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CYBER-PHYSICAL AUGMENTATION – AN EXPLORATION

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ABSTRACT

Ubiquitous technologies provide many product innovation opportunities for industrial design engineers, such as creating user centered cyber-physical systems with adaptive capabilities to individual users and environments. The exploration discussed in this paper aims to uncover needs to know for designers to successfully augment physical products with cyber functionalities, or create tangible elements with cyber-based products or to enrich products with full cyber-physical functionalities. For this exploration the authors could rely on experiences with design work of many students and on literature reporting on case studies. A third source has been descriptions of special cyber-physical systems. An analysis of the students' design work, the reported cases, and definitions and descriptions have led to conclusions that designers need to adopt new knowledge and procedures regarding ubiquitous technologies, knowledge management, adaptive behavior, system design, new prototyping techniques, user participation in cyber-physical systems and controlling the changing state of designed product in the use phase. For this design aspects have been identified and six design principles have been formulated. The identified design aspects can already be addressed in the application of cyber-physical augmentation. Future research will address the bridging between the design engineering and the cyber-physical world by adapting knowledge fields and methods, including the user in the design scope and by developing a knowledge construction method and an integrated design method incorporating the aspects, principles and (adjusted) techniques.

KEYWORDS

Cyber-physical system development, product-service innovation, functional augmentation, hardware technologies, middleware, cyber contents

1. INTRODUCTION

As a complement of the development of cyber-physical systems from scratch, cyber-physical augmentation is seen as an efficient way of exploiting the affordances of cyber-physical technologies. The objective of both approaches is a context-sensitive integration of digital sensing, computing and actuating hardware with control and application software and digital data and knowledge contents at all levels and scales. Cyber-physical augmentation (CPA) intends to extend the scope of functionality, operational intelligence, and provided services of some existing systems (such as medical rehabilitation systems, greenhouse systems, transportation systems, etc.) towards more benefits for the end-users, the environment, and/or other associated systems. Though CPA starts out from the functionality and constituents of existing solutions, it may lead to radically innovative and enhanced systems. It typically increases the complexity not only of the original system, but also of the implementation processes. At the same time, it may lend itself to a much broader range of services and advantageous system features such as reliability, adaptability, and efficiency.

CPA enables the realization of new functional and structural system features such as: (i) decentralized structure, (ii) autonomous operation of some constituents, (iii) dynamic networking, (iv) open system boundaries, (v) runtime adaptation, (vi) massively non-linear behaviour, (vii) multi-scale composition, (viii) proactive and contextualized operation, (ix) self-evolving capabilities, and (x) system of systems relations. User-centred design of these new functionalities in products and systems calls for new design principles, and requires additional skills and knowledge from system engineers.

This paper presents the findings of an explorative study concerning the basic principles, state of the art development, and future opportunities of cyber-physical augmentation, in particular in the field of product-service design. The exploration comprises the analysis of cases that fit the area of cyber-physical augmentation with the goal to identify additional design principles to successfully benefit from the opportunities given by the emergence of the technologies that enable the development of social cyber-physical systems (see section 1.2).

1.1. Cyber-physical systems

Applying cyber-physical augmentation will result in user-centred cyber-physical systems. Hence the concept of cyber-physical systems (CPSs) will be discussed here, looking at definitions both from US and EU. For instance, Energetics Inc. (US) described cyber-physical systems as smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components. They state that CPSs and the innovative products and technologies they support have the potential to create a source of competitive advantage for the U.S. economy in the 21st century [1], [2].

A recent EU-report envisions the confluence of the embedded and Internet worlds that has led to the concept of cyber-physical systems. CPSs refer to ICT systems (sensing, actuating, computing, communication, etc.) embedded in physical objects, interconnected (including through the Internet) and providing citizens and businesses with a wide range of innovative applications and services. These may also exploit the emerging Internet of Things and smart devices of the future and trigger the next of innovation towards intelligent and autonomous systems [3].

In these two definitions, the main elements are hardware and software (or ICT systems in physical objects), embedded systems, smart, provide innovative functionality, and potentially competitive. Figure 1 represents the elements of the concept of social cyber-physical systems that we have developed based on, among other these two definitions, but also based on other considerations.

A definition that includes more specific properties for cyber-physical systems, is given in [4] based on [5]: cyber-physical systems are complex, sophisticated, geographically distributed collaborative systems that operationalize two levels of collaboration, namely inter-system collaboration and hyper-system collaboration. Inter-system collaboration is among the functional agents of one particular system, while hyper-system collaboration means cooperation of hierarchically related and/or networked systems in an ad hoc manner.

