Towards Collaborative Human-Centric CPS

Javier Berrocal[1], Carlos Canal[2], Jose Garcia-Alonso[1], Juan Hernádez[1], Niko Mäkitalo[3], Tommi Mikkonen[3], and Juan M. Murillo[1]

[1] University of Extremadura, Spain
{jberolm,jgaralo,juanher,juanmamu}@unex.es
[2] University of Málaga, Spain
canal@lcc.uma.es
[3] Tampere University of Technology, Finland
{niko.makitalo,tjm}@cs.tut.fi

Abstract. The massive involvement of human in Cyber-Physical Systems is to a large extend managed through their smart devices. So far, these devices have been used as simple set of sensors capable of capturing the users context and uploading it to a central server. However, this architecture leads to a high consumption of the device's resources. Consumption that is dramatically increased when similar data are used in several CPS. Nevertheless, smart devices even increasing storage and computing capacities allow them to take a more active role in these systems. This paper presents an architecture where smart devices are treated as the bridge between the physical world and the cyber space. In this architecture, smart devices store and infer the user contextual and sociological information, reacting to the state of the user or collaborating with other computational infrastructures. This architecture enables the development of human-centric CPS with clear social orientation.

Keywords: CPS, Human-Cetric CPS, Mobile Computing.

1 Introduction

Cyber-Physical Systems (CPS) are a kind of systems with integrated computational and physical capabilities that can interact with humans. The CPS have been present for many years in different environment, such as supply chain [3] or eHealth [8]. The next step is taking advantage of the high penetration of technology in current society. For that, it is particularly interesting the massive involvement of humans in CPS.

Massive involvement of humans in CPS is to a large extent managed through their smartphones. Such devices are the perfect sensors [5]. They are almost continuously active, maintained by their owners and with the ability of measuring a broad variety of magnitudes, be it positioning, acceleration, direction or heart rate. Consequently they can compose a clear, reliable image of the context of their owners. However, the implication of humans in CPS still remains a challenge and the main reasons for that are the architectural limitations.

While traditional CPS can choose for decentralized architectures, in environment with massive involvement of human (in which data should be stored for further processing) a server-centric architecture is usually applied in order to have a central server in which store and process all the data. Although this architecture has shown adequate for simple scenarios, it poses some limitations for the new generation of CPS. The higher the number of physical world entities involved in the CPS is, the higher storage and computation capacities are required on servers. This could become unmanageable when large population is expected to be involved in the CPS. Limitations are much more serious if one considers that each person may be involved in several CPS. A smartphone acting as a sensor in several CPS simultaneously will get it resources (especially battery) quickly drained. The natural consequence is that the owner of the smartphone will probably lose interest in the benefits provided by the CPS and will leave it. An exodus of active members could make the CPS cease to have meaning.

This paper focuses on enabling a new kind of CPS with significant involvement of humans. The main contribution is at providing an architecture avoiding centralized data storage and computation. The principles behind that are simple: (1) instead of using smart devices as simple sensor devices, we can take advantage of all their storing and computation capabilities; (2) instead of uploading every data about owners context to servers, we leave them on smart devices keeping them reachable and shareable for any CPS interested on them; (3) instead of computing every CPS rule on servers, we delegate the responsibility for the computation of the rules involving the context of people on their smart devices. The main benefit provided by this approach is enabling people to be involved in several CPS whilst minimizing the data traffic, producing a sustainable bandwidth and battery consumptions. Thus, this work contributes to a new generation of human-centric CPS with clear social orientation. This is an ongoing work, which is currently being developed in collaboration among the University of Extremadura, the Tampere University of Technology, and the University of Málaga.

To describe the proposed architecture, this paper is organized as follows. Section 2 details the key challenges of building human-centric CPS. In Section 3, the technical details of our proposed architecture are described. The most relevant related works are discussed in Section 4. Section 5 contains our conclusions.

