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An Analysis of the State of Framework Development for Reasoning in Smart Cyber-Physical Systems

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Abstract. Smart CPSs (S-CPSs) have been evolving beyond what was identified by the traditional definitions of CPSs. The objective of our research is to investigate the concepts and implementations of S-CPSs, and more specifically, the frameworks proposed for the fuzzy front end of their reasoning processes. The objectives of the paper are: (i) overview of the various framework concepts and implementations in the context of S-CPS, and (ii) analyze the presented frameworks from the points of view of reasoning processes of S-CPSs that included the concepts of structuring knowledge, building awareness, situated reasoning, decision making, and system adaptation. Our major findings are: (i) model-based and composability approaches do not support a development of S-CPSs; (ii) awareness and adaptation behaviors are considered as system level characteristics of S-CPSs that are not achieved by traditional design approaches; (iii) a new framework development should support a compositional design for reasoning in S-CPS. Based on the findings above, we argue that a development of S-CPSs should be supported by a proper framework development for compositional design of smart reasoning and coping with the challenges of compositionality requires both software-level integration and holistic fusion of knowledge by means of semantic transformations. It needs further investigation if a compositionality enabling framework should appear in the form of a meta-framework (abstract) or in the form of a semantically integrated (concrete) framework.

Keywords. Cyber-physical systems, system smartness, framework development, smart reasoning platforms, reasoning mechanisms

Introduction

Cyber-physical systems (CPSs) are understood as systems that closely integrate constituents from the cyber and physical domains. They may be implemented on various scales, ranging from the nano-world to large-scale systems of systems. Their complex interaction with the environment and interoperation with other systems may lead to the emergence of specific phenomena and behaviors. Handling these requires a level of system smartness that goes beyond what was typically achievable with adaptive systems. Thus, smartness is regarded as a necessary feature for the development of next generation CPSs (nG-CPSs). It makes CPSs capable to build awareness of dynamic situations and operational states, and facilitates their adaptation

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to unpredictable conditions, users or environments.

A framework plays several roles in system design context. One of them is to give a guideline to develop a system model according to a developer's point of view. In the context of CPSs, a model can be developed from various objectives and perspectives such as software tools and programming, architecture and design, simulation and modelling, reasoning mechanisms, and cyber security. Therefore, the framework can be considered as an early conceptual model, which is later on gradually converted into a set of interrelated multi-aspect system models. Smart reasoning is a concrete example of these system-level properties. However, we miss a lot of knowledge concerning compositional development of smart resources of CPSs. A compositional approach operationalizes a top-down perspective and considers the systems in a holistic manner. It intends to create a synergy among the functional elements of the systems in order to realize system-level properties that cannot be achieved by integrating the local properties of the system components [1].

The research phenomenon can be observed that there is the lack of frameworks supporting a compositional design of reasoning mechanism for S-CPS. This leads to our assumption that the existence of the knowledge gap boils down to the need of a framework for this purpose. Thus, we put 'a framework' into the focus of our research. The specific objectives of our study are: (i) overview of the various framework concepts and implementations in the context of S-CPSs, and (ii) analyze the presented frameworks for reasoning from the points of view of the processed knowledge, building awareness, reasoning mechanisms, decision making, and adaptation.

1. Preparation of the literature study

1.1. The reasoning model for conducting the study

This paper reports on the results of the research we completed using secondary data to get insight in the current statues of frameworks for designing reasoning platforms for S-CPSs. More specifically, we focus on the issue of frameworks that supports compositional design of reasoning platforms, which create system-level smartness by implementing various reasoning processes needed in specific applications of S-CPSs [2]. We completed our study according to a reasoning model that identified three main constituents: (i) the domains that provided the context information for the research, i.e., cyber-physical systems and system smartness, (ii) the domain of discourse of the research, i.e., system development frameworks, and (iii) the domains that provided content information for studying frameworks, i.e. implementation of reasoning and generic components of reasoning. The latter domain included concepts such as (i) knowledge, (ii) system awareness, (iii) reasoning mechanisms (iv) decision making, and (v) system adaptation. These were seen as necessities to implement smartness in S-CPSs. It was a challenge for our study that there were many epistemological and methodological relationships among the domains and their elements.

