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Abstract. Nowadays Cyber-Physical Systems gain more and more attention in regard to the Industry 4.0 or Digital Transformation in general. These systems imply the tight integration of physical and software components and are becoming more complex, forming highly inter-connected systems-of-systems. Furthermore, as components and subsystems are becoming more intelligent, there is a need for a paradigm shift towards considering them as ecosystems of collaborative entities with growing levels of autonomy. There is, however, the lack of proper methodologies and support frameworks for the design of such systems. In this context a contribution to an approach for the development of Collaborative Cyber-Physical Systems is proposed. It introduces some core definitions, organizational and architectural aspects. The proposed approach is in line with the design science research methodology and is illustrated with some examples.

Keywords: Collaborative Cyber-Physical Systems, Industry 4.0, design methodology.

1 Introduction

Cyber-Physical Systems (CPS) are becoming complex systems, based on interconnected and tightly coupled hardware and software components with growing level of intelligence. Modern CPS might contain a large number of components, in fact, being a system-of-systems. These new systems are characterized by high levels of intelligence and autonomy of their components and requiring collaboration among those components as well as interaction with outer systems, which led to emergence of the Collaborative Cyber-Physical Systems (CCPS) concept [1]. CCPS focus on improving the networking among components and their joint efforts for accomplishing complex tasks, bridging not only the cyber and physical parts, but also the social one. The physical part of a CCPS consists of sensing and actuating capabilities deployed in a certain environment, while the cyber part ensures the needed abstraction level to integrate the physical devices together and provide high-level functionalities, while also allowing users to be an active part of CCPS.

Modern CCPS face not only technical challenges, but also architectural and organizational issues. Thus the borders of modern systems are extending such that often a CPS can be considered as a complex system or a collaborative ecosystem incorporating various elements with different aims, characteristics and even nature. While the smart objects become smarter and more able to accomplish complex tasks, conventional centralized approaches to organize them might limit their autonomy and thus their capabilities. This raises several issues in terms of organization and management of the smart autonomous entities that are combined to form a system. It also requires paying attention to the aspects of collaboration between them and users.

As some smart objects are mobile, their movements will affect the conditions of the whole system or environment, making it difficult to define strict borders for the smart environment to which they are assigned to, leading to a notion of changing or "fluid" borders. Moreover, for the cases of complex structures containing several autonomous environments/systems an approach to manage the mobility of objects, not only in terms of physical positioning, but also in terms of logical belonging is of particular importance. This also raises the issue of organizing collaboration at different scales and hierarchical layers. Another aspect is that systems need to adapt to changing environments through periodic analysis of those changes and context, developing an appropriate adaptation strategy. One small change may cause a "domino" effect on the other systems within the same ecosystem or affecting the successful accomplishment of a certain task.

Those topics are not well-developed in the literature, as most of the research works on CPS and Internet of Things are focused on low-level aspects, such as protocols, communication technologies, energy optimization, etc., and also on specific applications. Due to the variety of possible organizational approaches and involved technologies, the design process of complex CPS might be very challenging. As such there is a need for a methodological and framework support to help designing new CPS/CCPS. In fact, nowadays each time developers build a new system they start from scratch, possibly facing the same difficulties as in other systems. As an example, [2] identifies such difficulties in the telemedicine CPS solutions, stating the need for an environment that supports multirole distributed teams with "interface units" being used to connect monitoring devices to a "surveillance centre" which serves as hub. The proposed approach in this example goes back again to the classical master-slave paradigm, limiting the system's capabilities. In another work devoted to CPS implementation in the energy sector [3], the same approach with one aggregation point collecting all the data from devices deployed all over a building is presented. In these examples, selected just for illustration purposes, developers went through similar difficulties, namely determining how the devices have to be managed, how to support the human-system interaction, coping with different hierarchical layers, etc. In most cases mobility is not even considered. In this context, this work is a part of initiative to provide CPS designers with supportive techniques, strategies, and tools for the development, integration and evaluation of CPS. The aimed methodology and support framework needs to be general in order to be applicable to different application areas.

