Requirements Engineering for Cyber-Physical Systems

Challenges in the Context of "Industrie 4.0"

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Abstract. According to a widely shared view, manufacturing is currently undergoing its fourth industrial revolution, termed "Industrie 4.0" in the high-tech strategy of the German government. Smart Factories with vertically and horizontally integrated production systems are enabled through the realization of machines, storage systems and utilities as Cyber-Physical Systems (CPS), which are able to share information, act, and control each other autonomously. The development of CPS requires the collaboration of different disciplines, like mechanical engineering, electrical engineering and computer science. This creates new challenges for Requirements Engineering (RE), which needs to establish a common perception of the targeted CPS for the involved stakeholders. This paper will elaborate the specific challenges in RE for CPS based on a literature review. Natural Language Processing (NLP) is used as an approach to automatically translate shared informal requirements specifications to formal domain specific models for the involved disciplines, to develop a comprehensive RE methodology for CPS.

Keywords: Requirements Engineering, Industrie 4.0, Cyber-Physical Systems, Natural Language Processing, MSEE Integrated Project.

1 Introduction

Three industrial revolutions have led to paradigm changes in the domain of manufacturing so far: mechanization through water and steam power, mass production in assembly lines, and automation using information technology. However, for the last years researchers and policy makers have increasingly advocated an upcoming fourth industrial revolution. For example, the German government promotes the computerization of manufacturing industries in their "Industrie 4.0" program [1], while in the

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United States the Smart Manufacturing Leadership Coalition (SMLC) facilitates the broad adoption of manufacturing intelligence [2]. In order to follow these trends, elements like machines, storage systems and utilities need to be able to share information, as well as act and control each other autonomously. Such systems are called Cyber-Physical Systems (CPS) [3]. CPS emerge through the complex networking and integration of embedded systems, application systems, and infrastructure, enabled by human machine interaction. In contrast to conventional systems used for production or logistics, they can be seen as *systems of systems*, which require the collaboration of different disciplines such as mechanical engineering, electrical engineering, and computer science for their realization [4].

For the development of today's conventional production systems, methods and tools from the field of systems engineering are applied, which deal with the development of complex solutions, consisting of a large number of components whose interactions shall produce a desired result [5]. Systems have to be both appropriate and cost effective [6], which makes understanding the requirements of the customer and other affected stakeholders a prerequisite for successful systems engineering [7]. They are needed for planning the development process, assessing the impact of changes and testing the acceptance of the outcomes [8]. Inadequate Requirements Engineering (RE) is one of the main sources for the failure of development projects and culminates in exceeding budgets, missing functionalities or even the abortion of the project [9]. Consequently, in concordance with the principles of concurrent engineering, RE continues along the development process of a system and secures a consistent and traceable elicitation and management of requirements. There is an ongoing interaction be- tween RE and the development phases in systems engineering [8].

Therefore, adequate RE is also the key to success or failure of every CPS development project. However, CPS differ from conventional production systems in various aspects, leading to new challenges for the RE process. CPS are open systems, which have to be aligned with dynamic user needs in a global context. Furthermore, requirements towards CPS underlie evolutionary changes. The scope and emphasis of the relevant requirements change with respect to the final application and environment of the CPS [4]. Finally, CPS are based on integrating hardware, software, and service components, covering the whole life cycle, from ideation to decommission. The required competencies for CPS development and their support in all life cycle phases have to be included through collaboration with partners from the different disciplines [10].

The objective of this paper is to elaborate the specific challenges of RE for CPS in detail and give first recommendations for their solution. Therefore, in Section 2 the state-of-the-art in CPS and systems requirements engineering is described. Based on this theoretical background, the detailed challenges are extracted from a literature review in Section 3. Natural Language Processing (NLP) is used as an approach to overcome the language barriers between the involved disciplines in Section 4. The conclusion in Section 5 gives an outlook, how a comprehensive RE methodology for CPS could be developed.

2 Theoretical Background

In this chapter, the main characteristics of Cyber-Physical Systems are explained, followed by the state-of-the-art in Requirements Engineering for systems, in order to be able to identify the challenges of RE for CPS.

2.1 Cyber-Physical Systems

Cyber-Physical Systems (CPS) can be seen as systems of integrated computational elements interacting with physical entities. In contrast to embedded systems where the focus is more on the computational elements, CPS emphasize the link between the computational and physical elements. In this sense, CPS represent a network of inter- acting elements with physical input and output instead of as standalone devices. CPS are therefore complex systems and can be characterized by five distinct characteristics [4].

