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Usability Requirements for complex Cyber-Physical Systems in a Totally Networked World

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Abstract. *“The Internet has made the world “flat” by transcending space. [...] The Internet has transformed how we conduct research, studies, business, services, and entertainment.”* [1] Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components. Advances in CPS will enable capability, adaptability, scalability, resiliency, safety, security, and usability that will far exceed the embedded systems of today. CPS technology will transform the way people interact with engineered systems. *“CPS have a highly disruptive effect on market structures. They will fundamentally change business models and the competitive field of today [...]”* [2] Usability is a driving force for the rapid take-up and acceptance of these Cyber-physical systems. [2] In this paper we define CPS and highlight the importance of usability for CPS. Then we describe two different cases and provide different methods how to improve the usability of CPS.

Keywords: Cyber-physical systems, Usability, a best practice process model

1 Cyber-Physical Systems

Baheti and Gill define CPS as Systems that integrate the cyber world with the physical world. The computational and physical components of such systems are highly interconnected and coordinated to work effectively together, sometimes with humans in the loop.[3] *“Cyber Physical Systems (CPS) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.”* [4]

CPS will also contribute to safety, efficiency, comfort and human health. Therefore, it helps to solve some key challenges of our society such as the ageing population, limited resources, mobility, or the shift towards renewable energies, which were caused by the demographic transitions and globalized world. [5]

“The promise of CPS is pushed by several recent trends: the proliferation of low-cost and increased-capability sensors of increasingly smaller form factor. The

availability of low-cost, low-power but with high-capacity [...] and the wireless communication revolution [...] continuing improvements in energy capacity, alternative energy sources and energy harvesting. The need for CPS technologies is also being pulled by CPS vendors in sectors like aerospace, environmental control, [...] factory automation and healthcare who are increasingly finding that the technology [...] is seriously lacking.” [6]

About 98 percent of the microprocessors nowadays are working embedded, connected via sensors with the outside world. They are increasingly networked with each other in the Internet. The physical world merges with the virtual world, the cyberspace. [7]“A large variety of collaborative networks have emerged during the last years as a result of the challenges faced by both the business and scientific worlds. Advanced and highly integrated supply chains, virtual enterprises, virtual organizations, professional virtual communities, value constellations, and collaborative virtual laboratories, represent only the tip of a major trend in which enterprises and professionals seek complementarities and joint activities to allow them participate in competitive business opportunities.” [8] CPS extend the notion of these collaborative networks by the integration of physical nodes and their virtual representation as specific entities within collaborative networks.

The trends push CPS to perform well and be useful in the mentioned areas. People and the industry want to have user-friendly devices which are not only handy but also have great appearances with high performance as well as capacity and of course with lower prices. The demand of using CPS is pulled by several industries and that is why CPS is always being developed in the application areas such as industry 4.0, automotive and avionic industries, logistics structures and other engineering fields where CPS has a valuable contribution. [6]

Another essential argument about achieving the goals is to link human intelligence with computer power, set by Lanz and Torvinen as follows: *“The real operating environment is not stable or predictably behaving. Systems in all fields have become parts of bigger systems via cooperation and communication within each other [...] In order to operate in such dynamic and complex environment best of the both worlds; human intelligence and computers’ computing power needs to be utilized in right places.” [9]* *“Cyber physical systems research aims to integrate knowledge and engineering principles across the computational and engineering disciplines (networking, control, software, human interaction, learning theory, as well as electrical, mechanical, chemical, biomedical, material science, and other engineering disciplines) to develop new CPS science and supporting technology.” [3]*

The rapid research and technological advances in Internet of Things and increasing availability of sensors, actuators, and mobile devices have created an exciting new ubiquitous computing paradigm as an emerging paradigm is changing the way we live and work today. Via a ubiquitous infrastructure consisting of a variety of global and localized networks, users, sensors, devices, systems and applications may seamlessly interact with each other and even the physical world in unprecedented ways. To realize this usable and trustworthy computing that delivers secure, private, and reliable support for interconnected systems (i.e. organizations, services, objects) usability plays a pivotal role. [10]

2 Usability of Complex Technical Systems

“Usability is the ease of use and learnability of a human-made object. The object of use can be a software application, website, book, tool, machine, process, or anything a human interacts with.” [11]

Nonetheless not only usability is a crucial point of interaction of humans with technical and cyber-physical systems in the virtual world but trust and reliability is also a major issue to be considered. “[...] designing predictable and reliable components makes it easier to assemble these components into predictable and reliable systems. But no component is perfectly reliable, and the physical environment will manage to foil predictability by presenting unexpected conditions.” Especially in quite complex and critical environments like cyber-physical systems sometimes are trust and reliability becomes very important.

