Proceeding Paper

Does System-of-Systems Thinking Work for Self-Governance of Digitally Transforming Systems? †

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† Presented at the online workshop Digital Humanism: How to shape digitalisation in the age of global challenges? IS4SI Summit 2021, online, 12–19 September 2021.

Abstract: Keeping humans in the loop or bringing them back into the loop in dynamically changing socio-technical systems requires the human-centered arrangement of system designs and the adoption of digital artefacts according to human capabilities and needs. Design-integrated engineering of System-of-Systems (SoS) facilitates the complex interplay of cyber-physical technologies and humans both through model-driven and interactive handling. In this contribution, SoS thinking is introduced as an approach to self-governance of cyber-physical infrastructures and digital appliances. It allows socio-technical system development to be based on the focused articulation of stakeholder interests and behavior, by using them as a baseline for digital twin modeling. In this way, digital twins can represent the system designs and implementation details required for engineering. As such, they enable various pathways to SoS self-governance in cyber-physical settings.

Keywords: digital transformation; governance; system-of-systems; cyber-physical systems; digital twin; humanoid systems

1. Introduction and Overview

Digital appliances, such as home healthcare (including Internet-of-Things applications), affect human life widely by transforming society through their information processing capabilities and penetration intensity. Recent developments indicate that Cyber-Physical Systems (CPSs) will become the core of socio-technical systems (cf. [1]), e.g., when implementing concepts such as Industrie4.0 (cf. [2]), and affecting essential societally relevant systems, such as healthcare (cf. [3]). The latter has motivated various initiatives calling for and encouraging human-centered digital innovations, such as the Vienna Manifesto on Digital Humanism [4]. However, user-centered governance of digitally transforming systems is not a trivial task. For instance, each of us can experience the complexity of such an endeavor when downloading an app on the mobile phone, and connecting it to a sensor-based blood pressure measurement system as part of a smart healthcare system at home. However, such a system has the capability not only to remind us to measure the blood pressure regularly, but also to inform experts and family members if necessary.

Each of those tasks requires a variety of design and engineering decisions when transforming ecosystems. These decisions become crucial when addressing specific situations for individual users or role carriers, e.g., medical emergency: *What* defines an emergency? *Who* declares a situation to be an emergency? On the basis of *which data*? And *who is informed* by *which means*? When users or domain experts (re-)design systems and map their needs and knowledge to executable CPS components, they take governance on (continuous) transformation processes. But how can they be empowered in self-governed CPS design and engineering (cf. [1])? In the following, we suggest a component- and behavior-centered governance structure for Digital Twin (DT) modeling and executing human-centered socio-technical designs. Taking a System-of-Systems (SoS) perspective on

networked CPS components, specific concerns—such as handling emergency situations—can be addressed even in complex settings. It requires a human-centered level of abstraction to inform design, with engineering information for the stakeholders involved. In the following sections, we first detail the design-integrated engineering approach before presenting an example of the SoS perspective, supporting dynamic system transformation.

2. Design-Integrated Engineering of CPSs

CPSs are hybrid systems that make combined use of physical and digital components in socio-technical settings (see also Figure 1). Their embeddedness and mission criticality demand the precisely synchronized and seamless integration of complex sets of computational algorithms with physical components [5]. The physical part consists of various operational resources, which can be summarized as 'machine/material/environment' on the basis of the respective CPS context and processing of physical resources. The cyber/digital part, which can include various apps and services, incorporates data management, analytics, and computing capabilities. For operation, services and apps encode functions that allow the users to monitor and control processes. The physical part senses and collects data, and executes decisions delivered by the cyber/digital part (after it has analyzed and processed the collected data). The collected data form the basis for decision making, which enables the digital part to control physical processes. In this way, a bi-directional flow is established between the physical and digital parts.
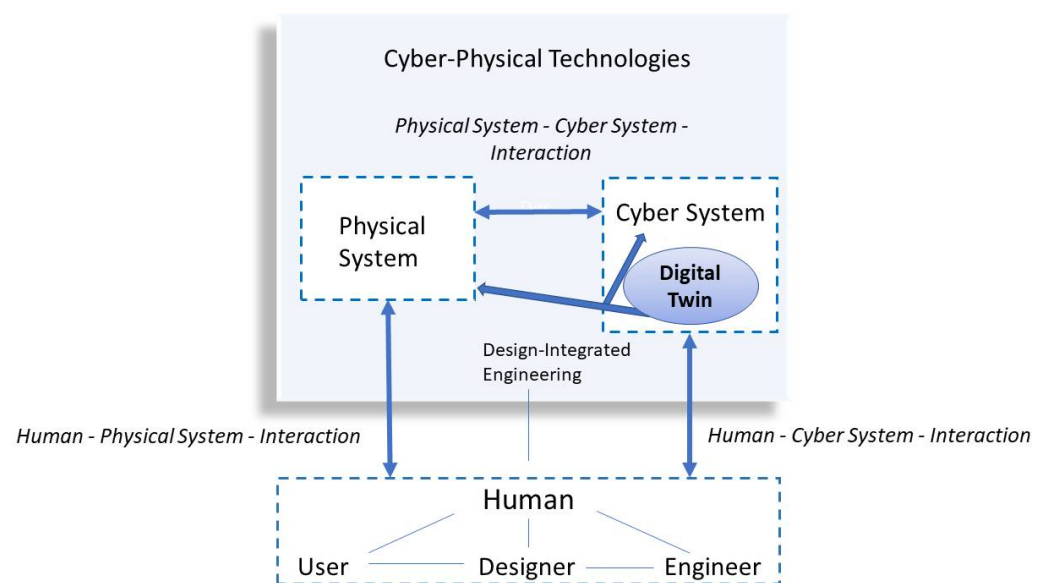

