Towards an Interaction Concept for Efficient Control of Cyber-Physical Systems

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Abstract. In this work, we introduce our interaction concept for efficient control of cyber-physical systems (CPS). The proposed concept addresses the challenges of the increased amount of smart/electronic devices along with increasingly complex user interfaces. With a dual reality approach, the user is able to perform the same action in the physical world as well in the virtual world by synchronizing both. We solve thereby the most important compelling issue of ease of use, flexibility, and bridging the gap between both worlds. Our approach is substantiated by two test scenarios by means of a characteristically CPS setting.

Keywords: cyber-physical system, smart home, dual reality interaction, synchronized environments.

1 Introduction

Nowadays, smart electronic devices enable us to build intelligent home automation systems for everybody, so called *smart homes*. These systems aim for assisting users assuring their independence as long as possible and improving overall quality of life [1]. The current state shows that these systems are usually constructed by integrating a wide range of standalone, network-compatible embedded systems with the aim to construct an all-in-one solution. These embedded systems range from simple sensors and actuators to small computational units, like smart phones, up to workstations.

Besides, every physical component comes with a corresponding virtual data representation. Those embedded systems form so called cyber-physical systems (CPS) [2]. CPS monitors and controls physical and virtual processes by so called *feedback loops* that affect the real and the virtual world simultaneously. Sensors or sensor compounds measure the current state of the environment (e.g., temperature, CO_2) and push these information to a particular software component. This component forwards the information to a subscribed software component over a networked connection. As this component holds an actuator, it manipulates the physical world, which causes an effect on all sensors.

The development, composition and optimization of this networked CPS is a complex process. However, ordinary people should be able to configure and interact with their smart environment with respect to their personal needs. Current

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approaches in smart home control, such as smart phones, tablets or workstations, provide inefficient user interfaces (UI) and a high configuration overhead. For instance, graphical user interfaces based on list views are used to handle devices and tasks but are unsuitable for growing amounts of devices or performing complex tasks. Moreover, the user has to become familiar with the UI but new devices and tasks may introduce new concepts and views which lead to further training periods.

To overcome these limitations we propose a dual reality interaction approach for cyber-physical systems by combining a three-dimensional smart home simulator (virtual world) with our smart home infrastructure (real world). Supporting interaction in both worlds we require for every real sensor and actuator a virtual counterpart with an identical visual representation. To provide the dual reality interaction we have to, semi-automatically, synchronize objects, actions and effects initiated by user inputs and environmental changes from the real and virtual world.

2 Related Work

Due to the inexorable growth of data in all areas of life, people face more and more the problem to understand the datasets they are confronted with. Thus, information visualization tools are required to assist end users who are not familiar in creating effective graphical representations [3].

Green et al. [4] explored in a study the user's expectations and demands for smart homes. They identified the following requirements from a user's point of view: *cost*, *reliability*, *security/privacy/safety.* To justify the cost of a smart home system the reliability, security, safety, and privacy are key issues and as such are intensively addressed by current CPS research [2]. In addition they identified *flexibility*, *ease of use*, *keeping active*, and *controlling* the smart home which are aspects of interaction. Controlling a smart home system demands an user interface which provides an easy and flexible way to interact with.

In the study of smart home usability and living experience conducted by Koskela et al. [5], it was found that two main user activity pattern can be distinguished on controlling smart home environments. The *pattern control* which is utilized to handle familiar and recurrent activity patterns whereas the *instant control* is used for impulsive and unexpected tasks. They suggest that these control patterns should be supported differently by provided user interfaces for smart home environments. Based on these findings they conclude to use desktop-based graphical user interfaces for *pattern control* tasks whereas usage of mobile devices is more suitable for *instant control* in real-use context. They argue that the diverse input methods available to desktop systems will support the work of planning and predetermination while in the *instant control* case the key aspects are the immediate availability, fast response and a centralized control device.

Introducing the concept of *dual reality*, Lifton et al. [8] bridges the gap between the real and the virtual world by using networked sensors and actuators, thus creating an implicit bi-directional communication channel. This approach facilitates to visualize the gathered data within the sensor network and hence it is perceptible by the user.