1.2. Method of data collection

The common tools used for collecting data were web search engines and a reference management software tool. To perform a query search, the term *framework* was considered as a main keyword. A wide range of relevant keywords were formulated concerning the reasoning model e.g. awareness, adaptation, smartness, and reasoning mechanisms. The reasoning model brought them into semantic relationships. We utilized the core collection of Web of Science as the primary data source. Other sources, for example, databases in specific disciplines related to CPSs and web repositories were used as a complement for qualitative analysis. To cover recent trend and development of S-CPSs, the chosen time frame was the past ten years (2008-2017). After the selection of the relevant scientific publications, the sample contained a total of 697 publications. It comprised of three types of document: articles, reviews and proceedings. A total of 209 papers discussing relevant frameworks were found by considering their title and the keywords identified by them. We found 33 proposed frameworks, which were closely related to the development of CPSs. These were analyzed deeply and will be discussed below in the section on framework development.

2. Cyber-physical systems (CPSs)

2.1. Manifestation and evolution of CPSs

The term 'cyber-physical systems' was coined about 2006. CPSs are regarded as a kind of model for next generation engineered systems that have their roots in a tight integration of hardware devices, embedded software and massive data streams [3]. Conventional CPSs are widely designed using the model-based approach. They are pre-programed with a set of rules concerning the given situations and regulated within the tasks close the Sensing-Processing-Actuation loop [4]. Most of the CPSs manifest as systems of systems. They belong to larger systems that are interconnected through communication networks as an open system. The complex interaction and interoperation among systems may lead to the emergence of phenomena and behaviors. CPSs are supposed to be able to deal with uncertainty and unpredictable situations in operation, and to adapt rapidly to anomalies in the environment. This requires some level of intelligence from CPSs. However, not all traditional CPSs are able to satisfy this requirement [5].

Engell *et al.* indicated a shift towards cognitive aspects of developing CPSs, and accounted on new research challenges associated with it [6]: (i) handling large amounts of data in real life; (ii) situation awareness (iii) learning and adaptation; (iv) analysis of user behavior and detection of needs and anomalies. They also claimed that cognitive CPSs could step forward to the upcoming generation CPSs. Concerning the evolution of CPSs, scientists and practitioners have different views. There is no agreement on the next generations of CPSs yet. In our view, CPSs are networked knowledge-intensive multi-actor systems and smartness is becoming a paradigmatic feature of their next generations. They have been sorted based on the level of intelligence (self-awareness) and the level of organization (self-adaptation), respectively [7]. Self-regulation and self-tuning are paradigmatic features of the first generation CPSs and they will be replaced by self-awareness and self-adaptation to become the second generation CPSs. These capabilities are not produced by a single component, but by a synergic operation of the entire system. It implies the need for different conceptual framing of CPSs and different principles in their development.

2.2. System smartness as a holistic capability

Smartness is an intermittent quality of human thinking, feeling, doing and making. Modern engineered systems are designed to be able to operate and to provide services smartly. Nevertheless, the concept of system smartness has not been consolidated yet, especially not in the context of emerging products. For some, the term *smart* is used as a synonym of 'sophisticated' or 'crafty'. For other, it means 'intelligent', 'automated', and 'knowledgeable' [8]. Accordingly, it is hard to identify the real contents of, and to come a common understanding of system smartness. Based on system theory, smartness is a system-level characteristic that enable the systems to operate beyond that they have been specifically programmed for, but without fundamentally changing their domain, objective and resources of operation [9]. Smartness is interpreted as a paradigmatic feature of a class of systems. In line with the reasoning of Gottfredson, it is a first level manifestation of a broader and deeper capability for comprehending our surroundings - 'catching on', 'making sense' of things, or 'figuring out' what to do [10]. Smart operation assumes a high-level functional and architectural synergy among the parts of a system.

System smartness has been addressed from various application perspectives in the literature. Dominant ones are (i) smart ubiquitous systems, (ii) smart software systems, (iii) sensor data driven systems, (iv) artificial intelligence enabled systems, and (v) context-aware adaptive systems. Typical characteristics for these systems are that the relationships among the component properties create distinctive patterns of operation on system level, that cannot be assigned to any of the individual components, only to the whole [11]. In this sense, smartness as performed by S-CPSs is a holistic capability. Smartness implies the needed for compositional system engineering, likewise safety, dependability, and adaptiveness. It goes beyond the reductionism that is usually applied in analysis and synthesis of conventional systems, and calls for more purposeful design approaches than the traditional model-based approach [12]. Ollesch *et al.* (2017) claimed that event-based control paradigms are vital enablers for adaptive analytical control mechanisms needed in S-CPS [13]. However, to date, very few accounts exists how to engineer smart CPS with intelligence based on real-time event processing. We argue that compositional design of S-CPSs needs also new principles (e.g. system level synergy) and a different (top-down specification) methods in system conceptualization.