Figure 1. Design-integrated Engineering of Cyber-Physical Systems.

CPS development aims to deploy systems that satisfy a set of requirements with respect to the control of physical components, including Internet-of-Things (IoT) elements. This property allows for complex applications in a variety of domains that are highly relevant for humans, such as production, mobility, and healthcare. They involve a variety of physical components (such as sensor systems, production machinery, and robots), leading to cross-domain development activities and interdisciplinary collaboration [6].

3. Digital Twins and CPSs

By providing a live copy of physical systems, digital twins can be used to accelerate business processes, enhance productivity, and speed up innovation with reduced costs [7]. As such, they have been considered 'a prerequisite for the development of a CPS' ([8], p. 2), even though they are mostly applied for monitoring and prediction in smart manufacturing [8]. In order to ensure that digital twins contribute effectively to various domains by representing a synchronized copy of the physical system, not only do the network

connections need to meet a set of requirements (low latency of real-time communication, data security and quality), but also their representation of the CPS needs to be accurate [9].

Using digital twins as more or less complete CPS representations (see Figure 1) forces developers to apply a systematic and structured process that allows monitoring and control of a system or product. This includes a runtime-relevant representation of the CPS behavior and traceable operations. Both serve for maintenance and further development, whilst also supporting continual system transformation. As development becomes more and more pervasive and interactive, design as an integrated engineering activity has taken a predominant role in participatory and collaborative development approaches, in which the users put their ideas into practice in a model that can be executed and run for operation. When design and engineering are intertwined, digital twins can control operation and/or feature development of a CPS and its IoT elements (cf. [10]).

4. System-of-Systems Governance

Development methods of CPSs have to take into account heterogeneous components that are highly connected. These components form constituents of a System-of-Systems (SoS) [11], as they can operate independently but also (optionally) in connection with other constituents [12], e.g., considering the Step Counter as a CPS component in Figure 2. CPSs have already been characterized as Systems-of-Systems, recognizing the managerial and/or operational independence of constituent or sub-systems [13]. In SoS, higher-level system objectives and cross-concerns, such as effective emergency case handling, can be addressed. However, they may require some design and/or engineering efforts (cf. [14]).
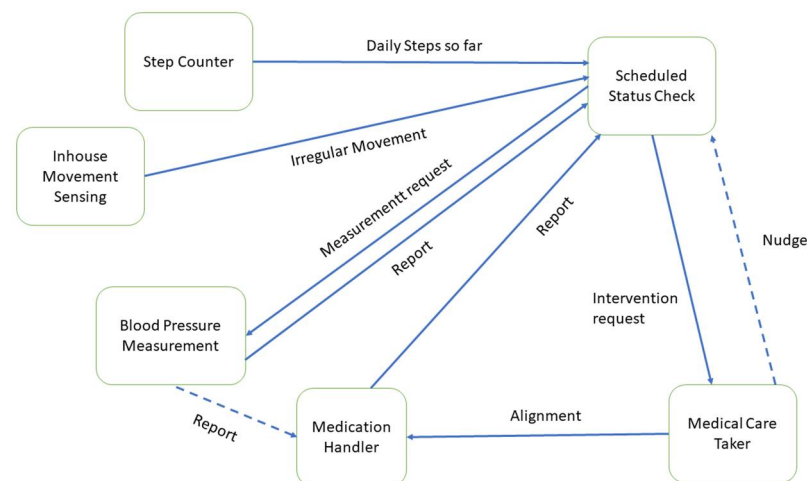

Figure 2. Capturing value streams for Design-integrated Engineering of Cyber-Physical Systems.