In our interpretation, CPSs represent a specific branch of complex technical systems [42]. They are confluences of knowledge and technologies of computing, networking and informing, and those of physical artefacts and engineered systems towards operating and servicing in human and social contexts. Starting out from the current practices, we have demarcated two implementation levels of CPSs. Low-end implementations are linearly complex, closed and architected, distributed and networked, sensing and reasoning enabled, smart and proactive, (often embedded and feedback controlled) collaborative systems. In the landscape of the technical systems, they are represented by complicated linear and tolerant complex systems.

High-end implementations are non-linearly complex, open and decentralized, heterogeneous and multi-scale, intelligent and partly autonomous, self-learning and context-aware systems. The latter family of CPSs comprises technical systems with self-sensing, self-adaptive, and self-evolving capabilities. They display organization without any predefined organizing principle.

These additional characteristics in various definitions point to interesting new required knowledge fields for design engineers confronted with the challenge to create such systems. For this paper the elementary definitions of cyber-physical systems represented in Figure 1 will serve as our basic interpretation of

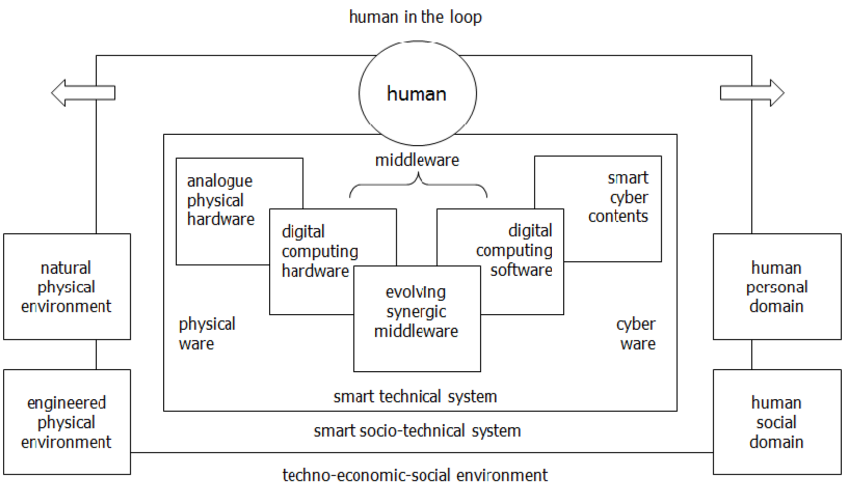

Figure 1 Elements of the concept of a social-cyber-physical system [42]

CPSs. Some specified definitions will be analysed in sSection 4 to identify additional needs to know for design engineers.

1.2. Social cyber-physical systems

In [6] it is posed that CPSs progressively interact with the human domain and the embedding environment. Therefore, they should be seen as complex socio-technical systems, in which human and technical aspects are combined: Social-cyber-physical systems (SCPS) should work, on the one hand, according to the expectations of humans, communities and society, and on the other hand, under the constraints and conditions imposed by the embedding environment. The adaptation to users and environment of the systems tend to ease off over time due to changing requirements of the users or environment, or to the evolution of the system itself. Therefore, SCPSs are supposed to flexibly adapt to the environment, and to the (communities of) users.

On the other hand, current technological limitations make CPSs intrusive. As Biamino [7] discussed, SCPSs should have some basic social abilities such as: detecting users and the social connections between them, and accessing users' data. The awareness of SCPSs should extend to the intangibles of social context, which includes social culture and norms, personal believes and attitudes, and informal institutions of social interactions. In this context, the following system characteristics have been identified:

- SCPSs are able to become aware of the users and their personal and social contexts, and to adapt themselves towards a symbiosis.
- SCPSs are able to achieve the highest possible level of dependability (trustworthiness and confidence), accountability, security, accessibility, and maintainability.
- SCPSs strive for operating as self-organizing open systems, with a minimal environmental impact and sustainability from ecological, economic and social viewpoints.

1.3. Cyber-physical augmentation

The concept of cyber-physical augmentation can be found in [8]: from a long-term point of view, machine-to-machine (M2M) systems with the capabilities of decision-making and autonomous control can be upgraded to cyber-physical systems. Recently, CPSs have emerged as a promising direction to enrich human-to-human, human-to-object, and object-to-object interactions in the physical world as well as in the virtual world. Cyber-physical augmentation is a promising direction for incremental innovation and comprehends an enrichment, an extension or an upgrading of systems, products, services and/or information into a cyber-physical system.

