User Interfaces for Cyber-Physical Systems: Challenges and Possible Approaches

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Abstract. Catchwords such as "Cyber-Physical-Systems" and "Industry 4.0" describe the current development of systems with embedded intelligence. These systems can be characterized by an increasing technical complexity that must be addressed in the user interface. In this paper we analyze the specific requirements posed by the interaction with cyber-physical-systems, present a coordinated approach to these requirements and illustrate our approach with a practical example of an assistance system for assembly workers in an industrial production environment.

Keywords: Industrial IT · User-Centered design · Usability · User interfaces · Cyber-Physical-Systems · Industry 4.0 · Augmented reality · Development processes and methods

1 Introduction and Motivation

The term *Cyber-Physical-System* (CPS) was coined by the National Science Foundation [11] and denotes a composition of physical elements (e.g., mechanical, electrical or electronic elements) and software elements (e.g., simulation, analysis, and control) that are connected through a communication infrastructure (e.g., industrial internet). Creating a network of embedded systems and connecting them to sensors and actuators results in complex distributed systems. These cyber-physical-systems exhibit the high degrees of freedom of software systems, but are also subject to the constraints of physical systems. The development and application of cyber-physical-systems raises many challenging research questions [10], which are currently being addressed in a number of international research projects. A key application area is the use of such cyber-physical-systems in industrial production, where they are referred to as *Cyber-Physical-Production-Systems*.

Industry 4.0 can be interpreted as a special form of a cyber-physical-production-system [3, 8]. The term was established by the high-tech strategy of the German federal government and characterizes the development of cyber-physical-production-systems as the fourth industrial revolution, in which "intelligence" is embedded in the elements of a production process [9]. Central technical topics associated with industry 4.0 include

networking (internet of things), the use of decentralized "intelligence" that allows the components to adapt to their context, high flexibility and versatility of systems based on modular units, and customized production down to a batch size of 1. Human-machine-interaction faces special challenges in such an environment, firstly because the user must be able to work effectively in such an environment, and secondly because a good user experience will be decisive for the acceptance of such systems in the workplace.

In the BMBF (German ministry of education and research) excellence cluster *Intelligent Technical Systems OstWestfalenLippe* 174 partners from industry and science conduct research and development to address the challenges that arise in making cyber-physical-production-systems a reality [17]. A key component in this research is the *SmartFactoryOWL*, a demonstrator factory that will cover 2000 square-meters in its final installment, and which integrates key research fields such as highly flexible and versatile production, plug-and-produce, and human-machine-interaction in a realistic production environment. The practical experiments for this paper were carried out at workplaces in the *SmartFactoryOWL*.

2   Specific Requirements for the Interaction with "Cyber-Physical Systems"

Interaction with industrial production systems is nowadays largely effected through (complex) graphical user interface. In recent years, many developments from desktop, mobile and web interfaces, as well as new interaction modalities such as multi-touch have been integrated. Current developments pose additional challenges for the designers of user interfaces in this domain [16, 19]:

- Users and customers change their attitude and expect a degree of user-friendliness that is similar to web and mobile apps.
- A growing number of manufacturers regard the quality of their user interfaces and the "user experience" offered by their products as a key differentiator in the market.
- At the same time user diversity increases [14] and customers expect future user interface to effectively assist a wider range of users, e.g., to address some of the needs of an aging workforce [6, 15].

These challenges are exacerbated by the introduction of cyber-physical systems. On one hand, the use of "smart" components leads to more flexible and adaptable systems, on the other hand this leads to increased technological complexity. A key challenge for the developers of user interfaces in this environment is therefore to reduce the perceived system complexity from the user perspective [20].

User-friendly design of human-machine-interaction is important in many domains, e.g., desktop or web applications. In addition to usability, that focuses on functional aspects such as usefulness, efficiency, effectiveness and the learning curve of the user interface, the more expansive concept of user experience, that also considers the emotional response of the user to the interaction with the product, receives increasing attention. Several design processes and design techniques have been developed and adopted in the web and desktop domain to ensure that user interfaces provide a suitable design and an

attractive user experience. In theory these are also applicable to the design of user inter-faces in industrial environments and for cyber-physical-systems. In practice, however, several important peculiarities prevent a direct application and must be addressed:

- **Interaction Hardware:** An important difference is the lack of standardization of interaction hardware. For desktop applications and web design the interaction hardware can be largely expected as standardized components, e.g., keyboard and mouse. New interaction devices can be added and are often largely compatible with established devices (e.g., mouse > touch-pad > touch-screen). In the context of cyber-physical-systems, such simple expandability is often not possible and the selection of appropriate interaction devices is more limited. This is especially true in industrial environments, where additional requirements such as robustness or dust and explosion protection must be considered.
- **Toolkits:** In the domain of desktop and web development well-established toolkits of interaction and presentation elements (widgets or controls) are available. Because their appearance and function was optimized over years, developers can focus on the composition of user interfaces from these elements. The direct use of these interaction elements in applications for cyber-physical-systems or industrial production systems can be problematic, because the metaphors that were used in their development are based on an office environment and may not fit well into an industrial environment. Also interaction techniques for important tasks (e.g., emergency stop) may be missing.
- **Development Processes:** The established user-centered development processes can in principle be applied to the development of cyber-physical-systems. Differences arise primarily for individual development activities within these processes. An important aspect is the consideration of the real ("physical") environment, on which the developers have very limited influence. Users interacting with classic desktop and web applications operate in a graphical virtual environments (GUI, website) that is entirely under the control of the program and can therefore be designed freely by the developers. When interacting with cyber-physical-systems existing physical system components need to be taken into account [5], on which only limited data is available and that can only be influenced in a limited way through special physical controls. Furthermore, the selection of interaction hardware must be included in the development process due to the problems outlined above.
- **Tools:** In the desktop and web domain rapid prototyping tools are used that allow to quickly create a user interface designs. In addition special test tools are available that support the evaluation of user interfaces in user tests. These tools are difficult to apply in the development of user interfaces for cyber-physical-systems in industrial appli-cations, because they are limited to the standardized interaction elements and the essential integration between virtual elements that are under complete control of the developers, and real "physical" elements that are subject to additional constraints, is not taken into account.

To support the desired rapid iterations with prototypes in early design phases, additional tool components are required, that integrate "physical" components and can possibly simulate them in early design phases.

3   Adjusted Design Approach

To address these challenges, we propose a combination of a user-centered-design process and a toolkit of components, which also includes novel interaction and visualization technologies. Central to user-centered development is a systematic design process. Iterative design processes have been established as "best practice" in user interface design and divide the development into several phases that are iterated taking into account the results of user tests. Our approach is based on the ISO standard DIN EN ISO 9241-210 [7] in which the activities *analysis of the context of use, specification of requirements, design and implementation,* and *evaluation* are iterated.

- **Analysis of the Context of Use:** the analysis and documentation of the context of use forms the basis for the subsequent development. In this activity the user groups, the tasks to be supported, and the usage environment are analyzed and documented. For industrial applications it is important that the technical environment is also analyzed to identify the available sensors and input modalities.
- **Specification of Requirements:** This design activity specifies requirements for the system, taking the context of use into account. In addition to the requirements of the customer and the end user additional requirements, such as usability, regulations concerning occupational safety, etc. need to be considered.
- **Design and Implementation:** The following activity is used to create designs. In the development of user interfaces in industrial environments, rapid prototyping strategies should be applied. The goal is to investigate a wide range of design alternatives at a reasonable cost. Especially with new user interface concepts like augmented reality, such an approach is central, because less experience and knowledge on similar systems is available.
- **Evaluation:** In this activity, the designs and the implemented solutions are tested with real users. Based on the results the other design activities are then iterated to improve the design.

An iterative design process as described in the ISO 9241-210 standard, is the established "best practice" for the development of desktop software, websites and mobile apps. The biggest challenge here is to integrate the user-centered activities into established software engineering processes [12]. In the industrial production environment, there are long-standing efforts to make workplaces ergonomic and user-friendly. While the basic phases of ISO 9241-210 can be applied to an industrial work environment, modified techniques and tools are required for their concrete implementation.

Developers of desktop, web and mobile applications are effectively supported by prototyping tools like Axure, that allow rapid implementation of graphical prototypes, which can then be tested with real users. The development of user interfaces for cyber-physical-systems requires taking physical-components into account, which are also subject to much longer cycles of change. One possible approach is the temporary use of virtual proxies (simulated placeholder) for these physical elements, which are then successively replaced by their real world counter-parts in later design

phases. A possible approach is to use the MR-in-the-loop methodology, which includes the Model-View-Controller Environment (MVCE) design patterns to address the incorporation of physical elements in a systematic way [18].

4   Interaction and Visualization Techniques, Tools

Developers can be best supported through a suitable design methodology and appropriate tools that provide interaction and visualization techniques optimized for cyber-physical systems.

In addition to traditional graphical user interfaces and their evolution such as multi-touch interaction techniques, user interfaces based on the paradigms of Mixed and Augmented Reality (MR/AR) have great potential for the interaction with cyber-physical system. Mixed and augmented reality systems enhance a real, physical environment with virtual, computer-generated elements (visualization techniques) and can interpret physical actions of the user (such as gestures or the manipulation of real objects) as interactions with the system (interaction techniques) [2]. Because cyber-physical systems are characterized by the combination of physical elements with computerized "smart" control mechanisms, MR/AR user interfaces form a natural match, since they also use a combination of physical and virtual elements for interaction.