3. Framework development

3.1. Foundational concepts of frameworks

The term *framework* has different connotations to different people and in various professions. There had been no consensus on the definition of the term framework in the field of system engineering [14]. As referred to the definition in Oxford dictionary, a framework is a structure of *somethings* serving a particular purpose. In scientific interpretation, the term *something* can be identified as an abstraction entity. Therefore, a framework is deduced to an arrangement of entities, which heavily depends on the context. Possible entity in a framework is e.g. theory, concept, variable, definition, function, system component, and method. A structure of and relations among entities can be arranged by various methods, e.g. causal relationships, hierarchical diagram, formal logical expression, topology, and mathematical model. A framework can be utilized for various purposes such as prescriptive guidance, explanatory accounts, generative constructs, analytical problem-solving, and predictive models. These components can be combined to develop a framework in thousand ways based on a developer's mental model. It can be taken from a conceptual idea to a detailed description guiding how a system should be designed. It is probably constructed from an outline of structure [15] to a sophisticated structure as seen in component-based framework [16]. This shows no standard model for building a framework, especially in the context of compositionality-enabling system development frameworks.

3.2. Various types of frameworks used in system development

Various adjectives are used to identify specific kinds of framework such as: general framework, conceptual framework, and model-based framework. There are many other specific names used to highlight the purpose, context, and/or methods associated with different framework types. To gaps all of them would need a rigorous taxonomy or classification. In the areas of system design, the following frameworks are used most frequently: (i) *Conceptual frameworks*, which are arrangements of concepts with several variations and contexts. It is a network of interlinked concepts such as a set of concepts, definitions of concepts and relevant variables, and building blocks of a theoretical model that together provides a comprehensive understanding of a phenomenon [15]; (ii) *Logical frameworks,* which define the logical skeleton of systems with a specific purpose. Typically, the relationships of system functions are represented by factors and their definitions, and logical expression language [17]; (iii) *Architectural frameworks,* which involve a common practice for creating, analyzing and representing system architectures during design and re-design processes [18]. They can be constructed on different level of abstraction ranging from high-level of system behaviors to specific models that represent explicit context, tasks, or functions; (iv) *Component-based frameworks,* which are skeletons of component-based system implementation that can be specialized by a component developer to produce custom components [19]. They are constructed based on system components and their relationships, which are usually composed by reusable, replaceable, and extensible modules; and (v) *Model-based frameworks,* which capture information in abstract concrete representations, applying simplification to understand the essence and details of a system, and to provide answers related to the performance of a system based on models [20]. A set of models is an enabler of constructing a model-based framework.

3.3. A brief analysis the components of frameworks

The frameworks for developing CPSs are combination of various components. The analyzed frameworks cover a large variety of application purposes including security, trustworthiness, reliability, data analysis and management, resource management, system verification, and adaptation issues. To impose on order and to create a comprehensive structure for future studies, we classified the frameworks into seven groups according to the application purposes: (i) control [16] [20]; (ii) dependability [21] [22] [23]; (iii) network and communication aspect [24] [25] [26] ; (iv) resource management [18] [27] [28]; (v) data-driven [29] [30]; (vi) reasoning for smartness [15] [17] [19] [31] [32] [33]; and (vii) compositionality [34]. The frameworks reported in the literature were classified by their type and was analyzed from the aspect of: (i) the set of included concepts and relationships, (ii) formal logical expressions, (iii) architectural arrangements. (iv) information flows, (v) associated computational methods, and (vi) implementation guidelines. The architectural arrangements were further analyzed from the perspective of (a) abstraction level, (b) generic structure, (c) functional structure, (d) component-based structure, and (d) behavioral structure. We have analyzed 33 frameworks that were specifically developed for supporting the design and implementation of CPSs. The result of the analysis is shown in Table 1. The shaded cells represent components of the particular frameworks.

Table 1. Analysis of the components of the framework.