Kahl and Bürckert [10] have developed and used an event-based infrastructure and a dashboard-like visualization to combine the dual reality approach with an intelligent environment. The virtual environment is used to monitore and to visualize changes or problems in realtime. In their smart shopping environment the smart physical objects are recognized in the real world (e.g., product position and stock of products) and the items state are synchronized with their virtual representation.

Franke et al. [9] shows a model-based CPS middelware to handle this bi-directional communication and which is suitable for domestic environments. This type communication helps to create and maintain the so called "synchronized realities", a concept introduced by Stahl et al. [11] creating an assistance system to increase social connectedness. It is motivated to synchronize a virtual environment with a remote intelligent environment, which means the system knows the status of devices and appliances in the real environment and their digital representation in the virtual world. Furthermore, the 3D environment model can be used for designing and evaluating smart homes. By the mean of context menu that is attached to the virtual object, the user is able to control real devices or he can switch on a real light by manipulating the virtual light cone. In contrast, a state change in the real world, like switching on the light is updated in the virtual world with a visualization, like drawing a light cone.

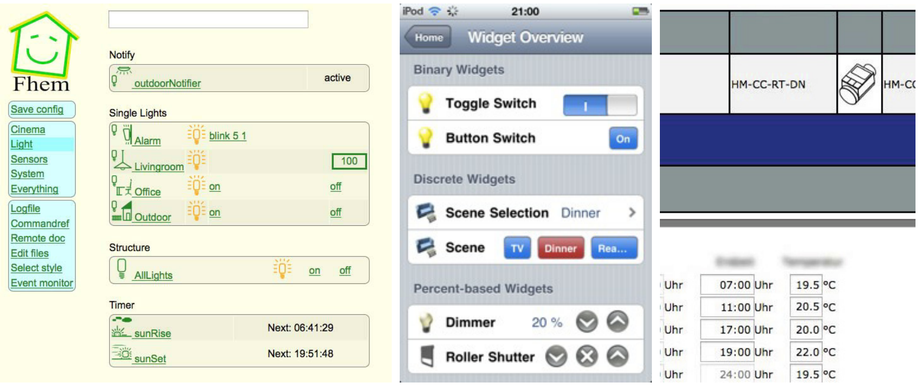
Current approaches to customize and control smart home environments are based on graphical user interfaces [6], [7]. While this is sufficient for pattern control activities we will show a different approach for instant control according to the requirements found by Koskela et al. [5].

3 A Concept of Synchronized Interaction

According to [8] the virtual world can be described as being an immersive 3D environment that allows for fluid interaction among inhabitants and enables them to shape their environment to a certain extent.

A typical interaction in the physical or the virtual environment can be decomposed into smaller actions. These actions form a workflow which starts with navigating to an object, followed by selecting, and finally performing a manipulation task on or with the object.

While moving towards an object (e.g., walking towards it) can be easily distinguished from other kinds of actions in the real world the interaction decomposition might not be obvious at any time. For instance, selecting an item (e.g., grabbing an physical object) becomes a manipulation (e.g., moving it) naturally without the user noticing. As a consequence of the physical interaction, the user is fully aware which object he is currently manipulating since he usually has physical contact to it. However, the manipulation tasks can range from a simple action (e.g. turning a lamp on and off) to rather complex ones (e.g., controlling a robot to get an item from a room).



(a) Fhem[1] (b) OpenHab[2] (c) HomeMatic[3]

Fig. 1. Example of user interface based on list views

In smart home environments the situation is different. To start an interaction, the user needs to navigate to a desired item by using a hierarchical or list view provided through browser-based control centers, apps (see Fig. 1) or by means of even more complex programs. After selecting the item in the graphical user interface the user gets listed the available manipulation operations and chooses one. These user interfaces often vary with the complexity of the tasks that can be performed. While a light switch can easily be represented by a toggle button, complex user interfaces are required in more sophisticated scenarios such as controlling a smart home robot. However, in contrast to real world interaction the user is not necessarily aware which item he is currently handling. Usually the selected item is a text label or icon on the screen without a visible relation to the corresponding physical object. Since the user does not get a natural feedback, either of its location by means of navigation towards it, or its appearance by means of having physical contact to it, the users awareness is not efficiently supported. On the other hand, the performed actions are not distinguishable from each other, because starting a manipulation task is usually done by the same user action, e.g. a button click gives no natural feedback about the task performance.

