash and Bode in control or Shannon in communication domain. Fig. 2 illustrates this complexity and a view of some of the key challenges in the context of CPS modeling. Various domains involved in the modeling and design effort are orthogonally mapped to the main models abstraction layers.

Addressing semantic challenges: Some researchers have investigated ways to address these challenges with mixed success. In Derler [5], a landscape of technologies ranging from hybrid systems modeling and simulation to concurrent and heterogeneous models of computation (MoC) is presented. The use of MoC in Ptolemy II [10] is possible thanks to well-defined semantics for concurrency and communication between actor-oriented component models. However, despite its many computational advantages, the use of superdense time models [11,12] for timing is not