FW Types	CPSs Design aspect	Issues	Ref.	C	Log	Architectural structure					Inf	ComP	Imp	Outcome
						Abs	Gen	FuN	Com	Beh				
Conceptual	Dependability	Reliability	[21]	■	■	■		■				■		Analytical
	Networking and communication	Network management and operation	[24]	■	■									Predictive
	Resource management	Self-organization based Resource Reconfiguration	[27]	■		■								Analytical
	Data-driven	Prediction improvement	[29]	■	■								■	Decision-Making
	Reasoning	**Comprehensive (learning, Adaptation)**	**[15]**	■		■								Explanatory
		Knowledge modeling, Decision support	**[31]**	■			■	■				■	■	Decision-Making
Logical	**Reasoning**	**Knowledge sharing; adapt to changes**	**[17]**	■	■									Decision-Making
Architecture	Dependability	Security	[22]	■			■					■	■	Analytical
	Networking and communication	Communication	[25]	■		■	■	■	■				■	Decision-Making
		Interoperability	[26]	■			■	■					■	Analytical
	Resource management	Comprehensive	[18]	■			■	■						Explanatory
	Data-driven	Service-oriented (Big data analytics)	[30]	■			■							Predictive
	Reasoning	**Knowledge repositorty, Adaptation**	**[32]**	■			■						■	Decision-Making
	Compostionality	System-level verification	[34]	■	■	■	■			■				Explanatory
Component-based	**Reasoning**	**Context reasoning**	**[19]**	■	■			■	■		■			Analytical
	Control	Design- Computational method	[16]	■		■		■	■			■	■	Decision-Making
Model-based	Control	Interoperability	[20]	■										Predictive
	Dependability	resilience/effectiveness	[23]	■	■		■	■						Analytical
	Resource management	resource sharing	[28]	■			■					■		Analytical
	Reasoning	**Awareness**	**[33]**	■	■					■				Explanatory

Remark: C =: Concepts; Log=: Logical Expression; Abs =: Abstration; Gen =: Generic; FuN =: Functional-Based; Com=: Component-based; Beh =: Behavioural; Inf =: Informtion construct; ComP=: Computational methods; Imp=: Implementation guidelines

The underlying concept of a framework is essential for defining guiding principles how a framework should be used. However, based on the objectives and utilities of frameworks, explorative, explanatory, analytical, predictive and decision-making outcomes are distinguished. Our analysis showed that most of the proposed frameworks are supporting analytical problem solving, predictive modeling, and decision making. Frameworks play multiple roles in the design process of CPSs, e.g.: (i) support observation and understanding of a phenomenon, (ii) address problems and propose problem-solving methods; (iii) offer means to combine cross-domain knowledge to create new concepts, (iv) provide a logical structure to verify conceptual ideas, and (v) provide multi-level architectural structure that can be seen as a blueprint for designing a system.

Constructing a framework may happen in an infinite number of ways due to a range of possible components that may include a set of abstract entities ranging from high-level system abstraction to low-level of component operation. This indicates that there is no standard method or *de facto* rules for guiding the construction process of a framework. This issue also makes a dilemma with regards to utilization of high-level abstraction frameworks that aim at explaining system-level behaviors as seen in [33] [34]. These publications could not offer guidelines how systems should be implemented driven by frameworks. Opposing most of the frameworks that capture low-level of operations, they propose implementation guidelines, but they do not provide information on the concerned system-level characteristic. Thus, it is probable that implementation of system-level properties like smartness could not be guaranteed. Consequently, the exemplified frameworks do not address the compositionality issue explicitly.

4. Reasoning aspects in S-CPSs and relevant frameworks

4.1. Review of aspects of reasoning in S-CPSs

System smartness needs a particular synthesis of reasoning mechanisms associated with knowledge transformation such as context-based reasoning, situation awareness, goal driven strategy planning, functional adaptation and behavioral evolution that interplay in a synergistic manner to produce smartness. In this section, we reviewed reasoning aspects and explored their relationships.

(i) ***Knowledge,*** i.e. is productive awareness and familiarity with semantic meaning of information in a given context. It is used for supporting the systems to perform cognitive processes based on common functions including sensing, perception, building situated awareness, reasoning and learning, planning and control, and actuating through a feedback-controlled loop [8].

(ii) ***System awareness,*** i.e., modeling of and reasoning about what is a product of knowledge processing and monitoring. Systems operating in dynamically changing environment should be able to build up awareness about (a) their context of operation (e.g. need for dynamic adaptation of tasks and objectives as response to external factors), (b) the situation they are operating in (e.g. understanding of the impact of the environment on the operation), and (c) self-awareness (e.g. understanding of the system's abilities and the availability of its resources for performing operations) [35].

(iii) ***Reasoning mechanism***, i.e. how a system basically uses its knowledge to figure out what it needs to know from what is already known. It refers to an inference process that involves logical operations on logical statements to draw conclusions. Several reasoning methods were applied in the context of smart systems, intelligent systems, and autonomous systems. For example, rule-based reasoning offers a natural way of handling and reasoning about knowledge, it has a modular nature offering easy extendibility of rules, and uniform representation of knowledge [36]. Probabilistic reasoning, such as Bayesian Networks (BNs), and Hidden Markov Models (HMM), is appropriate for reasoning with uncertainty [37]. Ontology based reasoning is typically used for conceptualizing the relationships between entities. It is typically coupled to other reasoning mechanism, such as rule-based reasoning to infer a situation from context information [38] or to case-based reasoning [39], in order to automate the decision-making process.