Based on above mentioned aspects, the following research question is defined:

> ***What could be a suitable set of models and organizational structures to support the increasing complexity of evolving CCPSs?***

In order to answer this question, the following hypothesis is set for this work:

> ***The increasing complexity of evolving CCPS can be effectively supported if an appropriate collaborative ecosystem is provided that combines a suitable organizational structure with intelligent adaptation and integration methods. Moreover, a hierarchical organization, supporting horizontal and vertical collaboration can increase autonomy and provide logical sections with higher level of independence, context awareness, enhanced responsibilities and mobility support.***

The following sections of the paper present preliminary results in this direction and some discussion on ongoing and future research.

2 Relation to Innovation in Industrial and Service Systems

Cyber-Physical Systems are an integral part of the Industrial and Service systems being utilized in a wide variety of application areas. One of the main innovation trends here is observed in the area of Smart Manufacturing, which strongly relies on the adoption of CPS. From the market point of view, the implementation of CPSs in manufacturing allows more flexible adaptation to demand changes, to product lifetime reduction, as well as support for the collaboration processes among all parties involved in manufacturing and related supply chains [4]. Furthermore, using CPS in manufacturing offers new capabilities for companies to provide services throughout the life cycle of products [5], e.g. post sale support will take new and more effective forms with the introduction of CPSs, which will also induce new business models for these companies. In particular, the notion of smart supply chain covers the entire range of issues related to both provision of the necessary materials and delivery of products to the customers or distributors, which requires effective CPS.

Many related research works appear more focused on industrial use cases, covering for instance the challenges of smart predictive systems [6], human-based [7], fog industrial computing systems [8] and other relevant topics responding to principles set by the Industry 4.0 paradigm. The concept of Industry 4.0 can be described by a number of dimensions, including: vertical integration, horizontal integration, through-engineering, acceleration of manufacturing, digitalization of products and services, and customer involvement in co-creation process [9]. CPS and collaboration aspects are present in all these dimensions, thus a clear case for CCPS.

Another application area for the ideas proposed in this work is the smart home, which is a good example of Service System. A smart home can be seen as an ecosystem containing various services provided for its inhabitants and visitors, while also facilitating the interaction with other service systems in its vicinity, eventually connected to the concept of smart city, smart energy grid, etc.

3 Design Approach

As CPS become larger and more complex, various authors have pointed out the need for proper design methodologies and support tools [10], [11], [12], [13]. As such, various proposals have been put forward for classical CPS design, with origin in different areas, e.g. embedded systems, software engineering, control, and thus reflecting the concerns of those areas. Service-based design, platform-based design, contract-based approach, waterfall and spiral models, hardware-software co-design, V-model, model-based development, standards-based design, are just a few examples.

Of special relevance is the identification of design challenges [11], [10] namely coping with the following characteristics: hybridity, heterogeneity, interoperability, distributed nature, dynamicity, complexity, adaptiveness / evolving nature, human-centricity, etc. According to [11], a design methodology should support the cross-domain developments and be component-based, learning-based, time-aware, trust-aware and human-centric. As we move towards cognitive and collaborative CPS, other challenges become relevant e.g. (i) learning capability, already identified in [11], but becoming more important in the context of big data, and (ii) collaborative facets, for which it is relevant to seek contributions in the area of Collaborative Networks / Business Ecosystems [1].

On the other hand, cognitive and collaborative CPS represent a new "unexplored territory" and thus engineering such systems becomes more and more like an engineering research activity. As such, our proposed approach for Collaborative Cyber-Physical system design is based on the Design Science Research Methodology for Information Systems Projects [14]. The underlying conceptual framework considers three main cycles Relevance, Rigor and Design, and three pillars (Figure 1):

- Application Domain (e.g. Smart Manufacturing, Smart Home, Elderly Care, etc.), which contains needs, limitations and challenges that need to be considered throughout the design cycle. It also identifies the main actors and the scenario where these actors are living in and the way they are communicating and organised within the CCPS.
- Research pillar, which concentrates on the implementation of the given scenario by designing the cyber and physical artefacts with further evaluation and testing.
- CCPS Knowledge Base, which provides access to base concepts, theories, and best practices for artefacts building.

