Collective Intelligence Aspects of Cyber-Physical Social Systems: Results of a Systematic Mapping Study

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1. INTRODUCTION

Cyber-physical systems (CPS) are systems that span the physical and cyber-world by linking objects and process from these spaces (see Fig 1). In a typical CPS data is collected from the physical world via sensors and computation resources from the cyber-space are used to integrate and analyze this data in order to decide on optimal feedback processes which can be put in place by physical actuators.

CPS have started to diffuse into many areas, including mission-critical public transportation, energy services, and industrial production and manufacturing processes. While CPS affect the lives of people that rely on them on a daily basis, they so far only interact with humans as passive consumers. The results of a recent study about adaptation in CPS [Musil et al. 2017] revealed an emerging trend to add an additional "social" layer in a CPS architecture to address human and social factors (see Fig 1). This trend shows the growing recognition of the importance of the social dimension of such CPS and of the need to evolve them into *cyber-physical social systems (CPSS)* [Wang 2010]. CPSS consist not only of software and raw sensing and actuating hardware, but are fundamentally grounded in the behaviour of human actors, who both generate data and make informed decisions based on data [Guo et al. 2015; Cassandras 2016; Xiong et al. 2015].

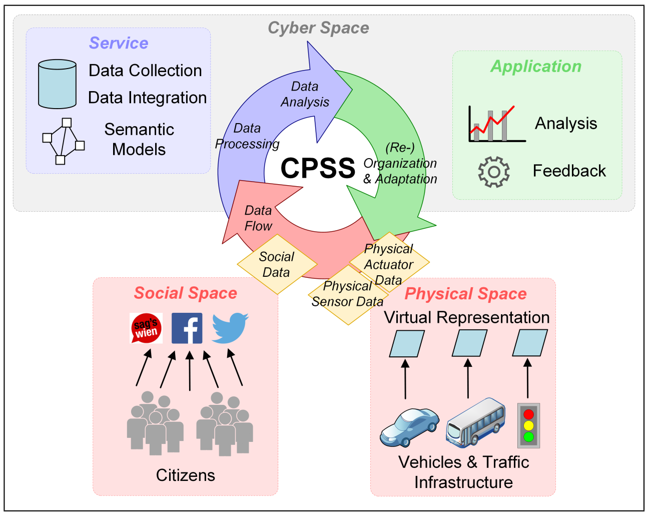

Fig. 1: CPSS example: smart transportation system

As CPSS extend CPS with a social dimension, the question of the relation between CPSS and self-organizational, crowd-powered systems and Collective Intelligence (CI) systems naturally arises. *What are the characteristics of the social component? What social data is used, and how is it integrated by the CPSS to enhance the collective capabilities of the cyber-physical system?* To answer these and other questions, we have recently performed a systematic mapping study of CPSS. In this paper we report on the study and some of our initial findings.

2. RESEARCH APPROACH: A SYSTEMATIC MAPPING STUDY OF CPSS

In order to get an overview of the current state of CPSS literature, we performed a systematic mapping study (SMS) following the guidelines of Kitchenham and Charters [2007]. The goal of a SMS is to review a specific software engineering topic area and to classify primary research papers in that domain in order to provide an overview of a certain topic [Kitchenham et al. 2011]. We briefly summarize the main stages and results of our study here (see Fig. 2) and point the interested reader to its detailed description in our study protocol [Sabou et al. 2018].

Our study focused on the following research questions covering important aspects of CPSS: (1) What is an overarching definition of CPSS? (2) What are the main CPSS characteristics and processes? (3) What architectural approaches are applied to design and describe CPSS? (4) What is the focus of current CPSS research? (5) What are typical application domains and concrete examples of CPSS?

The study was conducted by 3 researchers and 6 students. For each step, students received instructions on how to perform their tasks and data collection sheets.

Papers to be included in the study were identified through a manually performed *(1) keyword-based search* in five of the largest scientific digital libraries (see Fig. 2). The search spanned the period 2007-2017 and focused on the paper title, keywords and abstract. The following search query was applied:

(cyber AND physical AND soci) OR (cyber AND physical AND human) OR (cyber AND physical AND soci* AND distributed) OR (cyber AND physical AND participatory)*

The 3729 papers returned by the keyword-based search were assessed for relevance based on their titles and collected into a spreadsheet which allowed *(2) duplicate detection and removal* and lead to a total of 229 papers. From these papers, 60 papers were identified as relevant for the study by *(3) applying a set of selection criteria* on the information provided in their titles, abstracts and introductions. Researchers involved in the study *(4) assessed the quality* of the candidate papers and selected 22 of them to include into the study.

