Technical Report

Protocol for:

Patterns for Self-Adaptation in Cyber-Physical Systems

A Systematic Mapping Study

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Technical Report No. IFS-CDL 16-02

Issued: October 2016

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1 Introduction

Engineering *Cyber-Physical Production Systems (CPPS)* is challenging as these systems have to handle uncertainty and change during operation. A typical approach to deal with uncertainty is enhancing the system with self-adaptation capabilities.

However, realizing self-adaptation in CPPS is particularly challenging for software engineers due to the specific characteristics of these systems, including the seamless integration of computational and physical components, the inherent heterogeneity and large scale of such systems, and their open-endedness.

Therefore, it is important to provide consolidated knowledge to practitioners about how self-adaptation mechanisms can be used in addressing uncertainty in CPPS. Since research work specifically in the CPPS domain is rare, we take a generalization step and broaden the scope of the study to investigate the larger family of *Cyber-Physical Systems (CPS)*. CPPS form a distinct sub-category of the more general family of CPS. Though distinctively focused on production, CPPS, as a member of the CPS family, share many common traits with other types of CPS. Thus this study aims to investigate and assess state-of-the-art approaches of self-adaptation mechanisms and models applied to CPS across the technology stack from a software architecture perspective. To achieve this goal, we use a systematic mapping study (SMS) as research method. From this study, we consolidate design and engineering knowledge on self-adaptation in CPS and capture the derived knowledge base in form of recurring patterns. An additional

focus of investigation are CPS in the industrial production and manufacturing domain.

The patterns can support future CPS and also CPPS designers and engineers with the realization and coordination of self-adaptation concerns.

2 Research Method

In order to get an overview of the current state of literature focusing on self-adaptation approaches in CPS and get insights into recurring patterns and models, we perform a *systematic mapping study (SMS)*. To apply this research method in an unbiased, objective and systematic way, we follow the guidelines by Kitchenham and Charters [2]. In contrast to a systematic literature review, a systematic mapping study is applied to review a specific software engineering topic area and classifies primary research papers in that specific domain [1]. Thus the research questions for such a study are generally broader defined and more high level to provide an overview of a certain topic [1].

Research Question

To achieve the goal, the study aims to answer the following main research question:

RQ: How is self-adaption applied in cyber-physical systems in general?

The answer to this research question aims to identify how state-of-art approaches make use of self-adaptation mechanisms and models while architecting CPS. In addition, the study focuses on self-adaptation applied in CPS in the manufacturing domain.

Study Process

The study starts with defining an initial protocol. Since the protocol is a critical element of a systematic study, it is piloted by reviewing a sample of 4 papers. In the following, the study protocol is revised with respect to the pilot results. Once all researchers agree on the protocol, the phase of conducting the study starts by applying the search strategy and selection criteria, data extraction strategy, data analysis methods, and reporting strategy defined in the protocol.

The SMS will be conducted by 6 researchers. Two reviewers will define the initial protocol. The retrieving and selecting publications process will be performed by two other reviewers. The remaining four reviewers will then extract data from the selected studies. Finally, the four reviewers will synthesize and analyze the data as well as write the final study report. These final steps will be crosschecked by the other two reviewers. Fig. 1 shows the overall systematic mapping study process that is planned to be applied. Detailed information about each step is provided in the following sections.

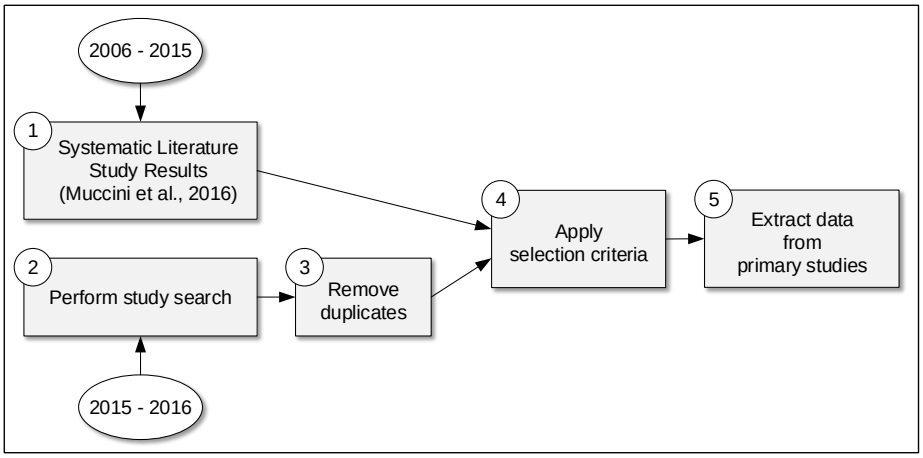

Fig. 1. Planned systematic mapping study process

3 Search and Selection Strategy

The initial set of primary studies under investigation is based on the replication package of the study "Self-Adaptation for Cyber-Physical Systems: A Systematic Literature Review" by Muccini et al. [3], where the search and selection strategy as well as the inclusion/exclusion criteria are defined, that were used for retrieving the studies. The scope of the systematic literature review includes studies from 2006 to mid 2015. Therefore, the review protocol from this SLR is reused to extend the set of primary studies by searching and selecting studies that were published since mid 2015 (end of scope of the SLR) and are relevant for this SMS.