In 3D virtual environment (VE), the interaction shares properties with real world and smart home interaction. While navigating can be seen as similar to the real world, selection and manipulation actions feature similar properties to the smart home environment. Additionally, VE provides the opportunity to enhance the user experience by incorporating information which is not visible in the real world but helps the user to understand his environment better. It is also possible to give the user more flexibility by providing interaction short cuts.

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[1] `http://fhem.de`

[2] `https://code.google.com/p/openhab/wiki/WebAppUI`

[3] `http://www.homematic.com`

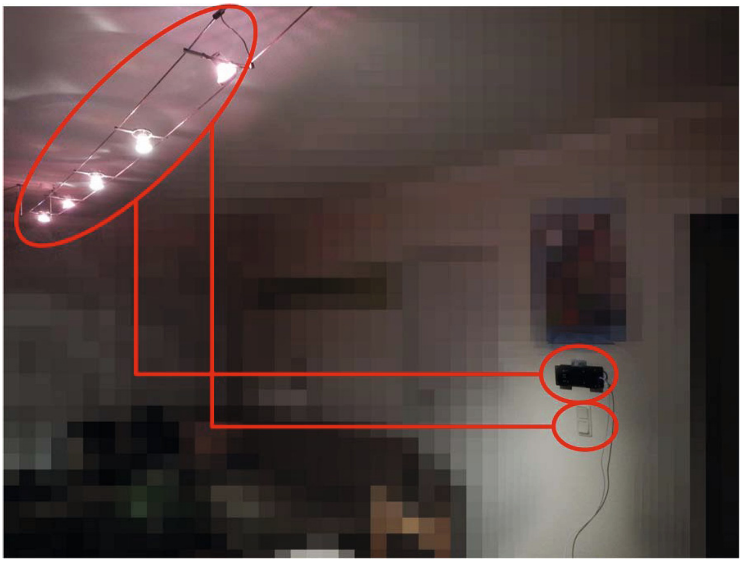

Fig. 2. Correlation detection between the physical and virtual environment

According to the cyber-physical system definition, we use a unique one-to-one correspondence between physical and virtual objects with the focus on mapping the real environment into the virtual world. This means, e.g., that every light switch in our physical environment get its virtual counterpart in the VE. To be efficient, this is done semi-automatically using a combination of sensing devices and actuators. For instance, we could detect correlations between a switch of a stationary ceiling light by means of an ambient light sensor in the same room (Fig. 2) This approach reflects the feedback loops and synchronizes the physical and virtual world permanently. However, it must be adjusted by requesting the user from time to time. Furthermore, we can visualize these - physically - relations between the elements in our virtual world.

Using mobile devices such as tablets or smart phones to interact with the virtual environment, the instant control activities can be supported by a single centralized device. These devices can either be carried around or are available in each room. Since the smart home is an all-in-one system the described virtual environment represents a viewport into the same shared world regardless of the used device.

Another benefit of our concept is the user's flexibility to achieve a goal. The smart home environment is adjusting to the user's performed actions. Normally, the user wants to perform a task himself whereas occasionally he wants support from the smart home for the same task, e.g., while being injured or disinclined. Whatever he decides to perform the smart home environment will be kept in synchronicity and therefore models the real world.

In the real world existing informal or invisible information about physical objects or environmental states can not be seen. Incorporating additional information into the virtual world can enhance the user experience and provides additional cues about smart home system states. Thus, the awareness of otherwise hidden information can be raised, e.g., visualization of CO_2 measurements in a sleeping room or showing the temperature state of a boiler or stove. Also, linking between physical and virtual objects can be visualized, e.g., the virtual representation of a physical light switch can be visually connected to the corresponding lamp within the VE by highlighting both in the same manner or by providing visual connection elements.

Overall, the user benefits from our comprehensible interaction concept, as we provide an abstracted and unified view on simple and complex control operations, as well as assisted configuration for smart home environments.

