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Multi-level self-organization in cyber-physical-social systems: smart home cleaning scenario

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Abstract

Cyber-Physical-Social Systems integrate various resources from physical network, cyberspace, and social world. These systems 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. Efficient interaction of these resources is essential for cyber-physical-social systems operation. The paper presents multi-level self-organization approach for cyber-physical-social systems that distinguishes three main level for the system resource interaction: physical level, planning level, and strategic level. Smart home cleaning scenario is proposed as an example of multi-level self-organization approach. Robot vacuum cleaner creates room map using the light-sensitive sensors and clean room using the map. For the efficient cleaning, it requires the lights switch on in the cleaning room. For this purposes the vacuum cleaner has to interact with the adaptive illumination control system. Manipulating robot move light furniture (e.g. chairs, or coffee table) or decorative elements (pots with flowers, vases, etc.). It interacts with the vacuum cleaner for synchronization of moving light furniture. For the strategic level, a special strategic planning service has been identified that determines general strategy of resources behavior in the scenario based on interaction with personal mobile device and current situation in smart home. Example of general strategies can be for example reduction in energy consumption, excellent cleaning. For the planning level, a special room management services have been proposed that provide general behavior the cyber-physical-social systems resources in physical level. Example of these strategies can be clean room 1 completely, after that clean room 2 or vice versa. For the physical level a vacuum cleaner, manipulating, and light control services have been proposed. The paper present ontology-based information model for smart home devices interaction. It allows the services of physical level linked to the appropriate smart room devices interact in cyber space while physical devices interact in physical space. Every resource in physical level of cyber-physical-social system is described by the ontology. Appropriate ontologies of vacuum cleaner robot, adaptive illumination control system, and manipulating robot have been proposed in the paper.

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Keywords: cyber-physical-social systems; ontology, self-organization, smart home

1. Introduction

Cyber-Physical-Social Systems is a new research field that integrate physical, cyber, and social worlds based on interactions between these worlds in real time. These systems 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 cyber-physical-social systems 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.

Cyber-Physical-Social Systems can be applied for the different areas, like command and control [1], production networks [2], smart home systems [3] and [4]. Different researchers develop models and methods for such kind

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systems, like [5] and [6]. In this paper, authors propose self-organization approach for cyber-physical-social systems and devices interaction for smart home cleaning scenario.

The paper presents multi-level self-organization approach for cyber-physical-social systems that have been applied for the smart home cleaning scenario is proposed as an example of multi-level self-organization approach. Robot vacuum cleaner creates room map using the light-sensitive sensors and clean room using the map that requires the lights switch on in the cleaning room. Manipulating robot move light furniture or decorative elements. It interacts with the vacuum cleaner for synchronization of moving light furniture.

The paper is structured as follows. Section 2 introduces multi-level self-organization approach for cyber-physical-social systems. Smart home cleaning scenario is proposed in section 3. It includes scenario general description, ontologies for smart home devices, and information model of smart home device interaction. The major results are summarized in the Conclusion.

2. Multi-level self-organization

In order for distributed systems like cyber-physical-social systems to operate efficiently, they have to be provided with self-organisation mechanisms. In a these systems such mechanisms concern self-organisation of 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 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 [9]. 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.

The key mechanisms supporting self-organising networks are self-organisation mechanisms and negotiation models. The following self-organisation mechanisms are selected [10]: intelligent relaying, adaptive cell sizes, situational awareness, dynamic pricing, and intelligent handover.

The following negotiation models can be mentioned [11]:

- 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 of 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-social systems. Thus, combining information and communication technologies 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 to lower. 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.

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 [12] 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.