Numerous demonstrators for new interaction technologies (e.g., [1, 20]) indicate the potential for improvement, especially in the industrial environment. However, designers of productivity applications often limit themselves to the functionality of established UI toolkits. Central reasons for this are the lacking maturity of the base technologies (e.g., displays, tracking) and interaction techniques that are often only developed to demonstrator status, lack of familiarity with the new technologies and their advantages and disadvantages, and the higher development effort caused by the absence of effective tools. The central goal of our work is to make new interaction and visualization technologies available to developers and designers. Therefore, we develop a set of interaction and visualization techniques for central interaction tasks in the industrial environment. The goal is it to develop a set of robust techniques that can be used by designers and developers similar to the widgets/control components in established GUI toolkits in close coordination with industrial customers. The central interaction tasks to be supported include:

- Spatial navigation to a place of interest.
- Visual highlighting of an object of interest in the field of view of the user.
- Visual guidance to an object of interest outside of the user's field of view.
- Alerting the user.
- Context-sensitive information presentation fixed to a object.
- Contextual information display on a mobile object.
- Process-oriented information representation.

First examples and results are presented in the following sections.

5   Example: Assistance System in Industrial Production

In the following, we illustrate our approach using the development of an AR-based assistance system for manual assembly tasks as an example [13].

The system guides users with picking and assembly instructions during their assembly tasks, in which it blends relevant information directly in the user's field of view. The current system was developed in a user-centered design process and with a focus on the procedures described above.

The results of this process are summarized below.

5.1   Analysis of the Context of Use

The AR-based assistance system for manual assembly tasks is part of the *SmartFactoryOWL*, a modular factory system addressing many aspects of an in-industry 4.0 environment. The factory uses a modular transport system with workpiece carriers, which combines a number of production cells (e.g., laser cells, robotic cells) as well as workplaces for manual assembly. The control of the system is decentralized and implemented using RFID chips that are embedded in the products or the workpiece carriers and support and act as a digital product memory.

Following the "plug-and-produce" concept, all cells and conveyor belts of *SmartFactoryOWL* are flexible and can be rearranged or removed. Thus, the production of a product could start with a complete manual assembly of a small series. When the production volume increases, robot cells can gradually be integrated into the production in order to reduce the workload for assembly workers.

In such a usage context, special requirements arise for an assistance system, since the system must be able to work with changing configurations of cells and conveyor belts and support dynamic changes in the production tasks controlled by the individual products (Fig. 1).

5.2   Specification of Requirements

As part of the *SmartFactoryOWL* we study the ergonomics and usability of user interfaces relating to various users during the operation of a smart factory (e.g., assembly workers, maintenance staff, plant engineers, etc.). A key component in this context is the support of manual assembly tasks. In order to do this, the assistance system should provide workers with information and instructions related to the product and assembly step the worker is currently performing. Since each product can be configured individually, a high diversity of variants has to be expected and workers need to be supported accordingly. In the *SmartFactoryOWL*, each product or workpiece carrier stores the necessary assembly steps on the integrated RFID chip and each module knows the production steps it can execute. For example, if a robot is present, it assembles parts of the product and registers the assembly steps performed on the RFID chip. In the following step, the assistance system of the manual workplace analyzes the remaining steps and provides the appropriate assembly instructions to the worker.

With respect to the user interface, the workers should be supported in the selection of the next component to be assembled ("picking") and then corresponding assembly

instructions ("assembly"). The presented information should not only be easy to understand, but also presented in a way so that the worker is not distracted from his current task. A key requirement is that the hands remain free for the actual assembly tasks and the assembly process does not have to be interrupted for the interaction with the assistance system.

5.3   Design and Implementation

In order to be able to develop the assistance system independently of the rest of the "physical" components, a simple simulation of the system as well as a virtual 3D model of the manual assembly job was implemented in an early phase of the design process. Later, the developed prototypes were integrated in the real assembly context. After having assessed different approaches, the decision was reached to develop a user interface based on augmented reality technology in order to visualize assembly information within the user's field of vision. This is particularly important for "picking" instructions, which can now be located directly adjacent to the corresponding real-world objects and thus enable a hands-free usage of the system.

