Ontology for Cyber-Physical-Social Systems Self-Organisation

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***Abstract*—Cyber-Physical-Social Systems (CPSSs) integrate various resources from physical, cyber, and social worlds. Efficient interaction of these resources is essential for CPSSs operation. Ontologies do not only provide for semantic operability between different resources but also provide means to create sharable ontology-based context models specified for actual settings. Usage of the context supports situation-driven behavior of CPSSs resources and thus is an enabler for their self-organisation. The present research inherits the idea of context ontologies usage for modelling context in CPSSs. In this work, an upper level context ontology for CPSSs is proposed. This ontology is applied in the domain of self-organising resource network.**

I. Introduction

Cyber-Physical-Social Systems (CPSSs) is a relatively new research field. Such systems tightly integrate physical, cyber, and social worlds based on interactions between these worlds in real time. CPSSs rely on communication, computation and control infrastructures commonly consisting of several levels for the three worlds with various resources as sensors, actuators, computational resources, services, humans, etc. Operation and configuration of CPS require approaches for managing the variability at design time and the dynamics at runtime caused by a multitude of component types and changing application environments. This is a relatively new research field demanding for new approaches and techniques.

Semantics is the basis to ensure that several resources arrive at the same meaning regarding the situation and data/information/knowledge being communicated. Ontologies provide for a shared and common understanding of some domain that can be communicated across the multiple CPSS' resources. They facilitate knowledge sharing and reuse in open and dynamic distributed systems and allow entities not designed to work together to interoperate [1].

CPSSs belong to the class of variable systems with dynamic structures. Their resources are too numerous, mobile with a changeable composition. Planned resource interactions in such systems are just impossible. Resource self-organisation is the most efficient way to organise interactions and communications between the resources making up CPSSs.

The presented work contributes to the areas of development of ontologies for CPSSs and of CPSS' resource self-organisation. It proposes an upper-level ontology for CPSSs. This ontology is used for multi-level self-organisation of CPSS' resources.

The paper is structured as follows. Section II introduces the upper ontology for CPSSs. It is followed by a description of multi-level self-organisation mechanism proposed for systems of this class. The developed upper level ontology is proposed in Section IV. The major results are summarized in the Conclusion.

II. Upper Ontology

CPSSs are expected to be context-aware. Sharable contexts lie at the heart of the context-aware systems. Ontologies provide means to create sharable ontology-based context models. Such ontologies are referred to as context ontologies. The context ontologies consist of the upper ontology for general concepts, and domain specific ontologies representing knowledge of different application domains [2-4]. The upper ontology is shared by these domains. As a rule, the upper ontology represents concepts that are common for all context-aware applications (*Context Entity*, *Time*, *Location*, *Person*, *Agent*, *Activity*, *Device*, etc.) and provide flexible extensibility to add specific concepts in different application domains (i.e., *Cell Phone* can be a subcategory of the category *Device*) [5-7]. Context is described as an ontology-based model specified for actual settings. Multiple sources of data/information/knowledge provide information about the actual settings. This information is integrated within the ontology-based model. The context model is a result of the integration.