Incremental enhancements of products has recently be discussed by Norman and Verganti in [9]. They explain that the methods of human-centred design have a common framework: an iterative cycle of investigation, an ideation phase, and rapid prototype and testing phases. Each iteration builds on the lessons learned from the previous cycle, and the process terminates either when the results are appropriate or when the allotted time has run out. This continual process of checking with the intended users lead to incremental enhancements of the product. This procedure results in continual improvement, with eventual termination at “the peak of a hill”. Generally stated, incremental innovation tries to reach a local maximum, where radical innovation seeks the highest overall maximum. Incremental product innovation aims for changes in a product to improve its performance, lower its costs, and enhance its desirability. Radical innovations, at their first introduction, are often difficult to use, expensive, and limited in capability. Incremental innovations are necessary to develop the radical idea into an acceptable product for consumers who follow the early adopters. Both forms of innovation are necessary. Without radical innovation, incremental innovation reaches a limit. Without incremental innovation, the potential enabled by radical change is not captured [9].

Cyber-physical augmentation is incremental product innovation with ubiquitous technologies. Augmentation goals can be any product improvement addressing one or more aspects or for the whole product such as extended functionality, improved sustainability, better performance, lower energy consumption, better adapted information richness, preferred user experiences, adaptability options or an enrichment to make products more attentive for its users. We have to note that we have considered low-end cyber physical systems as the target domain of CPA, and will discuss theoretical and practical advancements in this context.

1.4. Exploration sources

The exploration discussed in this paper aims to uncover needs to know for design engineers to successfully augment physical products with cyber functionalities and the other way around or enrich

Figure 2 Example of a students' product idea for 'innovate-with-ubiquitous-technologies' exercise [15]

cyber-physical products to both ends. To explore the potentials and practices of cyber-physical augmentation, multiple types of sources have been used: the first source are design projects conducted by our design students, especially those that were focussed on the application of ubiquitous technologies; secondly cases of product developments in which existing products and/or services have been enriched in the direction of cyber-physical systems; and the third source that has been used are descriptions and analyses in literature on specific types of current and future cyber-physical systems and their implications for design engineering. From these three sources, the needs to know for design activities in the field of cyber-physical augmentation have been qualitatively identified, and this exploration will be addressed in the following three sections. Thereafter the results of these analyses will be discussed and concluded upon.

2. STUDENTS' DESIGN WORK

Cyber-physical augmentation has been applied in an advanced design course known as "Innovate with ubiquitous technologies" in which more than 100 design students participated. The objective was to conceptualize and virtually prototype low-end cyber-physical systems. This advanced design course challenged our design students to incrementally innovate everyday products into cyber-physical product ideas by applying ubiquitous technologies [10]. For this they had to explore new knowledge fields and creatively adjust the known design methods for industrial design engineering [11], [12]. The participating students delivered 41 low-end cyber-physical product ideas, which can all be considered cyber-physical augmentations. These design exercise results have been analysed to identify needs to know for design engineers when applying cyber-physical augmentation [11], [12].

2.1. Assignments and topics

The students' design assignment was to enhance physical everyday products with cyber functionality, and enrich the product with communication and knowledge conversion functionalities. The products to be enhanced were for example a lamp, a bicycle, an electric drill, and a water heater. In this exercise the students had to explore a number of ubiquitous technologies and share their results. Afterward, they had to extend an existing product by applying a combination of ubiquitous technologies with the goal to improve a selected aspect such as new functionality, function and price trade off, performance, energy consumption, information richness, and user experience. They had to brainstorm to explore the design space and develop and evaluate multiple product ideas.

A new evaluation criterion was introduced in the exercise: being the level of ubiquity consisting of the following features: omnipresence in terms of functional affordances in space; permanent readiness for operation in time (alertness); small sizes, functional shapes, low energy consumption; problem solving by a cooperating cluster of entities; entities may be embedded in host artefacts/ environments; smart reasoning and adaptive information processing based on sensing, mining and communication; artefacts/ services interact with and impact the user in cognitive domain; and history, situation, user and context awareness is remarkable. After their evaluation, the students selected one of their innovative product ideas and presented the selected one with an abstract prototype [13], [14] including augmented reality. Finally the students made a cost and trade-off estimation considering both the existing and the proposed improved design.