1. **Merge of physical and virtual world:** CPS involve a multitude of parallel and interlinked sensors, computers, and machines, which collect and interpret data to decide on this basis and control real world physical processes. Thus, systems engineering needs to integrate industrial process and control systems with information technology [11].
2. **System of systems with dynamic system borders:** Depending on application and task, different CPS are arranged into a system of systems for a limited time. Consequently, CPS have to be able to actively configure services and networks with other systems or parts of systems, which may be unknown in the beginning, and provide new and composite components and services in a controlled way [12].
3. **Context-aware, partially or fully self-governed, with active control in real-time:** Relating to their specific task, CPS use the relevant services to capture their application environment and situation to coordinate a useful and valuable system behavior for all involved stakeholders. This requires continuous monitoring and assessment of environmental and application data [13].
4. **Collaborative systems with distributed and alternating control:** The CPS has to be able to perceive and assess the situation, the activities to be executed and the local and global goals of the actors. Decisions are based on this information and lead to a cooperative learning process [14].
5. **Comprehensive human-system interaction:** CPS have to incorporate human behavior also on a physical level, which requires the use of sensor and actuator technology, e.g. in the form of artificial limps. This leads to an extension of the human capacity to act and human cognition, supported by multimodal control interfaces, recognition, and interpretation of human behavior and interactive decision making between the system and single persons or groups [15].

2.2 Systems Requirements Engineering

Requirements define the needs of organizations, groups, or people along with their surroundings and describe what a solution must offer in order to satisfy those needs.

Their formulation, documentation, and maintenance are the main objectives of Requirements Engineering. It describes *"a process, in which the needs of one or many stakeholders and their environment are determined to find the solution for a specific problem"* [16]. Systems engineering involves RE as an independent activity not restricted to a specific development phase or project. There is an ongoing interaction between RE and the development phases in systems engineering, as can be shown with the V-Model [17] in Fig. 1:

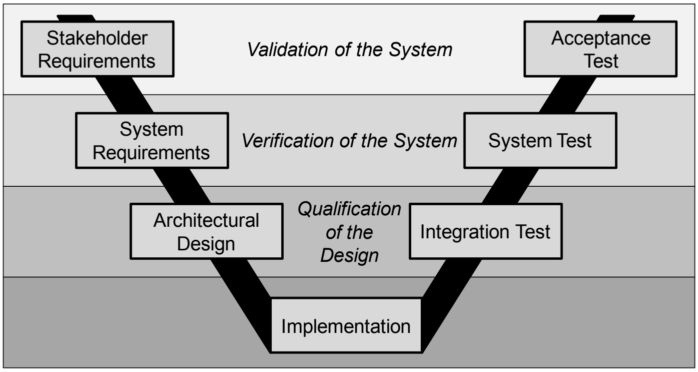

Fig. 1. Requirements engineering in the V-Model, according to [8]

Fig. 1 shows the activities performed during the individual phases of system devel- opment in separate layers. Requirements are important for all layers in systems engi- neering. It is necessary to validate requirements from lower layers against require- ments from upper layers and the stakeholder needs in order to check that the require- ments represent the original goals for the system development. Furthermore, the de- sign and implementation of the system has to be verified to check that it fulfills the requirements. In order to support the different tasks, the specification of requirements has to follow several contradictory objectives. To minimize the time to write require- ments and make them understandable for all of the involved stakeholders, often an informal approach is used without any constraints on how requirements are specified e.g. in natural language. However, to minimize the time needed to validate require- ments and verify the system design, a formal specification is required. Abstract se- mantics and syntax enable automatic checks like formal verification. Often a trade-off between formal and informal specification is implemented, e.g. by using controlled languages [18] or boilerplate techniques [19].

3 Challenges of Requirements Engineering for Cyber-Physical Systems

In their research agenda for CPS, Geisberger and Broy [4] identify engineering challenges for Cyber-Physical Systems. They emphasize the central role of

Requirements Engineering for CPS development, integration, maintenance and evolution. Involving users and other stakeholders from different domains actively into CPS development from the beginning and adaption of CPS to needs, habits and competences of the users, would require a more informal approach for requirements specification. However, the specification of formal requirements models is requested for detailing of requirements and mapping them to system elements, integration of mechanical engineering models with digital models from software and systems engineering for the collabora- tive description of requirements, as well as their implementation, validation, evolution and communication between stakeholders from different disciplines.

Penzenstadler and Eckhardt [20] agree that ensuring communication and consistency of requirements for CPS is a challenge due to the variety of stakeholders involved. Furthermore, viewing CPS as a system of systems, the independence of the constituent systems and their evolutionary nature leads to exceptionally distributed RE activities for a multitude of stakeholders with isolated RE approaches. The authors propose a RE content model for requirements elicitation and documentation at different levels as a solution. However this requires the adoption of a formal model by all stakeholders involved. Ncube [21] focuses on the systems of systems aspect. RE needs concepts and techniques to specify key interoperation influencing requirements. Furthermore, the complexity of systems of systems leaves requirements fragmented among many disciplines and sometimes conflicting, unstable, unknowable or not fully defined. Finally, the properties of systems of systems emerge from the cumulative interactions of the single systems. Therefore, RE methods and tools have to be able to verify emergent effects against requirements with predictable results.