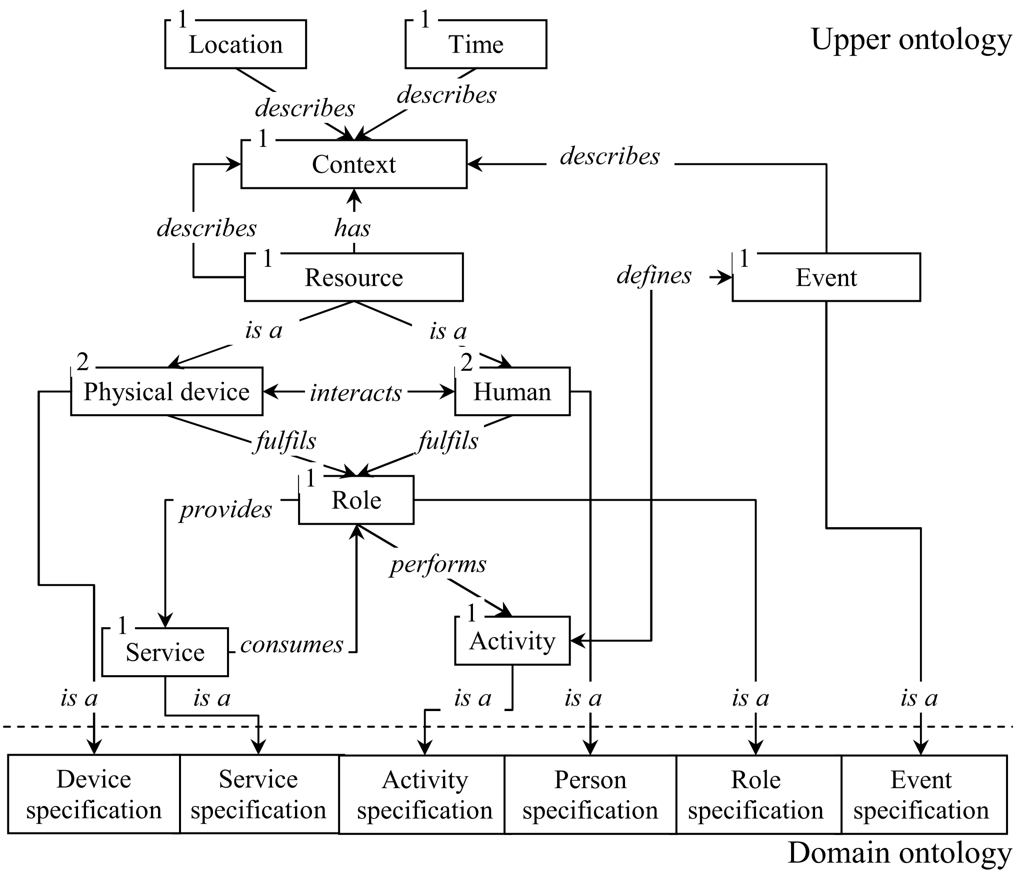

Fig. 1. Upper ontology for cyber-physical-social systems (CPSSs)

The present research inherits the idea of context ontologies usage for modelling context in CPSSs. According to [8], any information describing an entity's context falls into one of five categories for context information: individuality, activity, location, time, and relations. The individuality category contains properties and attributes describing the entity itself. The category activity covers all tasks this entity may be involved in. The context categories location and time provide the spatio-temporal coordinates of the respective entity. Finally, the relations category represents information about any possible relation the entity may establish with another entity.

CPSS consists of cyber space, physical space, and mental space [9]. These spaces are represented by sets of *resources*. In the upper ontology (Fig. 1) proposed for CPSSs, the resources are thought of as the entities whose contexts are to be described. The physical space consists of various interacting information and computational *physical devices*. These devices united on the communication basis organize the cyber space.

The mental space is represented by *humans* with their knowledge, mental capabilities, and sociocultural elements. Information from cyberspace *interacts* with physical space (*physical device*) and mental space (*human*).

Resource's *context* is described by *location*, *time*, *resource* individuality, and *event*. Resources perform some *activity* according to the *roles* they fulfil in the current context and depending on the type of *event*. On the other hand, the type of *activity* that a *resource* performs *defines* the type of *event*. For example, the *event* of a phone call defines the human *activity* as answer the phone. But, when a person raises the hand at the lecture time, this *activity defines* an *event* as, for instance, lecture interruption. This explains bidirectionality of '*defines*' relationship between *event* and *activity*.

The resources have some functionality in result of which they provide *services*. The services *provided* by one resource are *consumed* by other resources.

In Fig. 1, upper indices in boxes representing the ontology concepts indicate the taxonomical level of these concepts. All the concepts of the upper ontology are intended to be specialised in the application domains. An example of usage of the proposed ontology for self-organization of a service network in a CPSS is presented below.

III. Multi-Level Self-Organization in CPSSs

In order for distributed systems like CPSSs to operate efficiently, they have to be provided with self-organisation mechanisms. In a CPSS such mechanisms concern self-organisation of CPSS' resources. The goal of the resource self-organisation is support of humans in their decisions, activities, solution of the tasks, etc. At that, humans are the participants of the self-organisation process, as well.

The analysis of literature related to organizational behaviour & team management has showed that the most efficient teams are self-organizing teams working in the organizational context (Fig. 2). For example, social self-organisation has been researched by Hofkirchner [10], Fuchs [11], etc. However, in this case there is a significant risk for the group to choose a wrong strategy preventing from achieving desired goals. For this purpose, self-organising groups / systems need to have a certain guiding control from an upper level. This consideration produces the idea of multi-level self-organization.