Human-centered socio-technical system development requires methodological support for articulation and documentation of stakeholder behavior and interests. An effective way to address the 'who' and 'what' issues (see Section 1) is to elicit and document value exchanges, as proposed by Value Network Analysis (VNA) [15]. The identification of value exchanges involves the specification of stakeholders and/or tasks and their interactions (see network nodes and directed edges in Figure 2) that are specific for a scenario (cf. [16]). For design-integrated engineering, the nodes encapsulate role- or task-specific behavior—they are also termed Behavior-encapsulating Entities (BeEs) [17]. Value exchanges can either be formal or informal (see solid and dotted lines in the home healthcare scenario addressed in Figure 2, respectively) to achieve a certain goal [15,16]. They correspond to transactions between BeEs and deliver some service or object as a result to the receiving BeE. Refinements of each BeE can be used in the digital twin model that serves as a (representational) baseline for design-integrated engineering [17], including specific patterns of situation-relevant behavior [18]. Putting behavior-based designs to practice involves validating models and monitoring the operation of a CPS [16,18].

Within the context of SoS thinking, several challenges for self-governance need to be taken into account [19]: (i) how to develop intervention and interactive design capabilities; and (ii) how to achieve alignment of cross-concerns, such as handling medical emergencies in the highly interconnected and dynamic CPS settings. In the generic approach to BeE-centered SoS design thinking in Figure 3, different pathways to SoS-based self-governance can be identified. Either an existing node becomes a SoS node, e.g., the Scheduled Status Check (see Figure 2), or a node is added for SoS governance, e.g., Medial Emergency Case Handler for the home healthcare scenario. In both cases, the system functionality needs to be analyzed and adapted according to the SoS-specific design purpose.
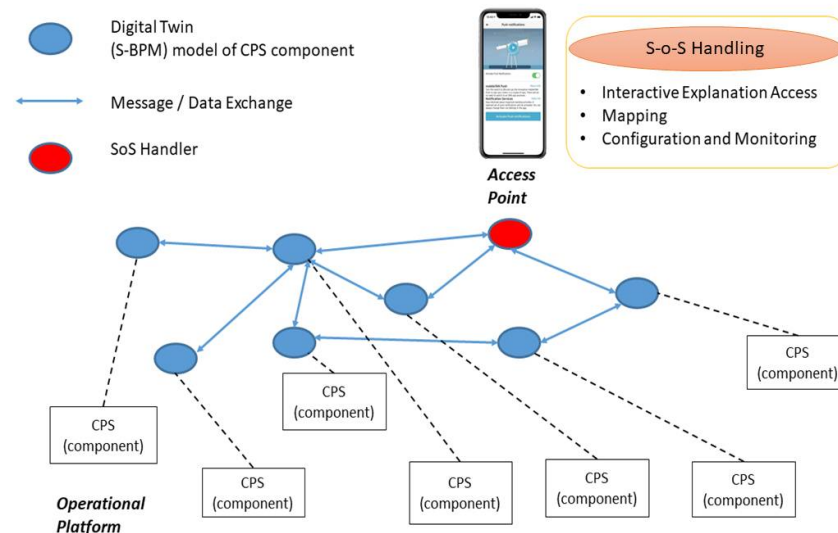

Figure 3. SoS design thinking for governing a CPS.

Another cross-concern is privacy management. For this governance case, e.g., as part of a CPS home healthcare appliance, the CPS components involved can be the ones included shown in Figure 2; however, they need to be considered from a different perspective (cf. [20]). In order to understand which privacy-relevant data are produced and shared between the components, SoS handling includes interactive explanatory access to each digital representation of a CPS component, e.g., in terms of detailed behavior diagrams (representing BeEs) when using S-BPM's (Subject-oriented Business Process Management) integrated modeling, validation, and execution approach [21]. It also includes collecting privacy requirements affecting BeEs, and could require CPS (re-)configuration. Monitoring helps checking whether the privacy requirements are met when operating the CPS.

5. Conclusions

Design-integrated engineering of CPS System-of-Systems enables humans to be kept in the loop, once designs can be (i) arranged as networked entities with intelligible behavior, and (ii) managed by concerned stakeholders to explore the CPS in operation as a collection of interacting digital entities encapsulating runtime behavior. Dedicated network nodes can facilitate the governance of (continuous) transformation processes, as they support analyzing cross-concerns, such as handling medical emergencies in healthcare CPSs. However, the digital behavior representation scheme and engineering architecture needs to be explored further, particularly for changes that go beyond functional adaptation, e.g., when incorporating socio-emotional behavior (cf. [22]).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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