The analyzed literature shows that Requirements Engineering for CPS creates specific challenges, especially for requirements specification and verification. On the one hand, a way has to be found to involve the system user into the development process and dynamically exchange requirements between a multitude of stakeholders from different disciplines. This demands for a more informal, generic requirements specification. On the other hand, for the identification of the system elements and emergent effects for the verification of requirements, more formal and domain specific modeling of requirements is needed. A solution could be the application of both, formal and informal requirements specification, connected by a (semi-)automatic translation. Natural Language Processing (NLP) could be used in such an approach.

4 Natural Language Processing

The CESAR project provides an overview of different Requirements Specification Languages (RSL) for systems engineering, according to their degree of formality [22]. In textual form, formality is increased from Guided Natural Language, over boilerplate RSL up to pattern based RSL. Guided Natural Language specifications are achieved by checking free text descriptions with a domain specific dictionary, highlighting ambiguous terms. Boilerplates are pre-formulated requirements, which are parameterized to describe stakeholders, capabilities or attributes, while patterns use a stronger formalism with fixed semantics. In graphical form, SysML is a visual modeling language for system design based on UML, which can cover multiple degrees of formality with its various underlying diagrams.

In the development of large and complex CPS one is highly interested in a high degree of automation. This becomes accessible, although not easy, when formal descriptions are used that are readable by machines. Conversely, formal descriptions are often not accessible for end users and differ heavily between the disciplines involved in CPS development. The most basic format, understood by the end user and all stakeholders is natural language. Therefore, at higher levels of abstractions, e.g. for stakeholder and system requirements, most of the descriptions are given in natural language text. However, they are therefore barely accessible for automation.

Natural language processing techniques can be utilized to overcome this problem and support requirements exchange between the system user and the stakeholders in CPS development. Several algorithms and tools for syntax [23] and semantics analysis [24] have been proposed for this purpose. Due to ambiguities that are contained in natural language one needs to take into account a trade-off between the degree of automation and the restrictions that are assumed on the text. In order to achieve 100% automation, all ambiguities need to be avoided which can e.g. be achieved by controlled languages [18] or boilerplate techniques [19]. This comes to the cost of basically learning a new language, which may not be practical implementable when texts are written by many stakeholders from different disciplines, which prohibits the application of domain specific ontologies or boilerplates.

Alternative approaches employ a dialog system between the designer and the machine in order resolve possible ambiguities [25]. The machine tries to process as much information as possible automatically and whenever no reliable conclusion can be implied the designer is asked for assistance. This approach has e.g. been used to extract formal models in UML or SysML to represent structure from natural language use case scenarios [26]. Also for translating natural language requirements to formal expressions, NLP techniques have been used [27]. Finally, NLP techniques can assist specification engineers when writing texts. Simple techniques such as spell checking and grammar checking are already common practice in state-of-the-art word processing applications. Techniques that go beyond these are the automatic detection of requirement sentences, measuring the clarity of a sentence, or measure the validity of the sentence with respect to specification guidelines.

The application of NLP to Requirements Engineering for CPS could help to solve some of the challenges identified in the previous section. User involvement would be supported, as requirements and validation feedback could be informally specified in natural language and callback in the case of ambiguities. Furthermore, information exchanged between stakeholders of different disciplines, e.g. in requirements workshops, could be semi-automatically transformed into the correct formal models for each discipline involved.

5 Conclusion

The development of CPS creates new specific challenges for Requirements Engineering, in contrast to conventional production systems. Relevant characteristics of CPS that have to be observed are the integration of physical and virtual elements, the constitution of CPS as systems of systems, context awareness, distributed control and human-system interaction. This results, on the one hand in intensified user collaboration and on the other hand in the involvement of many different disciplines during system development. In spite of distributed RE activities, communication and con- sistency of requirements have to be secured. Interoperability of the CPS elements has to be guaranteed by specific requirements. Dynamically changing and emergent behavior must be included in the CPS specification. Natural language could be used as an informal requirements specification for exchange between the system user and stakeholders from various disciplines, but is often unclear and ambiguous. Further- more, it can barely be handled automatically. As an approach to keep natural language as the form to exchange requirements, while still having unambiguous and automatically processible formal specifications, Natural Language Processing is proposed. The application of NLP could establish a dialog system, which supports resolving ambiguities and semi-automatically transform requirements in natural language into formal domain specific models. Further research in this area will be conducted to concretize NLP application in RE for CPS and propose first practical methods and tools.

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