The process of self-organisation of a network assumes creating and maintaining a logical network structure on top of a dynamically changing physical network topology. This logical network structure is used as a scalable infrastructure by various functional entities like address management, routing, service registry, media delivery, etc. The autonomous and dynamic structuring of components, context information and resources is the essential work of self-organisation [13]. The network is self-organised in the sense that it autonomically monitors available context in the network, provides the required context and any other necessary network service support to the requested services, and self-adapts when context changes.

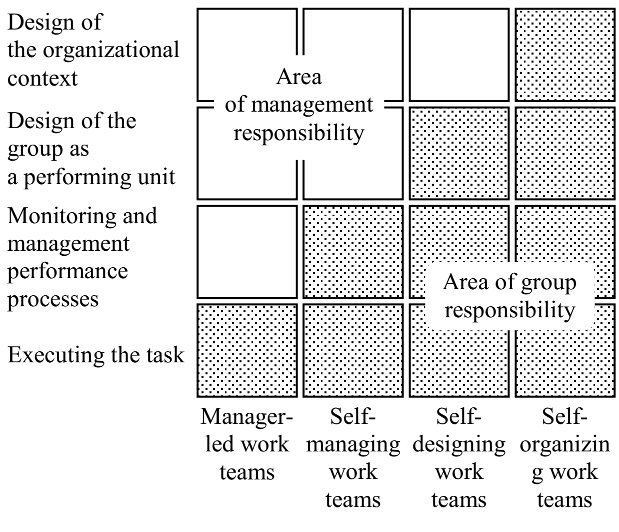

Fig. 2. Authority of work group types (adapted from [12])

To guide self-organising groups / systems, the guiding control via policy transfer from an upper level is used in the proposed approach [14]. This control enables a more efficient self-organisation based on the “top-to-bottom” configuration principle, which assumes conceptual configuration followed by parametric configuration. In this regard, each level can be considered as a scenario-based decision arena following certain complex knowledge patterns related to adaptable business models.

The key mechanisms supporting self-organising networks are self-organisation mechanisms and negotiation models. The following self-organisation mechanisms are usually selected [15]: intelligent relaying, adaptive cell sizes, situational awareness, dynamic pricing, intelligent handover.

The following negotiation models can be mentioned [16]:

- Different forms of spontaneous *self-aggregation*, to enable both multiple distributed services / agents to collectively and adaptively provide a distributed service, e.g. a holonic (self-similar) aggregation.
- *Self-management* as a way to enforce control in the ecology of services / agents if needed (e.g. assignment of “manager rights” to an service / agent.
- *Situation awareness* – organization of situational information and their access by services / agent, promoting more informed adaptation choices by them and advanced forms of stigmergic (indirect) interactions.

The presented multidisciplinary research aiming at multilevel self-organization is based on the idea from the new multidisciplinary 21st Century science. The idea is designing sociologically-inspired computing systems since social systems perform well by continuous organized adaptation. The research assumes investigation of how solutions to structurally similar problems of organized adaptation found in social systems can be applied to cyber-physical systems. Thus, combining ICT with the theory of social systems and knowledge of multiple disciplines would enable new methods and mechanisms for efficient self-organisation of resources.

To guide such self-organising groups / systems a certain guiding control is needed (e.g. via policy transfer) from an upper level. The multilevel self-organisation has not been addressed yet in research. This approach would enable a more efficient self-organisation based on the “top-to-bottom” configuration principle, which assumes conceptual configuration followed by parametric configuration. In this regard, each level can be considered as a scenario-based decision arena following certain complex knowledge patterns related to adaptable business models.