Technical complexity refers to either the fundamental interaction characteristics (input and output) of the technology being complex, or where the underlying system architecture is complex, linking a variety of different systems, architectures, agents, databases, or devices. [12] At some point a decision must be made regarding the system interaction approach that is made towards the user. While issues of technical complexity have been discussed for many years, the rapid pace of change in disruptive technology domains means we are now required to design for a whole new range of cyber-physical systems that are emerging into common use and demand the development of new interaction styles and new guidelines.

Contextual complexity includes the broader tasks, roles, or jobs the technology is proposed to support, especially when tasks are open-ended or unstructured. A well-designed system will consider this more contextually complex type of scenario when developing a system, to ensure that the appropriate information required to support these contextual goals is incorporated into the system.

One implication of the need to reflect both technical and contextual complexity in design is an emphasis on multiple methods. While laboratory and quantitative work still has an important part to play, most often addressing the issues of technical complexity, qualitative methods such as ethnography, interviews and content analysis, and detailed observation are also vital for capturing the factors that contribute to contextual complexity. In practice, we find that methods need to be used in combination so that all aspects of usability can be addressed.

3 Case Studies

Based on this, we present examples from our work in two specific domains that encompass both technical and, in particular, contextual complexity. We concentrate on considering the applicability of methods in complex situations.

The first example is a case, where security tokens connected to machines guarantee that only official products are produced, where the challenge of design and evaluation

is being able to effectively create intercultural systems, and capture the contextual characteristics of real and virtual working environments.

The second domain is energy efficiency management in large connected environments, where the variety of inputs and outputs, the challenge of working with traditionally disconnected domains, and the lack of design guidelines or standards pose challenges for the usability experts.

| Domain | Production | Energy |
|------------------------------|--|---|
| Case description | Security tokens connected to machines guarantee that only official products are produced | Energy efficiency management in large connected environments with variable inputs and outputs |
| Technical complexity | e. g. managing of different security tokens | e. g. balancing of energy; connection of different environments; managing the variable inputs and outputs |
| Contextual complexity | e. g. producing customer individual productions using different (customer) context | e. g. management of priorities of inputs and outputs, if there might be a higher need of energy |
| Usability | Using different methods to improve the usability: <ul style="list-style-type: none"> • Using cost-efficient and field-tested concepts • Repetitive and detailed model (also for customer specific projects) • Clearly specified process using an accepted framework and process model based on standards • Testing of products and processes using defined criteria • Considering always both sides: vendor and users • Etc. | |

Table 1: Case Studies

The cases demonstrate two points: They illustrate the importance of both technical and contextual complexity in different technology contexts and they provide example methods that can be applied to examine the human factor issues associated with complex usability. Because of the inherent complexity, it is often necessary to use multiple methods in combination.

Complexity takes on both a technical and contextual dimension. A number of methods are considered, and across both case domains there is an importance on using multiple methods to address usability, there is no one single method that can be used to ensure usability and this is particularly apparent in cases of usability of cyber-physical systems. Because complexity may exist from a number of different sources, it is necessary to sometimes use different approaches to unravel all the various issues that might lie within (see also table 1).

The various methods have its own strengths and weaknesses. Qualitative interviews are open to subjectivity on the part of the usability specialist, whereas more quantitative work is only as valuable as the reliability and validity of the data

being collected. Using a number of methods can improve accuracy and enables us to build a fuller understanding of the critical issues.

3 Summary and Conclusions

CPS connect the cyber world with the physical world. The cyber and physical components of these systems are strongly coordinated to work effectively with humans in the loop. [3] The rapid deployment of CPS leads to more and more interactions between human and the networked world. Usability, reliability, trust and security are the important key issues for the CPS success. The ability to interact with, and expand the capabilities of the physical world through computation, communication, and control is a key enabler for future technology developments. [3]

In this domain complex usability has two dimensions, a technical and a contextual dimension. The two are interdependent, and both are of high importance to usability specialists and the successful implementation of systems that are relevant to complex usability. It is unlikely that a single method will be sufficient to capture all aspects of technical and contextual usability. If methods are used in combination across the different aspects of complexity, then there is a possibility to identify critical issues to address them. There is a need to ensure that new methods are generalizable across applications or domains and new methods must acknowledge both the technical and contextual complexity of systems. This makes it necessary to have a toolbox from which users can select tools appropriate to the complex usability issues that they encounter.

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