A key issue in the design process was the selection of suitable display hardware. Design choices included separate displays on the workstation (e.g., tablets or mounted displays), projections, smart glasses (e.g., *Google Glass*) and AR glasses. As a spatial superposition within the user's central filed of vision was required, separate displays and *Google Glass* were discarded. The choice between a projection and using AR glasses was made in favor of the glasses as this allows for a stereoscopic display. At the moment, we are using *Vuzix STAR 1200* data glasses, which operate in the optical-see-through mode and can display stereoscopic 3D graphics. The glasses feature a built-in HD camera as the basis for an optical tracking system.
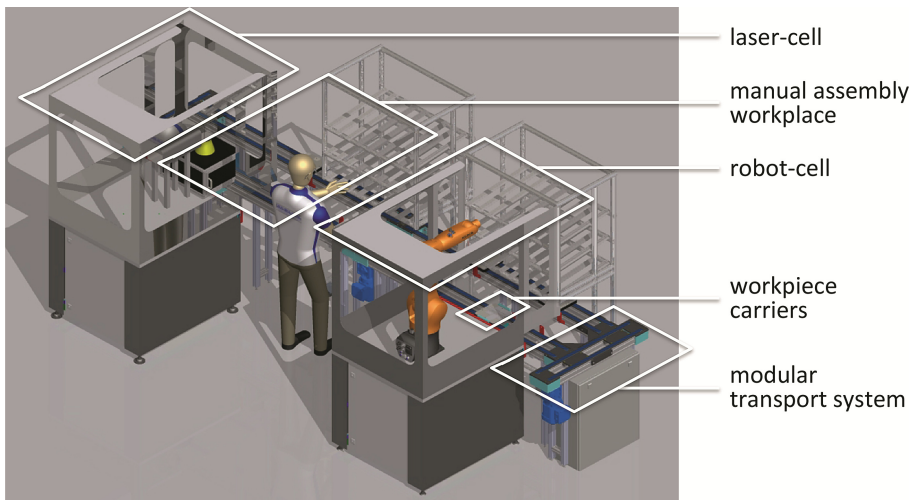

Fig. 1. Modular structure of the *SmartFactory OWL*

Another important design decision was the selection and development of appropriate imaging techniques (see Fig. 2). Both for the picking as well as for the assembly instructions various techniques have been examined in order to support efficient communication with minimal distractions.

Fig. 2. Different visualization concepts for picking instructions

The studies showed that the choice of an appropriate representation is highly dependent on the user. Generally, novice users regarded a realistic representation that simplifies visual recognition and the matching of virtual and real-world objects as helpful, and therefore preferred an animated representation of the assembly instructions. In contrast, experienced users preferred an abstract and static representation, especially as such a form of information visualization requires less attention. The development and evaluation of such visualization techniques is an open research field and provides the basis for the subsequent development of a "toolbox", which could comprise different visualization techniques that can be individually combined to suit the personal needs of each user. The strong effects of personal user factors, expertise and duration of usage on the preferred visualization style, makes techniques for dynamically adapting the representation method to the active user and his current task an interesting design approach (Fig. 3).

5.4   Evaluation

During the development process a number of tests were performed, for example, to identify appropriate output devices or to experiment with different representation techniques. A complete version of the system was then integrated into the *Smart FactoryOWL*. Since then, the system has been shown at a number of fairs and public events and was used for further experiments. During this time, the system has been successfully tested by hundreds of users (Fig. 4).

During the initial user tests we were able to identify several aspects that could be improved. Following an iterative design process, we are continuously improving the system by implementing the required features into the system. Especially longer tests with experienced users showed critical limitations. In particular the AR glasses we are currently using turned out to be too heavy and uncomfortable for extended use. While the initial tests were mainly of formative nature and intended for improving the visualization and interaction techniques, the implementation of augmented reality techniques has now reached a level of maturity that allows formal summative testing, in which the differences between individual techniques can be quantitatively measured and evaluated. Our aim is to use the knowledge gathered in these tests to formulate application instructions and guidelines.

Fig. 3. Picking support based on the augmented reality technology: the object of interest is visually highlighted in the user's field of view

6   Experience and Outlook

Our initial results show that the benefits of new interaction technologies are primarily related to specific tasks. For the development of future user interfaces for cyber-physical systems in industrial environments, this means that new interaction concepts, such as augmented reality, should not be seen as a replacement for conventional techniques, but rather as an extension of the design space, which enables designers to better adapted user interfaces to the interaction task. The efficient usage of these new possibilities requires special "toolkits" to make the various interaction technologies easy to use, as well as knowledge about the advantages and disadvantages of the different technologies in specific usage contexts. So far, the focus of our research was mainly on the use of augmented reality techniques in assistance systems for manual assembly tasks. In our current and future work, we extend the scope of our activities to cover additional interaction and technology components for assistance systems in general. The long-term goal is to create a collection of established interaction and visualization components for user interfaces that support interaction designers in the development of industrial applications.

Fig. 4. Manual workstation for the evaluation of interaction and visualization techniques

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