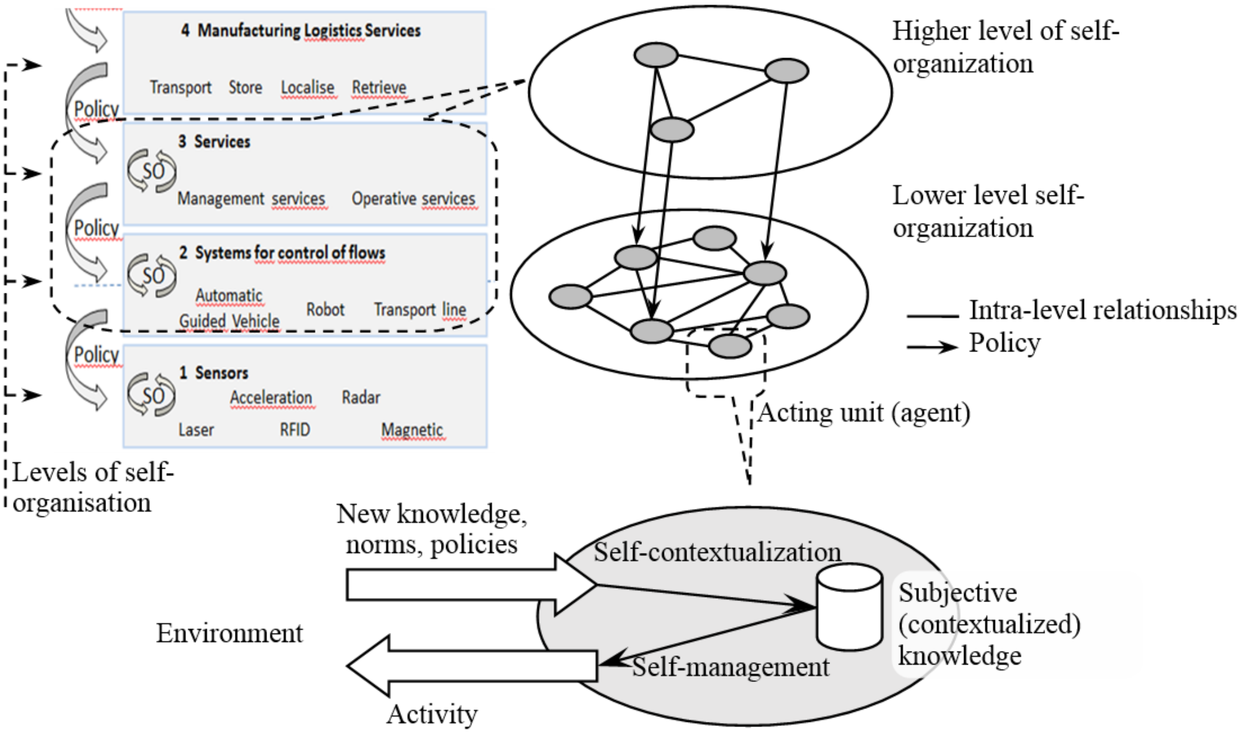

Fig. 3. Approach overview

The approach is based on the following principles: self-management and responsibility, decentralization, as well as integration of chain policy transfer (a formal chain of policies running from top to bottom) with network organisation (without any social hierarchy of command and control within a level), initiative from an upper level and co-operation within one level. The idea can be interpreted as producing “guided order from noise”. In accordance with [17] such system falls into the class of purposeful systems.

Intra-level self-organisation is considered as a threefold process of (i) cognition (where subjective context-dependent knowledge is produced), (ii) communication (where system-specific objectification or subjectification of knowledge takes place), and (iii) synergetical co-operation (where objectified, emergent knowledge is produced). The Individually acquired context-dependent (subjective) knowledge is put to use efficiently by entering a social co-ordination and co-operation process. The objective knowledge is stored in structures and enables time-space distanciation of social relationships.

In order to achieve the dynamics and self-organisation of the CPSS, its components (resources) have to be creative, knowledgeable, active, and social. The resources that are parts of a system permanently change their joint environment what results in a synergetic collaboration and leads to achieving a certain level of collective intelligence. This is also supported by the fact that individual resource behaviour is partially determined by the social environment the resources are contributing to (called “norms”). For this purpose a protocol has been developed based on the BarterCast approach [18] that originates from the following ideas: (i) each service builds a network representing all interactions it knows about; (ii) the reputation of a service depends on the reputation of other services in the path between this service and the service connecting to it.

The overall scheme of the approach is shown in Fig. 3. In the approach, agents represent various CPSS' resources. Since the structures and self-organisation models of all the levels are identical, the developed framework is fully scalable. This makes it possible to perform conceptual development of the agents, i.e. to define kinds of agents needed, their characteristics, etc. Then, at the implementation stage, the particular behaviour and functionality of the agents may vary in different application domains.