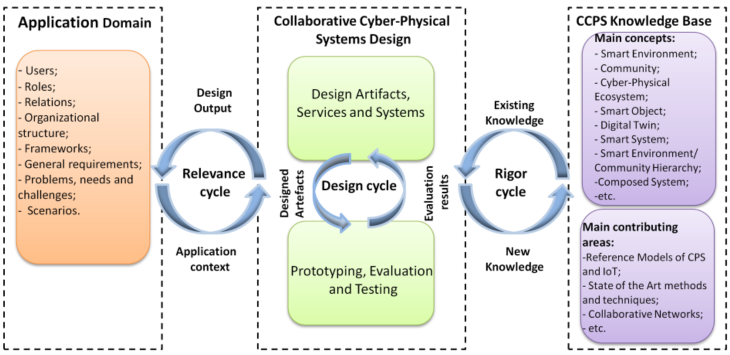

Fig. 1. – CCPS Design Methodology inspired on Design Science

To interconnect the pillars of the CCPS Design Methodology, and following the design science approach three cycles are adopted:

- Relevance cycle, which is responsible for bridging the Application Domain and the CCPS Research in terms of providing the input for the design phase, but also in terms of identifying formal criteria for assessing the output of the design Cycle inside the application area.
- Design Cycle, during which the artefact's design undergoes constant checking for concordance with stated requirements and needs, in order to reach a satisfying solution to the stated problem.
- Rigor Cycle, that assures the necessary link between the research process and CCPS Knowledge Base containing both the application-based expertise as well as existing generic solutions or artefacts. Moreover, this cycle accumulates the knowledge generated during the artefacts' design phase to be considered in further iterations.

Of special relevance in this context is the identification of the key concepts for the CCPS knowledge base that should reflect the collaborative perspective, which will be addressed in the following sections.

4 Base Concepts

In this section some of the main concepts that will populate the CCPS Knowledge Base are introduced. To be able to design a complex CCPS there is a need to consider various abstractions levels [15]. Moreover some inspiration for describing and designing complex CPS can also be found in the Nature [16], which leads to adoption of the concepts of Ecosystem, Environment and Users Community.

Thus, a definition of a Smart Environment is proposed as follows:

> *"**Smart Environment** is a surrounding, with changing characteristics enriched with sensing, actuating and computing capabilities focusing on improving its inhabitants' experiences through increased contextual awareness and extended interaction capabilities."*

A Smart Environment comprises physical as well as cyber artefacts which are deployed in the environment and provide a variety of services. Physical artefacts are represented, in fact, by Smart Objects:

> *"**Smart object** is a physical entity with a cyber identity, some computing power, storage, and communication capabilities. It might be equipped with sensing and/or actuation capabilities, able to monitor the surrounding environment and/or change it."*

Cyber artefacts might be of a several types, as for instance, the applications which are discovering and enabling the capabilities of the physical artefacts and ensuring bidirectional communication. Another important cyber artefact is a digital twin:

*"**Digital twin** is a virtual representation, in the cyberspace, of a physical asset, process or system, possessing real-time information about the represented entity and a model of its behavior.*
Each smart object can have a digital twin in the cyber part of a CCPS."

As the CCPS often presume that the end-users of a provided service can be humans and not only other sub-systems, these systems might be assigned to a certain group or "Users Community":

*"**Users Community** is a group of humans tied together by some social bond that creates in its members a "sense of belonging". The cohesion provided by this social bond usually leads to some sharing of intent or common interest, resources, preferences, risks, etc., materializing some notion of collective identity."*

Both "Smart Environment" and "Users Community" are the constituents of a Cyber-Physical Ecosystem:

*"**Cyber-Physical Ecosystem** is a complex structure composed of a group of interconnected entities forming communities of users and sets of digital twins, the environment where they live in and the complex types of relationships between them considering mutual influence on each other both on cyber as well as physical layers."*

It also considers collaboration between humans and systems, including identification of users' needs and response with corresponding service, conflicts resolution, policy implementation, and adaptation to changing circumstances. Moreover the CPS Ecosystem as well as the Smart Environment can be considered under a hierarchical composition point of view:

*"A **Hierarchy** assumes decomposition of some entity on smaller structural blocks/units which are characterised by some common aspect (e.g. location, devices types) or function/aim (e.g. energy management, air control). Those in turn might contain further structural units organised following the same principle while remaining affiliated to a parent entity and thus inheriting its attributes, rules and constraints."*

As the complexity and autonomy of CPS components increase, the CPS can be considered as System of Systems, consisting of a variety of building blocks or modules, which can be combined together in order to respond to users' needs bringing different functionalities in run time to create an "integrated service". This view is aligned with the notion of "*CPS components being freely composable*" as stated in [17]. Through combining resources and functionalities of smart, distributed entities we might achieve the concentration of necessary competencies to solve a certain problem which is not possible by a single component. This process needs to be dynamic, namely possessing the ability to quickly respond to the need with an appropriate "solution" and, if necessary, to add new components or replace those which do not deliver the required functionality. This idea is similar to the earlier notion of "coalition" of manufacturing components introduced in [18] and later revisited in other works such as [19]. While that initial idea faced several obstacles due to the lack of modularity of the physical manufacturing components, recent progress towards smart objects, represented by digital twins, makes it a promising approach. The notion of coalition or consortium gets its inspiration in the area of Collaborative Networks (CN) [20], namely from the concept of Dynamic Virtual Organisation (VO). Dynamic VOs are able to quickly respond to a changing market situation and are formed for a limited time. This idea presents a good potential in terms of application within CPS, as the components can be reused lately in order to respond to another need, thus this will allow to spare deployment of additional components with similar functionality. Thereby combining principles from CN, Coalition of Manufacturing Agents and the CPS background we define a notion of Coalition of Smart Components as:

> *"**Coalition of Smart Components** is a temporary association of a set of cyber entities – digital twins, representing physical components, which can be dynamically configured and adjusted to a changing surroundings/demand in order to provide an integrated solution."*

While in CNs partners for a VO are typically chosen from a pool of members of a Virtual Organizations Breeding Environment (VBE), here the components to create the coalition are selected from the pool of digital twins associated to a smart Environment.

Some of the definitions given above might be refined during the next stages of this ongoing research and some new might be added. However, these ones allow understanding the scope of the research and establishing the common basis. Three key concepts, Cyber-Physical Ecosystem, Smart Environment and Users Community, are intended to give the necessary abstraction level during the design and deployment phases. Cyber-Physical Ecosystems may also be small or large scale. An example of a small scale ecosystem can be a Smart Home, while a large scale example can be a Smart City. It is important to mention that not all smart objects necessarily require a digital twin, as simple sensors providing some measurements can be deployed as a part of more complex objects, while complex robots containing various actuators and sensors controlling and reacting on a variety of events might benefit from introducing the digital twin representing functionality on higher abstraction levels. Nevertheless, higher abstraction levels allow focusing on the collaborative and organizational aspects paying less attention to the low level technical details, which have been thoroughly addressed by other works.

5 High-level Modeling of Basic Concepts

This section provides a model for some relevant concepts, such as Cyber-Physical Ecosystem, Users Community and Smart Environment, which were defined in the previous section. The UML diagram (Fig. 2) shows the main relations among these concepts. The Cyber Physical Ecosystem is a "bridging point" between the Smart Environment, responsible for managing the cyber and physical components, and the Users Community, focusing on users' organization. It is important to mention, that the

Cyber-Physical Ecosystems, as well as the Smart Environments can consist of several sub-ecosystems or sub-environments building a hierarchy.

Each Users Community has a number of members; some of them, however, can be at the same time members of the other Users Communities. For instance, in a Smart House a person providing some repair services might be a member of the visitors' community and of the service providers' community. Being a member of a Users Community allows getting access to certain capabilities with privileges which depend on the assigned role. Thus, in fact, the role defines the access rights for each particular member. One open issue related to Users Community is the problem of "ownership", since although members may be owners of components, also a particular component might be the property of a Users Community and not of a specific member. This is not yet considered in the UML diagram.

