Modeling and evaluation of cyber-physical systems in civil engineering

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A cyber-physical system (CPS) is a coupled system integrating computing, networking, and physical processes. Through actuation, cyber-physical systems control the physical processes, usually with feedback loops, where the physical processes affect computing and networking processes, and vice versa. In civil engineering, the most common fields of CPS applications are structural health monitoring (SHM) and structural control. A typical CPS task is the assessment of a structure based on (i) collected measurement data and (ii) a corresponding model. However, for an accurate and precise assessment of a structure, the CPS itself must be modeled and evaluated. In this paper, a conceptual modeling and evaluation approach is proposed, in which each part of a CPS is evaluated individually. In this study, the conceptual approach is presented for modeling and evaluation of CPS in civil engineering. The evaluation is based on an abstract approach allowing a discussion of a principle (i.e. general) model structure of a CPS, identifying critical issues to be studied in more detail in future research.

1 Cyber-physical systems in civil engineering

Engineering applications are associated with physical processes, while computational models are usually developed to describe the physical processes. Specifically in dynamic (time-variant) physical processes, the application requirements may dictate user intervention during the physical processes. To enable such user intervention, information needs to be exchanged between the physical processes and the computational models. Moreover, in several engineering applications user intervention is automated through physical components employed to control the physical processes through feedback loops, essentially extending the computational models to computational and networking processes that describe and interact with physical processes. In this context, utilizing the dual nature of cyber-physical systems (CPS), which integrate physical and computational processes [1], has received considerable research attention in the fields of civil and structural engineering (structural testing) [2].

In civil and structural engineering, the trend towards cyber-physical systems predominantly concerns the field of structural health monitoring (SHM) and structural control [3]. Cyber-physical systems in civil and structural engineering do not fall into the category of conventional systems used for monitoring structures (e.g. centralized cable-based SHM systems). Rather, the advent of wireless technologies and the gradually increasing adoption of wireless sensor networks for structural health monitoring marks a transition phase from conventional SHM practice to cyber-physical approaches for SHM [4,5]. The distributed nature of wireless SHM systems and the ability of wireless sensor nodes to perform monitoring tasks in a decentralized manner have enabled partially or fully automated decision making in wireless SHM systems. Moreover, in CPS approaches in civil and structural engineering, SHM systems are typically coupled with structural subsystems (actuators) aiming to control the behavior of the monitored structure [6]. Examples of actuators in civil engineering systems are devices that modify structural responses, such as active (or semi-active) tuned mass dampers and magnetorheological dampers, or software components ensuring the robustness of the SHM system, such as fault diagnosis embedded algorithms [7]. Structural health monitoring and control devices are usually applied in “irregular” structures that exhibit unconventional dynamic behavior under time-variant loads, such as skyscrapers and tensegrity structures [8].

2 Types of coupling in cyber-physical systems

The behavior of the components of cyber-physical systems in civil engineering, i.e. of the structural health monitoring and control systems and of the monitored structure, is characterized by strong interactions and, therefore, by a high degree of coupling. As has already been highlighted, the adoption of cyber-physical systems in civil engineering is associated with unconventional structural systems (usually employed in structures of high significance, such as large financial centers); thus, ensuring the highest possible level of performance of such cyber-physical systems is of utmost importance to the structure’s stakeholders. In this direction, a methodology for assessing the quality of cyber-physical systems is necessary, accounting for the quality of the individual components of cyber-physical systems as well as of the complex coupling conditions between the components.

Fig. 1 indicates two principle types of coupling appearing in cyber-physical system modeling:

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- Coupling between cyber-physical subsystems ("inter-subsystem coupling")
- Coupling among the components of each cyber-physical subsystems ("intra-subsystem coupling")

For an overall quality assessment of cyber-physical systems, the coupling between cyber-physical subsystems must be assessed. However, existing modeling methodologies for cyber-physical system modeling do not address the issue of inter and intra-subsystem coupling clearly, and particularly, do not assess these couplings [9]. Thus, practical assessment of cyber-physical systems entails developing of a conceptual modeling methodology with sufficient expressive power to describe such couplings. The abstract modeling methodology based on category theory, introduced in [10], provides a sufficient level of abstraction to describe the coupling between cyber-physical subsystems. However, this modeling methodology has been developed for mathematical models (physics-based models), and its application to cyber-physical system modeling requires a further generalization, which is the objective of future research.

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