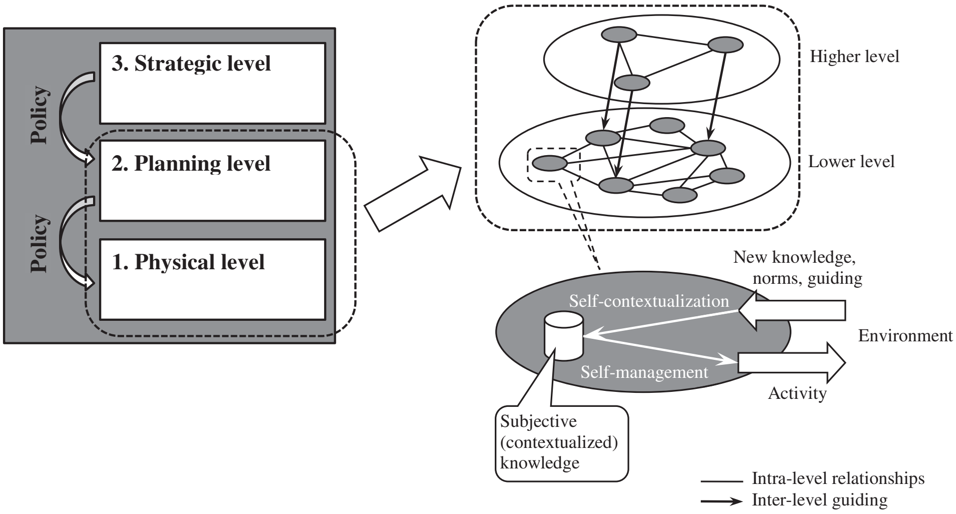

Fig. 1. Approach overview

In order to achieve the dynamics and self-organisation of the cyber-physical-social systems, 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 [13] 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. 1. In the approach, agents represent various cyber-physical-social systems 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 ontology.

3. Smart home cleaning scenario

3.1. Scenario description

There are many definitions and interpretations of "smart home" term [7]. For cyber-physical systems development the following definition is popular: "Smart Home is a house or living environment that contains the technology to allow devices and resources to be controlled automatically" [8]. For cyber-physical-social systems interaction with people through the personal mobile device as adding to smart home scenario.

For the scenario, the following resources are used for this purpose (see Fig. 2).

- Strategic planning service determines the general strategy of resources behavior in the scenario. General strategy is based on interaction with personal mobile device and current situation in smart home. Example of general strategies can be for example reduction in energy consumption, excellent cleaning.
- Personal mobile devices accumulates people preferences and desires and shares it with other cyber-physical-social system resources. For example based on interaction with strategic planning service the general strategy can be different.
- Room management services are services of planning level that organize the general behavior of cyber-physical-social system resources in physical level. Every service represents a room (or sometimes a part of room). Based on communication of these services and general strategy from strategic level the specific strategies for the physical level are formed.
- Robot vacuum cleaner creates room map using the light-sensitive sensors and clean room using the map (e.g. Yujin Robot iClebo Arte YCR-M05). For the efficient cleaning it requires the lights switch on in the cleaning room. For this purposes the vacuum cleaner interact with adaptive illumination control system.

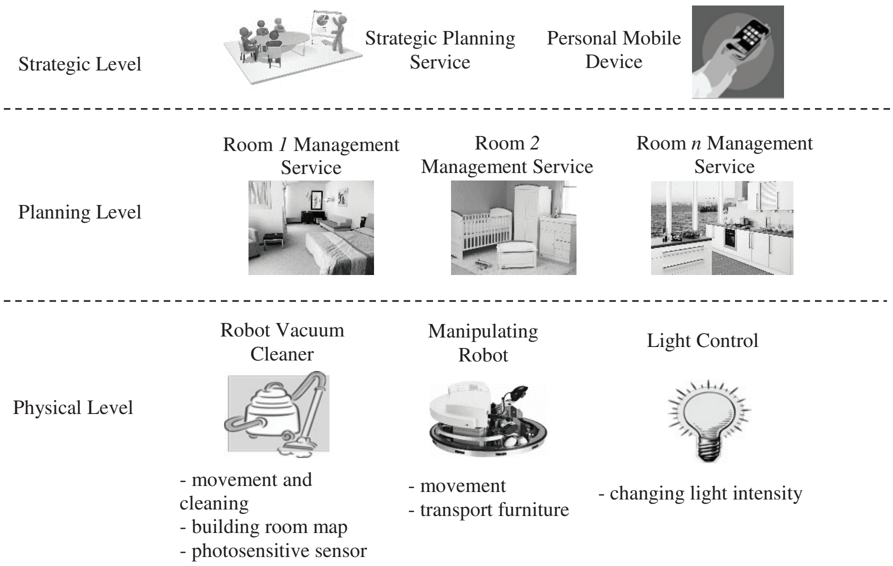

Fig. 2. The participants of the smart home cleaning scenario

- Manipulating robot (e.g. FESTO Robotino XT), allowing to move light furniture (e.g. chairs, or coffee table) or decorative elements (pots with flowers, vases, etc.) for efficient cleaning. It interacts with the vacuum cleaner for synchronization of moving light furniture.
- Adaptive illumination control system for illumination level changing interacts with vacuum cleaner and manipulating robot for allow them to use light-sensitive sensors.

3.2. Ontologies for smart home devices

Every resource in physical level of cyber-physical-social system is described by ontology. This approach provides semantic interoperability between different resources.