Sources

In order to cover as many as possible relevant literature about self-adaptation applied in CPS on an architectural level, we expect to identify candidate papers based on searches in four of the largest scientific online databases as sources of primary studies:

- IEEE Xplore Digital Library
- ACM Digital Library
- SpringerLink
- ScienceDirect

Search Process and Documentation

The following search string will be used to retrieve relevant primary studies [3]:

```
(software OR system) AND (architect* OR
"high-level design" OR "conceptual design"
OR "abstract design") AND ("cyber-physical"
OR "distributed control system" OR "networked
control system" OR "sensor actuator network"
OR "distributed scada" OR "federated embedded
system")
```

The involved reviewers will apply the search strategy to identify potential study candidates. The search results will be documented in a spreadsheet where the identified candidate papers will be collected and stored. In addition, duplicates will be removed. Each paper will be indexed by a unique identifier and title.

Selection Criteria

The identified set of candidate studies will be carefully assessed and filtered for their actual relevance to answer the research question by at least two reviewers. Therefore, the study goals and well-defined study selection criteria will be used to determine which studies to include or exclude. Hence we extended the inclusion and exclusion criteria defined in the SLR protocol [3]. A study is included if it is compliant to the following inclusion and exclusion criteria:

IC 1: Studies proposing, leveraging, or analyzing an architectural solution, architectural method or technique specific for CPS.
IC 2 (updated): Studies in which multiple types of self-adaptation are explicitly used as an instrument to engineer CPS.
IC 3: Studies subject to peer review [4] (e.g., journal papers, papers published as part of conference proceedings).
IC 4: Studies published since 2006.
IC 5 (new): Studies in which self-adaptation mechanisms are applied at least at two layers of the technology stack.
IC 6 (new): Studies comprising at least a minimal description of a concrete scenario or use case.

EC 1: Studies that are written in a language other than English, or that are not available in full-text.
EC 2: Secondary studies (e.g., systematic literature reviews, surveys, etc.).
EC 3 (new): Studies of poor quality (e.g., poorly described architecture or use case).

Results of selections and rejections will be crosschecked by two other reviewers and any disagreements will be discussed and resolved. Finally, the reviewers will finalize the set of studies to be included in the data collection process.

4 Data Extraction

For each study remaining after the selection process, involved reviewers will independently investigate and extract pre-defined data. Table 1 gives an overview of the data items that will be collected from the primary studies to answer the research question.

First of all, the data extraction form should provide standard information about the publication to be investigated (study title, publication year, venue, country). In addition, data items needed to answer the research question of the SMS are included. Data item (D5) captures the reported application domain of the study to ensure representative and evaluated results. In addition, the application description supports a better understanding of the approach, and maybe allows to draw conclusions about a more beneficial application of particular adaptation mechanisms in one domain. Data item (D9) focuses on different types of addressed uncertainties in the environment, in parts of the system itself, and in requirements/goals for which adaptation is applied. This knowledge supports a better understanding of the focus of current research and shows what uncertainty types are mostly addressed and what areas of uncertainties are not yet addressed at all. Data item (D10) summarizes different purposes and goals of applying adaptation mechanisms in a CPS, while data item (D11) is used to identify and investigate the types of adaptation mechanisms applied in the study. To generalize the technology stack that is commonly used for applying adaptation mechanisms, data item (D12) is used to create a general layer model. Finally, data item (D13) captures the interaction and coordination between different adaptation mechanisms across the layers.

The definition of pre-defined extraction forms with data items allows to survey each study in the same way (objectively) and reduces the room for bias. Each primary study will be assigned to and reviewed by at least two reviewers. After discussion of the individual results for each study with the other reviewers, the collected and agreed data will be documented in a spreadsheet in a consistent manner.

5 Data Analysis & Reporting

The process of synthesizing and analyzing the collected data includes the following steps:

1. Summary of identified application domains where proposed self-adaptation approaches are applied
2. Listing of identified types of adaptation mechanisms and how they are combined across the technology stack in CPS architectures
3. Analysis of associated data and characteristics described in the studies
4. Create descriptive representation of the collected data
5. Synthesis of the results to derive recurring patterns, models or tactics
6. Listing of potential and limitations for further research in the context of self-adaptation mechanisms for CPS

Table 1. Data Extraction Form

Data Item - Standard Information	
D1	Study title
D2	Publication year
D3	Venue
D4	Country
Data Item - Study Information	
D5	Application domain
D6	Overall architectural style
D7	Overall system goal
D8	Type of distribution
D9	Uncertainties considered
D10	Adaptation purposes/goals
D11	Adaptation mechanisms applied
D12	Location of the adaptation mechanisms in the technology stack
D13	Inter-adaptation coordination mechanisms

For analyzing and interpreting the collected data with respect to the research question, descriptive statistics have been applied. The results of the analysis describe the most interesting aspects of the data set and show frequency distributions, central tendencies as well as dispersions. The distribution density of variables are visualized in form of histograms or pie charts. Finally, the results are documented in a spreadsheet[1].