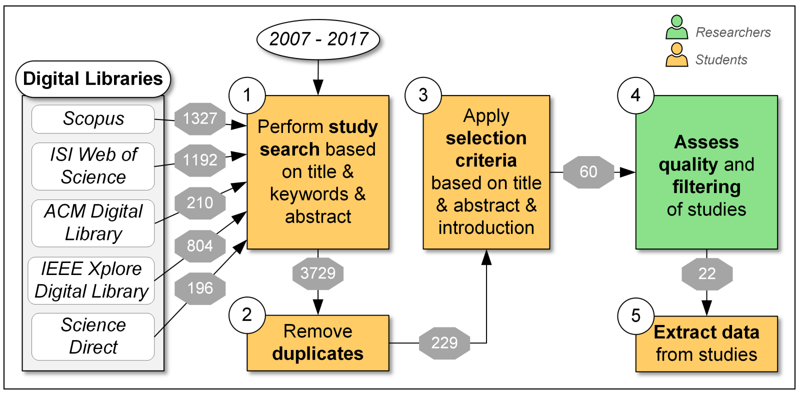

Fig. 2: Systematic mapping study process steps and results

(5) Data extraction was guided by pre-defined extraction forms which allowed to survey each paper in the same way (objectively) and reduced the room for bias. Besides bibliographic information, we collected data-items relevant to our research questions, e.g., *CPSS definition, application domain, CPSS purposes, CPSS process steps/activities, involvement of human actors, data sources, collected data, architecture design*. The process of *analyzing and synthesizing* the collected data included the application of descriptive statistics and interpretation of the results with respect to the research questions.

3. PRELIMINARY RESULTS AND DISCUSSION

In a first round of data extraction we collected data from a total number of 22 papers. Preliminary results of this data collection are summarized in the following. We identified a variety of CPSS application domains, whereby *Smart City/Building/Office/Home* is the most common, followed by *Intelligent Transportation*, *Smart Power & Energy Management*, *Social/Smart Manufacturing* and *Emergency Evacuation & Medical Environment*.

A main characteristic of the surveyed CPSS is that they collect and integrate large amounts of heterogeneous, poly-structured data from a variety of sources. Besides sensor data from physical devices, a hallmark feature of CPSS is that they also capture social data via mobile apps comprising customer feedback, social preferences, emotional status or personal schedule data, but also from social networking services (e.g., Facebook, Twitter), collective rating & review platforms, and information from websites such as safe-place or emergency support centre. Findings show that CPSS typically disseminate consolidated information and triggers back to physical actuators and human users, so that ideally there is an optimization of the locally performed tasks, but also an optimization of system-wide processes and crowd/community needs. In the existing generation of CPSS, this feedback, however, is mostly targeted towards sensors and actuators of the cyber-physical system and less on the actual users or crowds. Many systems use social platforms only as passive data sources and only few of the surveyed CPSS actively disseminate triggers and feed requests back to users or social platforms. Examples of such 'social actuation' are Twitter messages, which inform an appropriate user about identified abnormal energy use with a request to check this issue [Crowley et al. 2013], or notifications about dangerous events via a car infotainment system which delivers information to the driver through in-vehicle screen, audio system or steering wheel vibration [Smirnov et al. 2016].

Looking at the results, three observations can be made, which are discussed in the following.

Firstly, since CPSS originate from CPS, the majority of current application scenarios are closely related to typical CPS application scenarios that are enhanced with some kind of social media or crowdsourcing elements. Subsequently, this also reflects the circumstance that in CPSS scenarios well-known CPS approaches dominate and these methods are then extended with crowd-powered approaches. A CPSS is a system-of-systems, which is integrated with one or more social software or crowdsourcing platforms. In particular, there is currently a lack of methods to explore and analyze the design of data integration, dissemination and actuation phases especially with respect to orchestrated machine and human interaction. The challenge is to provide an appropriate mixture of crowdsourcing and CI approaches to enhance information collection and coordination capabilities of CPSS.

Secondly, it has been observed that in the current state-of-the-art there is a diverse interpretation of the term 'CPSS' and in particular of its 'social' part. These interpretations of social involvement range from humans simply being the users of the system to humans being involved similarly to what is expected for collective intelligence-style systems. We conclude that, in order to further advance CPSS research and the involved socio-technical processes and its associated social data, it is important to come up and agree on a shared terminology and definitions in the research community. Existing know-how from the CI community could certainly support these ambitions.

Thirdly, although CPSS typically tend to affect larger communities or considerable proportions of a society, concerns like privacy, data security, architectural design methods have not been topics of the surveyed papers.

4. CONCLUSION AND FUTURE WORK

The systematic mapping study presented in this paper is an important step towards gaining knowledge about CPSS and the current state-of-the-art. Preliminary results revealed that CPSS are system-of-systems, that heavily depend on a social/crowdsourcing sub-system, but that is used as a passive data source. In a next step, we plan to perform a more detailed analysis of the collected study data. Although the preliminary results are promising, future work is needed especially with regard to the social system component of CPSS and its collective intelligence aspects, in particular to gain a deeper understanding of how dissemination mechanisms can be enhanced with human actuators to close the feedback loop. Furthermore, a more applicable definition of CPSS is needed for a common understanding of what constitutes a CPSS and what not.

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