The Smart Environment includes software entities being digital replicas of the physical components, the Digital Twins. Physical components are of two types, namely Composed entities and Smart Objects such as sensors and actuators. Furthermore, components can be of two types: mobile or static. Mobile components can move among different Smart Environments, as well as among Cyber-Physical Ecosystems.

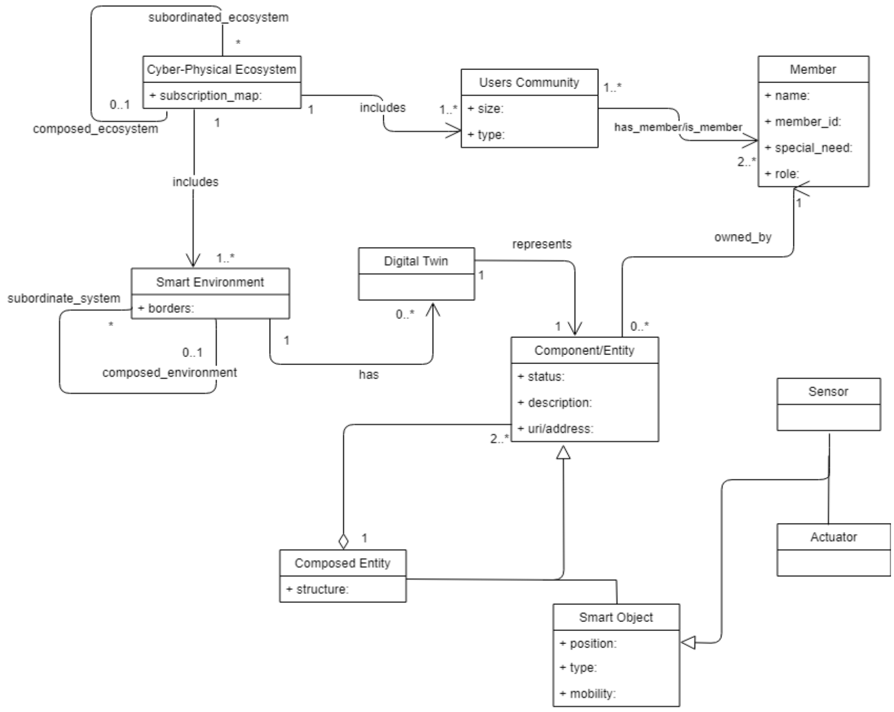

Fig. 2 – A partial UML model of relevant concepts

The mobility of components sets another challenge regarding "borders", which means, when the mobile component leaves the host environment it does not possess a link to this environment anymore, but to the new one. One possible representation of this aspect is presented in Fig. 3:

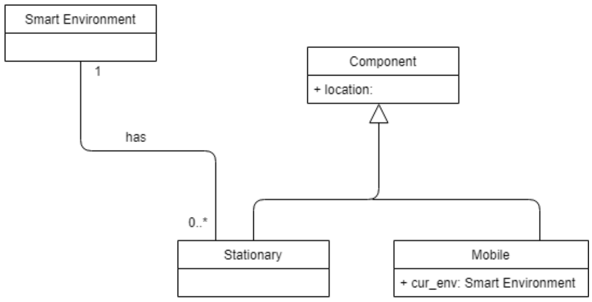

Fig. 3 – Mobile and stationary components

Complementarily, and for further clarification of the stated concepts, the i* modeling language [21] is also used. It supports two modeling concepts, namely:

- Strategic Dependency Model, reflecting the agents or actors and the relationships among them;
- Strategic Rationale Model, which allows capturing the context behind the agents or actors through some basic elements, as tasks, goals, resources and soft goals.

In Fig. 3 the key concepts are presented in a Strategic Dependency model as agents showing the main relations among them. There are three main types of relations in this type of diagram: Goal, Resource and Soft Goal. This model allows giving an answer to some basic issues: “Which goals need to be achieved by an agent?”, “Which goals an agent asks to be achieved by the other agents?”, “Which resources are required?”