2 Key Challenges of Building Human-Centric CPS.

Most CPS being built today follow a server-centric architecture. As figure 1 shows, this architecture is usually divided in two spaces. The physical-space, where the network of sensors and actuators are placed, and the cyber-space, where the processes and services controlling the CPS behaviour are deployed.

This architecture leads to very stable and reliable systems that provide suitable support for many environments. However, if we try to apply it to new contexts with massive involvement of people (such as smart-transportation or

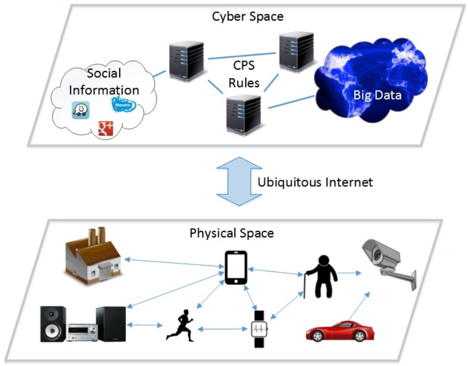

Fig. 1. Common architecture of CPS.

smart-cities scenarios), it suffer limitations related to the amount of information that needs to be gathered.

The constant advances in technology and, specially, the increasing storage and computing capabilities of smart devices allows them to take a more active role in the architecture, enabling the development of this kind of CPS. However, the inclusion of these new role raises important challenges, which can be categorized in two sets, 1) human-related challenges and 2) smartdevices-related challenges. Next, we describe these key challenges.

2.1 Human-Related Challenges.

The increment in the relevance of people in CPS poses a set of challenges that are not addressed by traditional CPS. Following are the most relevant challenges.

CPS adapted to the context of their users. As the general population becomes to use a greater number of smart devices and wearables, the contextual information of the humans can be more easily gathered. This information can be used to adapt the CPS behaviour to the context and needs of their users. Similar benefits can be obtained if a CPS can be adapted to the contextual information of a set of users, providing a more consistent improvement.

There are several approaches working on the development of context-aware CPS [8], [3]. They propose different methods for monitoring and detecting the activities performed by users in order to adapt the deployed CPS to the performed actions. However, in order to exploit all the benefits of human-centric CPS, these systems should be able of obtaining more contextual information of the users, such as their preferences, interests or motivations [15].

Inference of complex sociological data. The complexity of the information obtained from the users mostly depends on the sensors involved. Usually, this information is relatively simple and about the physical state of the user. Nonetheless, from that data much more complex information can be inferred.

Currently, there are some infers adapted to the smartphones capabilities, such as AndroJena [1] or RDFStore-JS [2], that are able to process the raw data stored in the smart devices. However, their deployment still implies a high consumption of the smart devices resources. Therefore, there is a research challenge to develop efficient infers in order to compose more complete profiles of their users.

Privacy issues caused by obtaining contextual and sociological information. Finally, as more contextual and sociological information is inferred from the users, the privacy of the information becomes a serious concern [11].

There are works focused on different aspects of the privacy and security in a CPS. For example, some researches are focused on specific cryptographic mechanisms [13] or new architectures to manage the security [11].

Nevertheless, the management of the users' information also depend on the policies established by each user on each individual system. In environments where the smart devices participate in multiple CPS, the privacy management leads to duplications, since similar policies should be established in each environment. As it is highlighted in [14], there is a key challenge of approaches providing capabilities to easily establish security policies about who, how and when such information can be accessed.

2.2 Smartdevices-Related Challenges.

Directly related with the above described human-related challenges, there is a set of technological challenges. Following are the most relevant ones.

Battery consumption. The amount of the information that can be obtained from a user usually depend on the available battery. Furthermore, once the information is obtained, in a server-centric architecture, such data must be uploaded to a server. Uploading these data also leads to battery consumptions.

Current systems work around this challenge by gathering information every certain time or only when specific situations occurs. This technique sacrifices precision and freshness of the information for battery savings. However, real time information is crucial in many environments and situations. There is a technological challenge for obtaining fresh and updated information without incurring significant consumption of the battery life.