(iv) ***Decision making***, i.e. completion of a process of choosing the best alternative among multiple actions for the purposes of attaining a goal or a set of goals. Logical reasoning is performed as a brain behind decision-making processes [40]. This implies that knowledge is required for reasoning to make decision, especially in complex, non-linear problems where the system operation is defined by implicit objectives during operations [41].

(v) ***System adaptation***, i.e. the planning of adaptation based on the outcome of previous processes. The self-adaptive capability should incorporate reasoning about the objective of the system operation, investigating possible strategies for performing adaptation, and planning and executing adaptation plans based on available cyber and hardware resources [42]. An implementation of true self-adaptive behavior is still in its infancy.

4.2. An analysis of frameworks for computational reasoning

Frameworks for computational reasoning were analyzed from the same aspects as frameworks of CPSs. Reasoning frameworks are shown with bolded fonts in Table 1. Similar to the frameworks for CPSs, we found no comprehensive framework that provides multi-aspect guidelines addressing all relevant aspects of designing reasoning mechanisms for smart CPS. Only the framework of knowledge modeling and decision making by [31] provides support for designing computational methods for reasoning at the time of designing cyber physical systems. However, this framework lacks features that would facilitate the composition of reasoning methods and analysis of their interoperability. It is also notable that the many frameworks lack support of designing architecture of computational reasoning mechanisms and information flows between components.

No holistic framework covering all aspects of reasoning mechanism has been developed so far. Existing reasoning frameworks for designing adaptive software systems facilitate only specific aspects such as context awareness or knowledge modeling and management to support the execution of self-adaptive process loop. Integration of these dedicated frameworks into a holistic solution should go beyond simple interconnection of these framework implementations. Their fundamental concepts architecture, architecture, and information flow should be based on the same principles and guidelines. Without a rigorous unifying framework, system integration and integration of the analysis results for various frameworks remains ad hoc. This requires a multi-aspect framework that can integrate reasoning mechanisms on various abstraction levels ranging from defining system objectives to concreate implementation of adaptation at run-time.

5. Discussion of findings

As discussed by many researchers, the paradigm of cyber-physical systems is rapidly evolving. In the process of transition from first generation CPSs to second generation CPSs, the system capabilities of self-regulation and self-tuning should be replaced by cognitive capabilities included self-awareness and self-adaptation [7]. They go beyond what can be analyzed and designed based solely on reductionism and traditional model-based approach. In describing system smartness, the intended operation of the entire system should be concerned at designing the reasoning enabler of S-CPSs. Based on the aspects of reasoning in S-CPSs, it is able to create several procedural reasoning processes including sensing, situation awareness, situated reasoning, planning, decision-making, adapting, and actuating. Transforming knowledge throughout different processes require different appropriate reasoning methods. This means it is impossible to apply a single reasoning method through the entire processes. It is not only a selection of applicable methods, but also the interoperability of the selected methods must be taken into consideration. This implies that reasoning for S-CPSs should be manifested in compositionality.

However, the frameworks currently used for the development of traditional CPSs typically support model-based development and operation and entail component-based implementation. Consequently, they are facilitating a composability orientated approach in system development. We claim that there was no specific framework proposed for a compositional design for a smart reasoning platform in the recent literature. We also argue that there is a high probability that one single monolithic framework would not be sufficient. Instead there seems to be a need for a composite framework that is able to capture the various aspects of system conceptualization and design that can be the basis of multi-aspect system models, e.g. system behaviors, including reasoning methods and their interoperability, knowledge transformation throughout the multiple reasoning processes, exploration of adaptation strategies, and self-adaptation.

6. Conclusion and suggestions for the future work

The frameworks that underpin the conceptualization of S-CPSs play an important role. The major issue is what kind of framework is needed and how this framework should facilitate the development of S-CPSs. It can be conceived that the compositionality enabling framework should capture at least conceptual, functional, architectural, informational, interoperation, behavioral aspects. It also needs further investigation if a compositionality enabling framework should appear in the form of a meta-framework (abstract) or a semantically integrated (concrete) framework. Another conclusion is related to coping with the challenge of both software-enabled constituent integration and multi-aspect knowledge-synthesis. It seems to be necessary to import many relevant principles of compositional software development, but it will ultimately be sufficient. Holistically smart system operation needs integration of data, information and knowledge, which can be achieved only through number of semantic transformations. Future research should focus on data, information and knowledge fusing technologies that enable the implementation of compositionality.

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