4 Proposed Setup

After explaining our interaction concept we present our proposed system realization. It is constructed by using three state of the art frameworks. Hence, we introduce the used components and show afterwards how the interplay between them leads to synchronized environments. We clarify the workflow and the interaction approach using two different scenarios.

4.1 Components

As shown in Fig. 3, we use the Modular OpenRobots Simulation Engine (MORSE) [12] to visualize the virtual world providing human and robot models. Information gathering from real world sensors and for communicating with actuators of our environment we use the Semantic MiddleWare (SeMiWa) [9]. To combine the virtual world of MORSE with the physical world of SeMiWa we utilize the Robot Operating System (ROS) [13] mapping the virtual and physical items and to localize them within a global shared coordinate system. Fig. 3 illustrates our entire system and the communication between the individual parts.

SeMiWa: All sensors and actuators are abstracted by our model-based, semantic middleware (SeMiWa) [9]. For instance, this middleware abstracts sensor stations of the Tinkerforge[4] toolkit. Each station consists of a temperature, a humidity and an ambient light sensor. In smart home all stations are assigned to a specific location, which is described by spatial coordinates. Beside the sensors SeMiWa controls the actuators in the real world transmitting control instructions to these components.

ROS: Firstly, we use ROS to synchronize the sensor's and actuators physical coordinates with the simulated world. We apply the *Simultanous Localization and*

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[4] `http://www.tinkerforge.com`

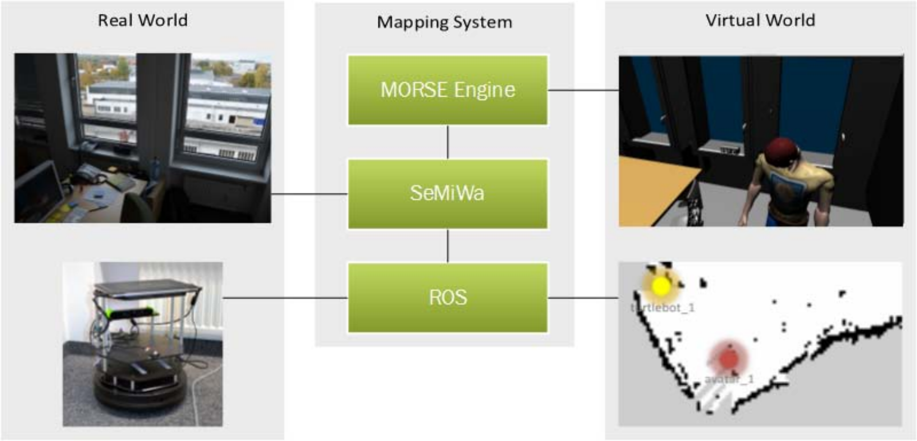

Fig. 3. The dual reality component architecture bridging the gap from the physical to synchronized reality

Mapping (SLAM) method integrated in ROS, a technique where a robot builds a map of the environment and estimates simultanously its pose within the environment. The measured SLAM map is the reference of our coordinate system, as this format can be used efficiently for mapping and localization. Additionally, this format was integrated in forehand in the MORSE simulator. In our scenario, we will use Turtlebots[5] for mapping purposes. Secondly, we reuse the modules of ROS to get an abstraction of robot abilities, e.g., object identification, picking and carrying with the Turtlebot.

MORSE: To interact in this dual reality, we use the human-robot interaction (HRI) module of MORSE [12]. In contrast to the classical intention, we permanently update the simulated virtual world with the real one. This means, each physical sensor updates the state of its virtual representation and vice versa. To achieve this behavior, we had to extend the MORSE simulator using the middleware infrastructure SeMiWa. The HRI module provides an *avatar* to pick and release objects, and investigate object states. As illustrated in Fig. 3 the human can walk with the avatar through the VE in order to manipulate it. Regarding to our ceiling light example, a person can switch on a particular lamp in a specific room without the demand to search for this lamp in a classical user interface. The MORSE simulator also gives us the capability to teleport the avatar to a specific room supporting interaction short cuts. Thus, the step-by-step navigation through the environment is not necessary but is nevertheless possible.