Providing information directly from smart devices. In a traditional CPS architecture, smart devices act as mere sensors and they are only used to gather information. However, this situation can be counterproductive for devices involved in several CPS (since the same information should be uploaded on different servers).

Currently, there are approaches defining models for the deployment of services on smartphones [12], [6]. Thus, the information collected may be stored in the devices and be accessible by any CPS whenever it is required. These studies only establish an architecture to deploy services on mobile devices. To the best of our knowledge, there is a research challenge for the definition of architectures for the deployment and provision of these services in an human-centric CPS.

Service composition and orchestration in human-centric CPS. If users devices start providing services, not only servers but also other smart devices could make use of them. This enables the development of distributed CPS, where smart devices are able to execute rules orchestrating different services.

There are some works in the CPS and mobile fields focused in the orchestration of services, such as [7] or [16]. Nevertheless, in a human-centric CPS, processes should be adapted to the human context [17].

2.3 Addressing the challenges.

All the above challenges should be addressed to build a collaborative human-centric CPS. To address them, existing techniques could be added to traditional CPS. However, more efficient results could be obtained by applying a paradigm shift changing the role played by smart devices. Their ever increasing computing capabilities allow them to be a more active element.

Below, an architecture providing a model for collaborative contextualization of smart devices is detailed. In this architecture, smart devices gather, infer, and store the contextual and sociological information of their users and are able of executing the CPS rules delegated to them. Thus, new human-centric CPS minimizing the data traffic and the battery consumption can be developed.

3 Architecture for Collaborative Human-Centric CPS.

The architecture defined empowers smart devices to take a much more active role in CPS, meeting the challenges described in the previous section. Figure 2 shows a high level view of our proposed architecture. In it, smart devices are treated both, as high level computation entities for the cyber space and as reliable sensor and actuators for the physical world, becoming the bridge between the two spaces.

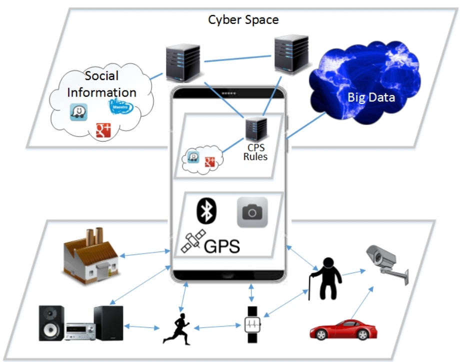

Fig. 2. High level view of the architecture.

Figure 3 shows a technical diagram of the proposed architecture. This architecture is composed of two key components, *Smart Device* and *Human Centric CPS Coordinator*, which are detailed below.

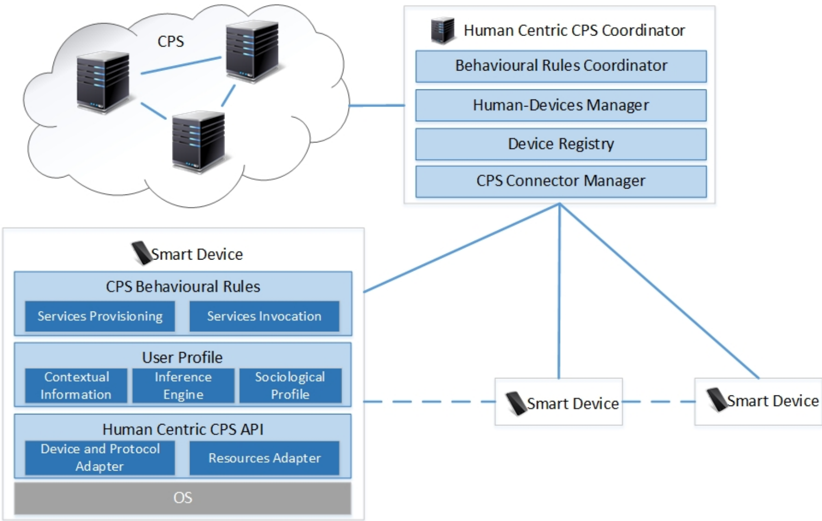

Fig. 3. Technical details of the architecture.