6 Threats to Validity

As with any empirical research, there are threats to the validity of this study that need to be considered. The following potential validity threats have been identified and discussed how to mitigate them in order to strengthen the outcomes of the study.

– *Quality of the selected primary studies.* We defined several inclusion/exclusion criteria to ensure sufficient quality of the selected primary studies for the mapping study, but we do not apply a systematic and detailed quality assessment procedure in order to critically evaluate the quality of each paper as it is common in systematic literature reviews. To mitigate this weakness to some extent, we particularly added the inclusion criterion that each primary study must provide a description of a concrete scenario or use case to

[1] Spreadsheet with analysis results and visual representation is available at: `http://qse.ifs.tuwien.ac.at/ci/material/pub/mde-cpps17/`

draw conclusions for real world applications. In addition, we discussed and excluded some papers with determined poor quality during the mapping study.

- *Adaptation of data items.* Based on our expertise, we defined a set of data items for the data collection of the mapping study. During piloting the data extraction form, we identified some data items that did not always fit for the selected primary studies or were omitted. Based on the results of this initial review, we updated the data extraction form for the remaining studies to ensure a consistent data collection and analysis of the results.
- *Limited CPPS expertise of research team.* The research team consists of experts in the fields of self-adaptation, software architecture, cyber-physical systems and collective intelligence systems without special experience with cyber-physical production systems. In order to reduce bias, we consolidated other researchers with expertise in the CPPS domain and discussed the outcomes.
- *Generality of the results for CPPS.* Due to a general lack of knowledge on self-adaptation specifically in CPPS and the nature of a mapping study to provide a broad overview of a research topic area, we reviewed state-of-the-art self-adaptation approaches related to the larger family of CPS. However, during the mapping study we focused on self-adaptation applied in CPS in the manufacturing domain and eventually included some primary studies with described use cases in this domain. During the data analysis, we came to the conclusion that these studies are no outliers and informally discussed the results with CPPS experts. Nevertheless we are careful to generalize the results for CPPS and see a need for further research in this direction to enhance the validity of the results.
- *Small number of primary studies.* Since CPS and specifically CPPS is still a quite young research field, the number of primary studies providing insight on how self-adaptation can be used in addressing uncertainty in these systems is small. Thus the data extracted from this mapping study can only be considered as evaluation of the current state of the art. This study should be replicated after a period of time.

References

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Appendix: Included Primary Studies

Table 2: Final list of primary studies included in the systematic mapping study

Title	Year	Source
An Architecture of Cyber Physical System based on Service	2012	http://ieeexplore.ieee.org/document/6394593/
An Architecture Framework for Experimentations with Self-Adaptive Cyber-Physical Systems	2015	http://ieeexplore.ieee.org/document/7194662/
C-MAP: Framework for Multi-agent Planning in Cyber Physical Systems	2013	https://link.springer.com/chapter/10.1007/978-3-642-45062-4_32
Context-Aware Vehicular Cyber-Physical Systems with Cloud Support: Architecture, Challenges, and Solutions	2014	http://ieeexplore.ieee.org/document/6871677/
Towards Context-aware Smart Mechatronics Networks: Integrating Swarm Intelligence and Ambient Intelligence	2014	http://ieeexplore.ieee.org/document/6781254/
A multi-agent RFID-enabled distributed control system for a flexible manufacturing shop	2014	https://link.springer.com/article/10.1007/s00170-013-5597-2
Multi-Agent Control System for Real-time Adaptive VVO/CVR in Smart Substation	2012	http://ieeexplore.ieee.org/document/6474950/
Coupling heterogeneous production systems by a multi-agent based cyber-physical production system	2014	http://ieeexplore.ieee.org/document/6945601/
Cloud Robotics: Architecture, Challenges and Applications	2012	http://ieeexplore.ieee.org/document/6201212/
Continuous Collaboration: A Case Study on the Development of an Adaptive Cyber-physical System	2015	http://ieeexplore.ieee.org/document/7173939/
Cloud-Assisted Context-Aware Vehicular Cyber-Physical System for PHEVs in Smart Grid	2015	http://ieeexplore.ieee.org/document/7156067/

Cyber-physical-social system in intelligent transportation	2015	http://ieeexplore.ieee.org/document/7152667/
Cross-layer Virtual/Physical Sensing and Actuation for Resilient Heterogeneous Many-core SoCs	2016	http://ieeexplore.ieee.org/document/7428044/