The interoperability between the agents at the technological level is provided via usage of common standards and protocols, the interoperability at the level of semantics is ensured via usage of a common ontology.

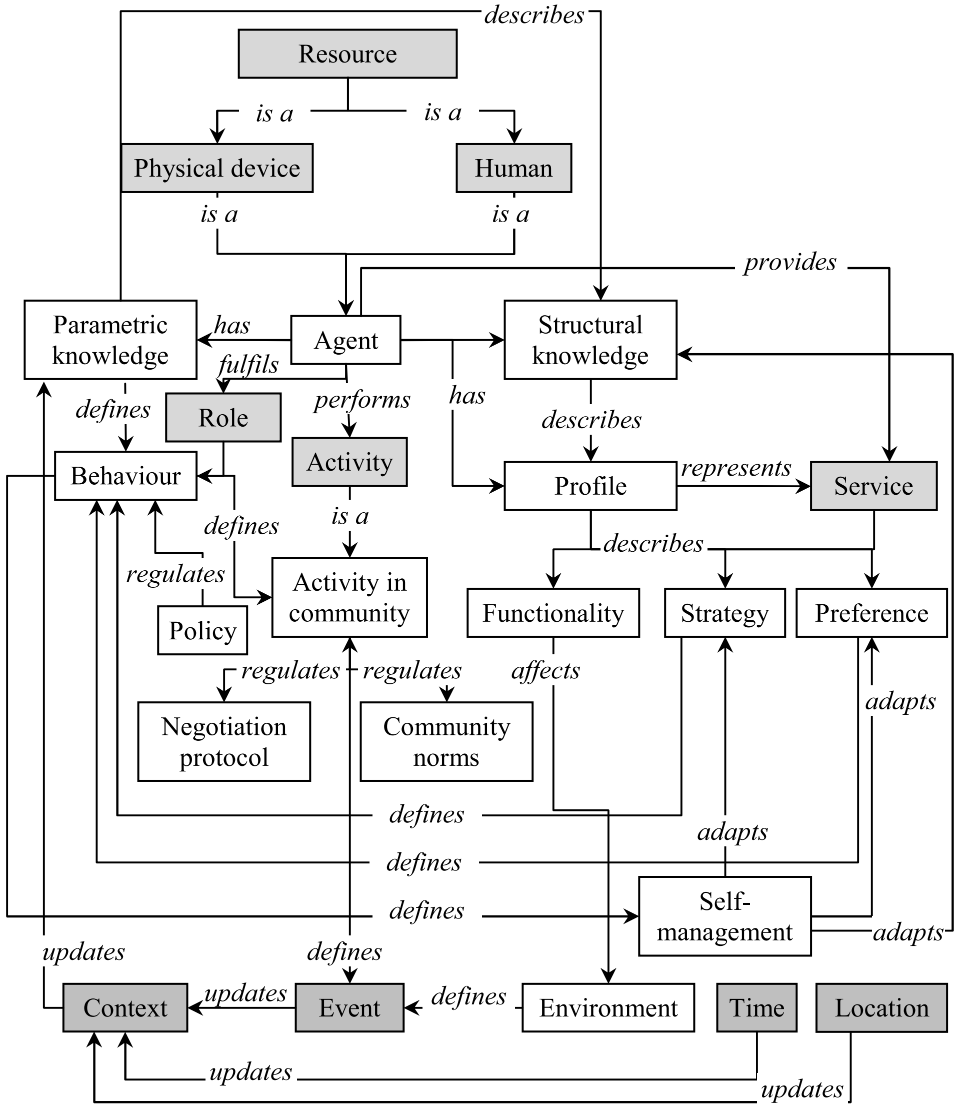

Fig. 4. Middle-level ontology for CPSSs self-organisation

IV. Ontology for CPSSs Self-Organization

Fig. 4 represents the developed ontology for CPSSs self-organisation. It is a middle-level ontology based on the upper ontology above. The concepts of the upper ontology are greyed. The concepts defined in the middle-level ontology are expected to be specified in particular application domains. The main concepts are described below.