3.1 Smart Device Component.

This component should be present in the smart devices and is in charge of gathering the contextual information of the user, inferring his/her sociological profile and executing some of the CPS rules adapting them to the user's profile. In order to do so, it is divided into three subcomponents.

Human Centric CPS API. This subcomponent abstracts the rest subcomponents from the device operating system and from the access to the device's resources. It offers an API that facilitates the gathering of the user's contextual information.

Since this information can be gathered from internal and from external sensors (connected to the device, e.g. wearables), this subcomponent is divided into two modules. The *Resources Adapter* module provides access to the internal sensors of the device, normalizing the gathered information to be used by the rest of the architecture. The *Device and Protocol Adapter* module provides access and normalizes the information obtained from external sensors.

User Profile. This component generates and maintain the profile of the device owner.To that end, it contains three modules: *Contextual Information*, *Inference Engine* and *Sociological Profile*.

The first module stores all the contextual information gathered using the *Human Centric CPS API*. The information stored is formed by the values provided by the sensors plus a timestamp. This allows us to create a timeline with the user information. The frequency with which the sensors are consulted is defined in the component *CPS Behavioural Rules*.

The *Inference Engine* interprets the contextual information to derive higher level sociological information, such as where users live or work, their usual route to go to work or their coworkers. To do that, this engine execute different rules. For example, in order to infer the people related to the device owner, a rule based on the proximity of other devices is executed. Thus, if the devices of the same people are close to a given device every day in working hours, it will be inferred that their owners are coworkers.

The inferred information is stored in the *Sociological Profile*.

CPS Behavioural Rules. This subcomponent contains the CPS rules delegated on the device. These rules determine the actions that will be performed by the other components of the architecture (i.e. the contextual information that will be gathered, the frequency of obtaining it, or the rules inferring the sociological information). In addition, by having different set of CPS rules, this component facilitates the involvement of the same device in different CPS, reducing the resources consumption and unifying the privacy management.

Additionally, this component is in charge of the communications with other devices. To do that, the *Service Provisioning* module provides services for the provisioning of the owner contextual and sociological information to other elements of the system. Similarly, the *Service Invocation* module is used to consume services from other elements in the CPS. The services provided and consumed are also defined by the CPS rules.

3.2 Human Centric CPS Coordinator

This component manages the devices that are part of a system and coordinates the communication with other CPS. To do so, it is divided into four subcomponents.

CPS Connector Manager. This component is the centralized access point for external systems. For server-centric CPS it would be very difficult to connect and communicate with distributed human-centric CPS. To simplify this integration, this component expose different services for accessing to the CPS functionalities. When one of the exposed services is invoked, the CPS Connector Manager transmits the request to the appropriate devices and manages the coordination between them to provide an unified response.

Device Registry. It maintains information about the different devices managed by the system. These are the data required to identify a device and to communicate with it (i.e. a unique identifier) and the services exposed by the device (such as the users' preferences, the device's battery level, etc.).

Human-Devices Manager. It manages the relationships between users and the devices that are part of the CPS. For each user, devices are classified into three categories: companion, non-companion and external devices. Companion devices are those that have deployed on them the smart device component and, therefore, maintain the sociological profile of their owner. Non-companion devices are other devices owned by users. External devices are devices that are part of the system but are not owned or directly related to any particular users.

Behavioural Rules Coordinator. This component contains the CPS rules defining complex coordinated behaviours between the devices. These rules determine centralized services, which are offered to individual devices, as well as complex services, requiring an aggregation or a coordination between devices that cannot be directly managed by the devices themselves.