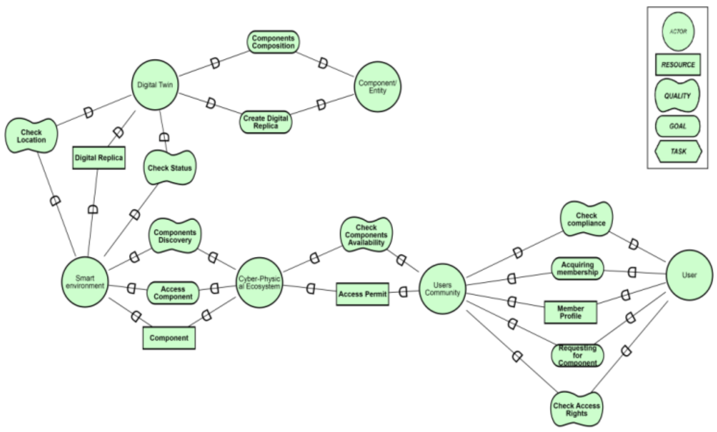

Fig. 4 – Partial Strategic Dependency Model of key concepts

For illustration of the Strategic Rationale Model (SRM), one particular focusing point, namely the way of acquiring the membership to a Users Community, was chosen. SRM allows decomposition of tasks into sub-tasks. In Fig. 5 two actors are represented, one Member asking for a membership and the Users Community processing the request.

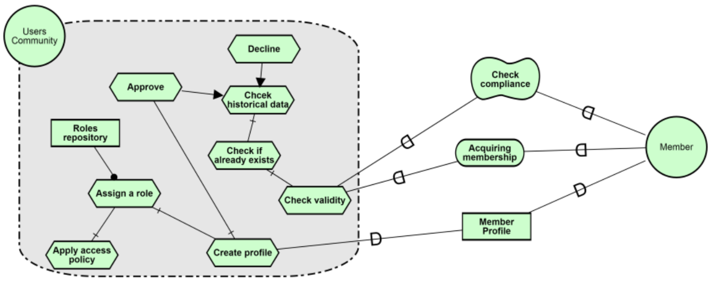

Fig. 5 – SRM Model of membership acquiring

6 Collaborative Facets in CCPS Design

As mentioned above, the convergence of ideas developed within the area of Collaborative Networks and the foundations of the CPS is central point for this work. Namely the aspects related to VBEs and VOs are particularly relevant. Virtual Organisations Breeding Environment can be described as a pool of organisations possessing the "potential and will to cooperate with each other and that are prepared to rapidly join a VO in response to a business opportunity" [20]. Analogously, a Cyber-Physical Ecosystem contains a pool of ready to cooperate entities/components. The counterpart to a VO is a Coalition of Smart Components (CSC). In order to define the stages of the life cycle of the CSC, the corresponding model developed for VO creation can be adopted. In the simplest case, the VO creation process involves: establishing the VBE, partners search and suggestion, negotiation, launching and dissolution. Table 1 attempts to map the steps of VO creation process to the creation of CSC:

Table 1. Mapping the steps for VO Creation to CSC Creation

VO Creation	CSC Creation
VBE – is "a strategic alliance of organisations which adhere to long term cooperation and adopting common operating principles having the goal of increasing their chances towards collaboration in potential VO".	In the proposed approach, the Cyber Physical Ecosystem is analogous to a VBE representing a pool of Components (through their corresponding digital representations or Digital Twins), which provides a basis for building coalitions.
Partners' search and suggestion – finding partners based on some criteria,	Formalizing the challenges and identifying necessary competencies to respond to the

such as fitness of competences, trust level, etc.	problem/collaborative opportunity. Build a taxonomy/structure of needed capabilities and how they can be combined. Discovery of components with defined capabilities (e.g. offered services) and selection based on some criteria, such as availability (free/occupied), location, (if in the required location or if it can move to desired location), etc.
Negotiation – an iterative process aiming at reaching agreements among partners and adjust needs with offers.	Negotiations can be made within a Cyber-Physical Ecosystem considering the needs of components owners, scheduling plans and the desired output.
VO launching involves ICT infrastructure configuration, orchestration of collaboration spaces, resources allocation, informing of involved members and manifestation of new VO in the VBE space.	On this stage the responsibilities for each component are set, the structure of the Coalition and its representation in the ecosystems are properly defined.
VO Dissolution – dissolution occurs when the VO has fulfilled its goal or the fulfilment seems not possible anymore due to various circumstances.	When the task is finished for which the Coalition was established it is either dissolved or evolved to respond to another collaborative opportunity.