Agent is used to represent CPSS' resources of both types: physical devices and humans. The agent is an acting unit of the multilevel self-organisation process. The agent has *structural knowledge*, *parametric knowledge*, and *profile*. The agent is characterized by such properties as self-organisation, self-management, autonomy, and proactiveness and performs some *activities in the community*.

Structural Knowledge is a conceptual description of problems to be solved by the *agent*; the agent's internal *ontology* represents this kind of knowledge. The internal ontology harmonises with the common ontology. The structural knowledge describes the structure of the agent's *parametric knowledge* and the structure and the terminology of the agent's *context* and *profile*. Depending on the situation the structural knowledge can be modified (adapted) by the *self-management* capability.

Parametric knowledge is the knowledge about the actual situation. This knowledge is the structural knowledge filled with the information characterising this situation.

The agent's *context* is any information that can be used to characterize the situation of the agent. The context is purposed to represent only relevant information and knowledge from the large amount of those. Relevance of information and knowledge is evaluated on a basis how they are related to a modelling of an ad hoc problem. The context is represented by means of the agent's internal *ontology*. It is updated depending on the current *event*, *location*, and *time*. Information from the agent's *environment* and results of its *activity in the community* define *events* and vice-versa.

The context updates the agent's *parametric knowledge*, which in turn defines the agent's *behaviour* according to the agent's *role*. The presented approach exploits the idea of self-organisation to autonomously adapt *behaviours* of multiple agents to the situation in order to provide their *services* according to this context and to propose context-aware decisions.

The agent's *profile* is represented by means of the agent's internal *ontology* and in a way understandable by other agents of the CPSS. It represents the *services* this agent provides. The set of *services* defines the agent's *functionality*. *Functionality* is a set of cyber-physical-social functions the agent can perform. Via the *functionality* the agent can modify its *environment*. The agent's functionality can be modified in certain extent via the *self-management* capability.

As well, the agent's *profile* describes *preferences* and *strategies* of this agent. *Preference* is an agent's attitude towards a set of own and/or environmental states and/or against other states. The *preferences* affect the agent's *behaviour*. The agent can modify its *preferences* through *self-management*. *Strategy* is a pre-defined plan of actions rules of action selection to change the agent's own state and the state of the *environment* from the current to the preferred ones. The strategy defines the agent's *behaviour*. The agent can modify its strategy through *self-management*.

Environment is the surroundings of the CPSS the agent is a part of, which may interact with the CPSS. The environment produces events, which in turn affect the agent's *context*. The agent can affect the environment if it has appropriate *functionality* (e.g., a manipulator can change the location of a corresponding part).

Self-Management is an agent's capability achieved through its *behaviour* to modify (reconfigure) its internal *ontology*, *functionality*, *strategy*, and *preferences* in response to changes in the environment.

Behaviour is the agent's capability to perform certain actions (*activity in community* and/or *self-management*) in order to change the own state and the state of the *environment* from the current to the preferred ones. The *behaviour* is defined by the agent's *preferences* and *strategies*, as well as by the *policies* defined on a higher level of the self-organisation.

Policy is a set of principles and/or rules coming from a higher level of self-organisation to guide *behaviour* and achieve rational outcomes on a lower level of self-organisation.

Activity in community is a capability of the agent to communicate with other agents and negotiate with them through the agent's *behaviour*. It is regulated by the *negotiation protocol* and *community norms*.

Negotiation protocol is a set of basic rules so that when agents follow them, the system behaves as it supposed to. It defines the *activity in community* of the agents.

Community Norm is a law that governs the agent's *activity in community*. Unlike the negotiation protocol the community norms have certain degree of necessity ("it would be nice to follow a certain norm").

CONCLUSION

The present research deals with a new research field of CPSSs. In the research, a CPSS is considered consisting of sets of resources representing cyber, physical, and mental spaces. The paper presents the upper ontology for CPSSs and its application for self-organization of CPSS' resources.

The main concepts of the upper ontology show their share ability in the application area. The concept "resource" distinguishing two types of resources (physical devices and humans) indicated that there is no necessity in this division. In the application domain the two resource types were merged into one concept. That is, humans are full members of the CPSSs. Sometimes they fulfil role of resources in providing information, knowledge, services, etc. Another time they are users of the CPSSs in consuming information, knowledge, services, etc.

ACKNOWLEDGMENT

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