The vacuum cleaner robot ontology is presented in Fig. 3. There are three high-level classes have been identified: available sensors (class "Sensors"), room lightness (class "Lightness"), and operations that robot can implement (class "Operation"). Room lightness can be dark that is not sufficient for light-sensitive video sensor of vacuum cleaner (class "Dark") and light that allows to use video sensor (class "Light"). Sensors can be contact (class "ContactSensor") and contactless like video sensor (class "VideoSensor"). Contact sensors do not depend on lightness while video sensor requires light lightness. Operations that vacuum cleaner can implement are floor cleaning (class "Cleaning") and movement in a room (class "Movement").

Movement of vacuum cleaner can be random that suppose of using only contact sensors (class "Random") and organized that requires of using both contact and contactless sensors (class "Organized") for planning of movement vacuum cleaner through the room.

Continuous line in Fig. 3 shows taxonomical relationships between classes in the vacuum cleaner robot ontology while dashed line shows associative relationships that determine that one class is required another one (e.g. organized movement of vacuum cleaner is required of using video sensor that rquires light lightness).

Ontology of adaptive illumination control system if presented in Fig. 4. It consists of high-level classes: lightness sensor (class "Sensor") and operation (class "Operation"). Lightness sensor measures lightness level (class "LightnessLevel"). Just one operation that is accessible for adaptive illumination control system is a light control (class "LightControl"). Classes "LightnessLevel" and "LightControl" has associative relationship (dashed line).

The ontology of manipulating robot is presented in Fig. 5. There are four high-level classes have been identified: physical characteristics of robot (class "Characteristics"), room lightness (class "Lightness"), sensors that the robot have (class "Sensors"), and operations that manipulating robot can implement (class "Operations").

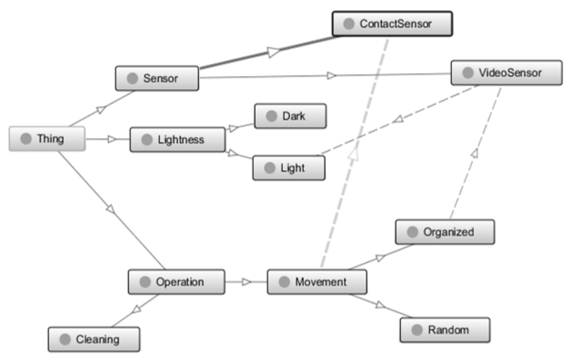

Fig. 3. Vacuum cleaner robot ontology

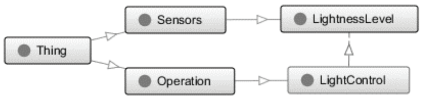

Fig. 4. Adaptive illumination control system ontology

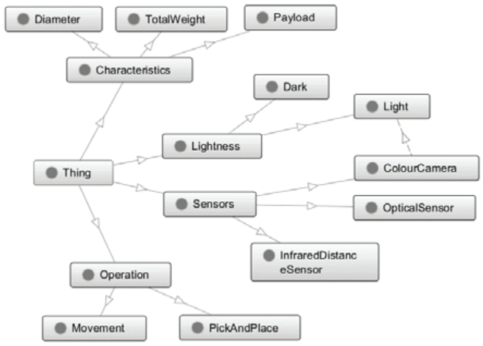

Fig. 5. Manipulating robot ontology

Physical characteristics of robot is a diameter (class "Diameter"), weight (class "TotalWeight"), and load-carrying ability (class "PayLoad"). Room lightness (the same as for vacuum cleaner robot) can be can be sufficient for light sensitive sensors working (class "Light") or not sufficient (class "Dark"). Sensors are divided into three types: infrared distance sensor (class "InfraredDistanceSensor"), optical sensor (class "OpticalSensor"), and video camera that is light sensitive sensor (class "ColourCamera"). Operations that manipulating robot can implement is a movement robot in the room (class "Movement") and pick and place objects (class "PickAndPlace").

3.3. Smart home devices interaction in cyber-physical space

Interaction of smart home devices in cyber-physical space based on presented in Fig. 6 ontology-based information model of smart home device interaction. When devices have to solve joint task in physical space their cyber modules interact in cyber space, agree about joint behavior and then they solve the task in physical space.

Interaction of services in smart space is based on Smart-M3 platform [14] that makes possible to significantly simplify further development of the system, include new information sources and services, and to make the system highly scalable. The key idea of this platform is that the formed smart space is device, domain, and vendor independent. Smart-M3 assumes that devices and software entities can publish their embedded information for other devices and software entities through simple, shared information brokers. Platform is open source and accessible for download at Sourceforge*. Information in the Smart-M3 is kept in the special RDF triple store. The platform allows to upload OWL ontologies and RDF triples for the devices.