3.3 Component interactions.

To better show how the different components interact between them, we are going to details their interaction using an smart transportation CPS example. This example make use of the route that the drivers are going to follow in order to foretell potential traffic problems and, accordingly, to suggest alternative routes to the drivers. To that end, users have a smart device that act as their virtual representative in the system. These devices contain the CPS rules for inferring the usual routes, detecting anomalies or reporting them.

The systems, in order to be able to infer the routes or to detect the anomalies, gathers the contextual information from the user using the Human Centric CPS API. Concretely, the CPS rules indicate the usual frequency at which the device position is obtained, and a different frequency when the device is connected to the car bluetooth. This allows us to obtain more precise information when the user is driving and to save battery when he/she is not.

From the information gathered, the inference engine establish the usual route a user follow to go to work. This information is stored in the sociological profile of the user and also provided as a service, so that the traffic control centre can gather information on the expected traffic. The CPS rules can also establish a trigger to be fired when a user is stopped or driving at low speed. When this happen, the service invocation subcomponent is used to contact other users following a similar route. If most users are experiencing a similar disturbance, an alarm is sent to the traffic control centre.

Finally, the Human Centric CPS Coordinator can provide more complex services. For example, it can offer a service providing the areas of the city that are expected to have a higher traffic density. To provide this information, the Behavioural Rules Coordinator executes some rules, first, searching in the Device Registry those devices capable of providing the expected route of the users; secondly, invoking the specific services to obtain it; and, finally, aggregating and exposing the gathered information to the traffic control authorities.

Therefore, this architecture facilitates the development of a new kind of human-centric CPS, maximizing the collaborative capacities between devices and minimizing the data traffic and the battery consumption.

4 Related Works.

Currently there are a number of works exploiting the capabilities of smart devices in order to make them more active.

VITA [5] proposes an architecture for mobile devices in order to facilitate the development and management of mobile crowdsensing apps (for collecting or aggregating sensing data). Also, this system support the allocation of computational and human tasks to different smartphone in run-time. This system is a step forward in the use of smart devices as an active element in the human-centric CPS, but it still delegates a lot of the responsibility on the servers.

In [10], the authors indicate that mobile phones can be used to form wireless sensor networks in order to sense various information, such as to identify people in crowded areas. In these networks the autonomy of the mobile phone is critical, so that they have optimized the OLSR routing protocol to increase it. This protocol facilitates the achievement of the challenge associated with the battery consumption in human-centric CPS.

PeaaS [4] aims to use smartphones as virtual representation of their owner. By using smartphones in this way, the sociological profiles of the smartphone owners are transparently gathered and provided to other systems. These profiles can be used to better adapt human-centric CPS to the needs and requirements of their users and, since PeaaS revolves around maintaining the users' private information, privacy is greatly improved over traditional systems.

Social Devices [9] aims to exploit the capabilities of smart devices to better acknowledge the social connections between their owners. These social connections can be translated to the cyber space of the CPS to help implement the architecture detailed above. Mainly, Social Devices will help deal with the management of the multiple devices owned by a user and with the coordination of composed services provided by those devices.

These last two works have been used as the basis for developing the architecture presented in this paper.

5 Conclusions.

In this paper, we have presented an ongoing work detailing an architecture for human-centric CPS allowing smart devices to store, infer and provide information on their owners and allowing servers their coordination. The use of this architecture enables the development of collaborative and contextualized human centric CPS. With the additional advantages of reducing the consumption of the smart devices resources and increasing the user privacy. The benefit provided by the architecture, however, are only significant for CPS with certain characteristics. Its focus on adapting the system to the context of the users, makes this architecture to be especially oriented to CPS with massive human involvement. Nevertheless, the proposed architecture is prepared to deal with traditional CPS and can perfectly coexist with them.

As further work, we are planning to apply the defined architecture in real-world scenarios. Concretely, we are implementing it for an automotive scenario. These experiments will be used to measure the reduction in the consumption of the smart devices resources.

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