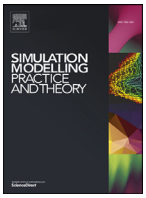
Simulation Modelling Practice and Theory 000 (2017) 1–15

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat



Model continuity in cyber-physical systems: A control-centered methodology based on agents

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Multi-agent systems
Control-based methodology
Actors
Parallel actions
Model continuity
Cyber-physical systems
Simulation
Real-time execution
Power management
Smart micro-grid

ABSTRACT

A Cyber Physical System (CPS) is given by the integration of cyber and physical components, usually with feedback loops, where physical processes affect computations and vice versa. Design and implementation of complex CPSs is a multidisciplinary and demanding task. Challenges arise especially for the exploitation of heterogeneous and different models during the various phases of system life cycle. This paper proposes an agent-based and control-centric methodology which is well suited for the development of complex CPSs. The approach is novel and supports *model continuity* which enables the use of a unique model along all the development stages of a system ranging from analysis, by simulation, down to real-time implementation and execution. In the paper, basic concepts of the methodology are provided together with implementation details. Effectivenesses of the approach is demonstrated through a case study concerning a prototyped CPS devoted to the optimization of power consumption in a smart micro-grid automation system.

1. Introduction

Cyber-physical systems (CPSs) [1–4] integrate a physical system with a computational part through a network infrastructure. Their exploitation is advocated in various domains including avionics, automotive, traffic management, health care system, mobile communications, medical technology, manufacturing, smart grid, procurement and logistics, industry and building automation, plant construction and engineering [5]. A correct design for CPSs is of great importance as they are often applied in safety or business-critical contexts [6].

CPS development challenges arise from the necessity of adopting powerful software engineering methods for the cyber part, capable of ensuring modularity and evolution of a software architecture, while at the same time guaranteeing an effective control of the runtime platform and communication network for the fulfillment of the physical plant real-time constraints. Design difficulties [6–8] are related, for instance, to the needs of conjoining continuous dynamics of the physical components with the discrete time model of the cyber components. In addition, the use of open and public networks requires the handling of security concerns [9] arising from the real-time operation of a CPS.

Architectural means for CPS modelling are described, for instance, in [10], where the use of agents [11] and their interactions (events) to one another and with the external controlled environment are the basic concepts. The adoption of crosscutting agent coordination policies at both the local and the global/system level emerged as a fundamental way to

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https://doi.org/10.1016/j.simpat.2017.12.008
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Please cite this article as: F. Cicirelli et al., Model continuity in cyber-physical systems: A control-centered methodology based on agents, Simulation Modelling Practice and Theory (2017), https://doi.org/10.1016/j.simpat.2017.12.008

control the achievement of system goals. Multi-agent systems have demonstrated their advantages as an open and flexible software technology capable of unifying control aspects in smart grid applications [12]. As an example, agents were used to handle the power management problem in a smart home automation system [13]. Holonic agents, instead, are used in [14] as basic architectural building blocks for the development of manufacturing automation systems.

In this work an original agent-based control framework [15,16] is advocated for CPSs, which rests on mechanisms for managing control and coordination aspects of agents as in [10]. Managing control aspects means that the approach makes it possible to use, in a transparent way, different message scheduling and dispatching policies according to a chosen time notion (real or virtual) so as to fulfill specific application requirements. The control framework acts as an *operating software* solution that integrates both flexibility of an agent-based design [13] with time-sensitive control structures which coordinate agents' evolution. A unique feature of the adopted framework, not supported by other existing agent-based approaches for CPSs, is *model continuity* [17,18], which consists in the possibility of transitioning unaltered an agent model throughout the entire development life cycle, from analysis, down to design, implementation and real-time execution. The approach provides also a concurrency model which favours predictability and determinacy by avoiding common pitfalls of multi-threaded programming [19] (see Section 3.2).

With respect to other approaches supporting model continuity [17,18], the proposed framework distinguishes by its abstraction mechanisms which enhances separation-of-concerns during the development of CPSs. In particular, the following abstraction entities can be exploited: (i) agents to structure the *business logic* of the application to realize, (ii) *boundary elements* to interface the application with the external physical environment, (iii) the environment Gateway (*envGateway*) taking into account aspects related to modelling, analysis and implementation of the physical part of a CPS and more in general of the external environment in which an application runs, and (iv) customisable time-sensitive *control structures* suited to scheduling and dispatching system events and message exchanges. Model continuity depends on different concretizations of the boundary elements, the envGateway and the control-specific components. The envGateway requires to be re-interpreted when moving from the analysis to the implementation phase. It offers a transparent yet uniform way for dealing with communication protocols and hardware equipments needed for sensing and acting upon a controlled environment. During system analysis, besides the modelling of single sensors and actuators, the envGateway takes also into account the causal-effect relations tied to operations carried out on the environment. As an example, turning-on a lamp through a relay implicitly affects the value read by a luminosity sensor, placed near the lamp itself.

During the simulation phase the envGateway can also interface software components like ordinary differential equations (ODEs), modelling continuous time behavior of a system plant. From this point of view, the proposed approach can integrate continuous models within an overall discrete-event based framework. As an example, such techniques as quantization [20,21], experimented, e.g., in the DEVS community [22], can be used.

In this paper the above mentioned agents and control framework is tailored to CPSs and the focus will be on proposing a methodology which addresses all the development stages of a system.

The paper is an extended version of authors' previous work published in conferences [23] and [24]. With respect to previous authors' works, the contributions of this paper are the following: (i) the methodological aspects of the proposed approach are better defined and weaved so as to cover all the development phases, ranging from modelling, analysis, to final implementation of a CPS; (ii) more insights are provided about the envGateway design and about the hardware equipments necessary to instrument a real CPS; (iii) the methodology is practically demonstrated through a case study concerned with optimizing power management in a smart micro-grid home or industrial electric power system.

The paper structure is as follows. Section 2 describes related works about CPS methodologies and challenges. Section 3 details the proposed methodology and outlines the adopted agent and control based framework. Section 4 presents the case study and applies to it all the phases of the methodology. Some experimental results are reported and discussed. Section 5, finally, draws some conclusions and furnishes indications about some on-going and future work.

2. Related work

CPS engineering challenges include the use of integrated models, facing issues related to interoperability, reconciliation of Newtonian time of the physical part with the discrete time of the cyber part [8], privacy protection, security, non-functional requirements, timing constraints, humans-system cooperation and so forth [5].

Service-oriented architectures (SOA) and multi-agent systems (MAS) are two important software technologies which have proved their effectiveness in general ICT systems and whose exploitation for CPS is deemed promising to sustain a revolution in industry automation and smart factories [25–30].

A service-based approach for developing CPS is proposed in [25] which exploits service-oriented architecture concepts and/or cloud concepts to realize service-based CPS. The approach deals with some design challenges of CPSs such as dynamic composition, dynamic adaptation, and high confidence CPS management, hardware heterogeneity. Three tiers were defined: an *Environmental Tier* for dealing with the target physical environment, a *Control Tier* for making decisions for networked physical devices, and a *Service Tier* for managing reusable services. The final goal is that of allowing the handling of complex and resource-consuming processes even on downsized mobile Internet devices which are usually involved in a CPS.

Another service-based approach is discussed in [26] where the WebMed middleware is proposed. The goal is promoting the use of the service metaphor for the development of CPS applications. By exploiting the service-oriented computing, WebMed fosters the realization of loosely coupled CPS infrastructures that expose the functionality of physical devices as

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