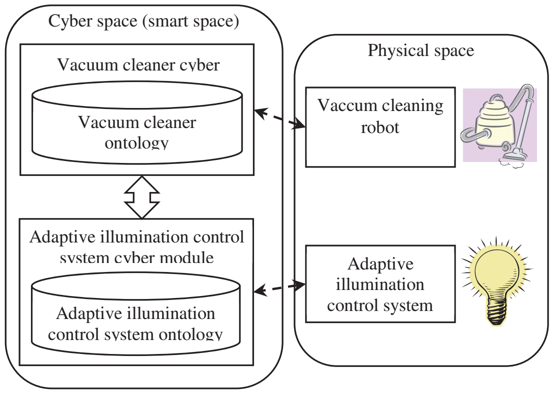

Fig. 6. Information model of smart home device interaction

Every device in the considered scenario is described by the ontology for providing semantic interoperability between them (Fig. 7). Every device uploads its own ontology to the Smart-M3 ontology library when connects to the system. The ontology represents the device. It contains information about device requirements and possibilities (see Sec. 3.2). Requirements represent the information that robot has to get for starting it scenario. Possibilities is the information that robots can provide related to the considered system. When a service has information that can be helpful for other services in smart space it uploads this information in according with previously uploaded own ontology. If a service requires an information for performing an action in according with the system scenario it use the special ontology matching service to determine if needed information is accessible in smart space or not. Ontology matching service implements matching of the service ontology with the smart space ontology library [15] and determine which information in smart space is corresponded to the required one. If the ontology matching service finds this information, the service downloads it from the smart space.

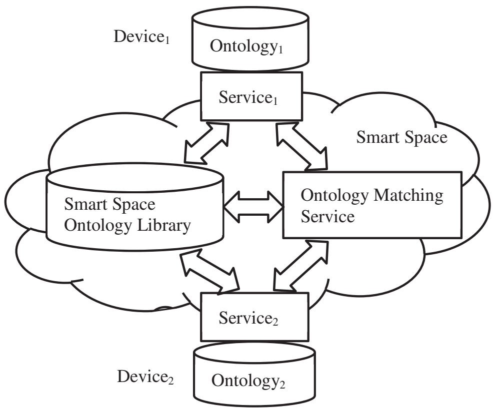

Fig. 7. Ontology based smart space services interoperability

* Smart-M3 platform, URL:http://sourceforge.net/projects/smart-m3

3.4. Evaluation of devices interaction in cyber-physical space

The following scenario that is a part of considered smart home cleaning scenario has been evaluated. Two robots should find an object around each other and then the nearest robot move to the object. They do not know about the position of another robot and moving to another robot is restricted. In this way, the whole task can be split to the several subtasks:

- Task 1. Each robot should scan an area around. While scanning robot controls the incoming data from the gyroscopic & ultrasonic sensors and recording turn angle with measured distance.
- Task 2. Each robot should find the objects. The measurements from the previous step are processed. Processing determines objects that were captured by the ultrasonic field of vision. The result of parsing will be angle where the object was found and distance to this object.
- Task 3. Each robot should find another robot. Robots shares found objects through the smart space. Then they compare the distances to objects. If there are more than two equal distances, robots should check that the object is not the other robot. For this purpose random robot moves to object and repeat all moves from the Task 1. These steps are repeated until only two distances become equal.
- Task 4. Each robot should interoperate with another robot and decide who will go to the object. When the object is found robots choose the shortest distance to the object and the robot that owns the distance moves to the object.
- Task 5. Selected robot should carry out defined task with the object.

The scenario presented above has been implemented by using two autonomous robots. These robots are Lego EV3 cars with ultrasonic and gyroscope sensors. Each car is driven by two independent large motors and controlled by control block with LeJOS installed on the SD-card and WiFi USB-adapter for local area network connection. For the control block the LeJOS has been chosen because it is provide full functionality OS with JRE Environment as well as plugin for Eclipse IDE for easy developing and debugging of applications. Applications can be developed in other IDE/editors but it is need to compile a *.jar file and move it to the control block through SSH.

4. Conclusion

The paper propose multi-level self-organization approach for cyber-physical-social systems operation that have been applied to the smart home cleaning scenario. There are three levels for cyber-physical-social system have been identified: strategic level, planning level, and physical level. Ontology-based information model for smart home devices interaction that allows the services of physical level interact in cyber space while physical devices interact in physical space has been proposed. Every resource in physical level of cyber-physical-social system has been described by the ontology. Presented in the paper approach allows to extend available at the moment in the market cleaning robots by the smart services that implement optimization of robots behavior and increase quality of operation. These services take into account current situation in the smart home and people preferences that is transmitted from the strategic level to the physical one.

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