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[5] `http://www.turtlebot.com/`

Fig. 4. A complex manipulation involving a robot

4.2 Scenarios

We describe the workflow with two examples to explain the user interaction with the components. The first scenario illustrates a simple user interaction to manipulate and control electronic devices in the smart home. The second demonstrates a more complex interaction task involving robot control.

Scenario 1: Simple user interaction controlling electronic devices.

As a common task we choose the control of a physical lamp. In the real world the user turn on the light by using a physical switch. Since the switch is connected to the smart home the system recognizes the action and in consequence it turns on the corresponding light. Additionally, the virtual worlds gets updated with the new state of the lamp. Whereas in the virtual world the user can turn on the light by clicking on the corresponding virtual switch. The user input is recognized by MORSE and creates an light switch event within SeMiWa which relays the event to the real world actuator to switch on the physical lamp.

As a failure detection mechanism the Tinkerforge sensor station controls the execution of the task by measuring the ambient light and checks for possible mismatching world states. If the measurement is within an expected range the system recognized the successful execution and updates the world model accordingly, thus keeping the real and the virtual environment synchronous. Otherwise the system informs the user about the failed action.

Scenario 2: A complex manipulation involving a robot.

As CPS consists also of complex devices like robots, we abstracted our concept from direct robot interaction to a more sophisticated object interaction. For instance, the user moves to a room, marks an object of interest and gets an overview of available manipulation tasks.

This more complex scenario involves mainly two objects, a carried object and a carrier robot (Fig. 4). As these worlds are synchronized, the user is able to decide an appropriate interaction path for itself, e.g., to order a robot to get the pill organizer from the kitchen or to go to the kitchen and get it themselves. If the user is currently within the kitchen its more efficient to grab it by hand. In contrast if the user stays in another room it might be easier to task an assisting robot. For example, the room is out of reach for the current user situation due to distance or other circumstances. In the virtual world, he is able to select the room or teleport to it, look around to find the pill organizer and define it as a goal for the robot by clicking on the virtual representation. Afterwards, the user have to call for the simulated robot and in the same way, the real robot gets for its journey. After both robots reach their goal, the avatar put the object on the simulated robot. In the real world, a gripper, which is installed in the kitchen, puts the real object onto the physical robot. The avatar instructs the robot to go for the human, which finally gets its object physically.

5 Conclusion and Outlook

Our interaction concept supports the instant control activities according to the study by Koskela et al. [5]. The favored mobile devices are supported by our approach by means of using tablets and smart phones as interaction devices. With our approach we created an interaction concept and virtual environment that can be utilized by such devices. This setup also supports dynamic changes by e.g., using robots or other actuators. The utilized dual reality approach from [8] which we extended by an semi-automated, synchronized reality concept allowed us to support the ease of use of such systems, according to Green et al. [4], by using real world user actions in a 3D virtual world to control smart home environments. As a result we get a smart home environment based on the previous mentioned components which is able to recognize some failure states and is able to inform the user. Besides the convenience requirement we also fulfill the requirement of flexibility mentioned by Green et al. The user can decide which actions to take without the system demanding a certain interaction style thus seamlessly incorporating people's lifestyle.

With the usage of robots to map the environment before or even while using it, we are able to localize sensor and actuator positions and synchronize those in the virtual world. In future work this could be extended to automatically create the 3D representation of the smart home utilizing indoor 3D reconstruction based on vision or other cues.

Due to the focus on the domestic environment this concept is directed to handle single user and small user groups such as families. We do not envision a utilization of the proposed interaction concept for larger groups. While the usage in such a scenario is possible to some extend adjustments would be necessary to coupe for issues that large user groups raise such as permission and access control. Also in contrast to [11] in which the authors motivate to bring different locations into a shared virtual environment to support communication between inhabitants, we used the "synchronized realities" approach to combine the real and virtual world of a single smart home environment at one location to support our interaction concept.

Currently, we are planning to conduct an exhaustive evaluation on identifying more classes of objects that are neccessary to synchronize. In addition, we are working on preparing a long-term user study in an elderly care environment to measure the suitability of our interaction concept. Furthermore, we intend to enhance our system to work not only on direct manipulation of objects, but also on a cooperative manner between the smart environment and the user.

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