As evaluation scenario, our ongoing work focuses on the area of home automation or smart home. Home automation includes a variety of possible applications. For instance, let us consider one of the core tasks of smart home, which is the provision of a comfortable living environment. For ensuring the comfortable living environment various components, with sensing and actuating capabilities, are involved and for this purpose a Coalition of Smart Components needs to be established. This CSC will include components such as temperature, humidity, air quality, and smoke sensors, and corresponding actuators as air conditioner, thermostat, lights, etc. Within the CSC these components are cooperating providing an integrated impact to the Users Community, i.e. jointly contributing to provide the service desired by the user. Moreover, as different users can have different preferences considering temperature, humidity, etc., other components possesing the ability to recognise the presence of a particular user may join the CSC.

For the stated scenario we have already started initial developments, for which Prolog language and a frame engine developed on top of it are used as the development environment.

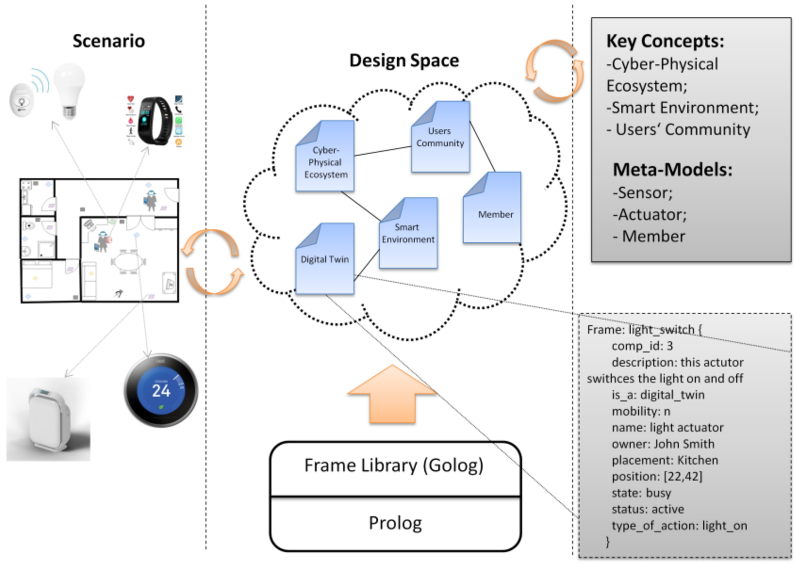

Fig. 6 – General view for the planned developments

Following the previously introduced CCPS methodology, the approach for further developments is illustrated in Fig. 6. The framework considers 3 segments, the first one focuses on the target scenario (in this example a smart home), in the centre is the design space supported by a Frame Engine and Prolog which allows usage of the object-oriented and logic-based approach, and the left side represents the knowledge base, which provides the meta-model of relevant concepts. Frames are used as the base modelling formalism.

7 Conclusion and Further Work

The convergence of theories and ideas developed in the area of Collaborative Networks with the base CPS background led to emergence of the concept of Collaborative CPS which is intended to improve the potential of conventional CPS to adapt to changing users' needs and benefit from increasing intelligence level of CPS components. This collaborative perspective facilitates the development of Service Systems, as they require dynamic configuration of resources in order to produce an integrated impact. In this regard, one challenging aspect is to establish a CCPS design methodology for which an approach is highlighted in this work. Basic concepts and definitions for CCPS, combining ideas from CN and CPS, were also proposed in the scope of this work. Moreover, the idea of establishing Coalitions of Smart Components, based on background for VO creation, was proposed and a mapping of the VO creation to the CSC creation was established.

Some of open challenges are the aspects related to components mobility and corresponding issues of ownership / belonging and borders for the Cyber-Physical Ecosystem. Ongoing work focuses on the application of the proposed concepts and approach to a real use-case in the area of home automation.

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