2.2. Resulting innovations by students

Results vary from an app for the I-phone to a well-considered system for drilling holes in a wall or a system to control the tire pressure of bikes with intelligent bike spokes and a bike pump. For illustration purpose, one example will be presented here. In this example the students had to augment a bicycle with ubiquitous technologies and they came up with a Touristic Bike System “BC Cleta” that guides the user by means of a GPS system through a city. The target group are tourists that like to discover cities by bike in a surprising way, as shown in Figure 2. The applied technologies are wireless networking and haptic sensation.

BC Cleta is a transport system for tourists to make the touristic experience more personal and active. Tourists who are unfamiliar in a city will be guided through the town over their own preferred route by a GPS system in a rental bike. This GPS system will use haptic feedback and lighting for a more intuitive interaction and to avoid difficult instructions and stress to maintain the holiday-kind of atmosphere.

The core of the product idea is to connect the bike wirelessly to an access point (Figure 3) where the user defines a route. The GPS system incorporated in the bike will instruct the user to turn left or right, by vibrating the left or right handle respectively. The vibration will start soft and intermittent when approaching the turning street and will become more intense and constant when the turning street is reached. To facilitate the information uploading, the user will wear a dedicated bracelet and use a tagged bike-key. Through the IDs, and by swapping the bike-key identifier at the tower, the access point will identify the bike to which the information has to be transferred, and the route will be uploaded automatically. The bike has been equipped with a receiver to receive the information from the towers at any time. There is a light indicator at the handlebar to notify the proximity of a tower or a BC-Cleta-office to the user, facilitating the return of the bike, or to change the route. After pushing a button at the handlebar the bike will bring the tourist to the nearest tower.

Figure 3 Illustration of the Touristic Bike System [15]

2.3. Analysis of the students’ cases

Knowledge and techniques that have been applied in these cases and are related to the cyber-physical characteristic of the product ideas are:

- Factual knowledge of ubiquitous technologies.
- Abstract prototypes as design technique to document and communicate the knowledge structure and working principles in a product idea
- New techniques to enhance the creativity in applying ubiquitous computing (UC) knowledge. E.g. Instead of conventional “how-to’s” in brainstorming sessions [16] one could ask: “To which product my product want to communicate and why”. And “What information would they like to exchange” [12].

The knowledge and techniques that were apparently lacking in these cases:

- Knowledge about the energy consumption and provision for these kind of products and systems.
- Methods to well consider the user role in a cyber-physical system: spectrum ranging from active to passive [11].
- Methods and techniques for forecasting the product adaptations in the use phase.
- Procedures to construct and develop the knowledge contents of the product.

3. CASES DESCRIBED IN LITERATURE

3.1. Cyber-physical product spectrum

Many cases have been described in literature, varying in the extent to which cyber and physical parts cooperate. Examples can be found in many references such as [5], [17], [18], [19], [20], [21], [22], and [23]. Harrop et al. don’t actually provide a case, but the topic discussed is nevertheless interesting exemplifying where software can be extended with hardware[24]. The authors address future technologies and functions of mobile phones and the allied hardware. For them “hardware is the new software”. Topics include new technologies like tightly-rollable displays, and functional issues such as how to radically improve the human interface. For illustration purposes, only two cases will be described concisely.

3.2. CPA-cases in literature

Case 1

Many cases have been described by consortia funded by the European Commission, for example in [25].

[26] includes a short introduction to Rosetta, which is an integrated system aiming at prevention and management of the problems that can occur to elderly people suffering from chronic progressive diseases, such as Alzheimer. The Rosetta system monitors activities of the resident with various sensors. It generates an alarm signal for the caregiver in case of a deviant (in)activity or wandering with the resident or in case of long-term variations in the patterns of daily living. It supports the resident directly in his daily activities.

The target group of the system includes both the patients and their (in)formal caregivers. Rosetta has been based upon the Unattended Autonomous Surveillance (UAS) system. In that sense Rosetta can be seen as the cyber-physical augmentation of the UAS and the UAS as the cyber-physical augmentation of a simple personal alarm system. The development of the UAS has been described in [27]. Most noticeable elements in their report related to the application of cyber-physical elements are:

General. Issues of safety, privacy and trust are important in these kind of systems.

Users. The user experience of multiple stakeholders need to be considered: patient, his relatives, caregivers, maintenance people, and medical staff. The involvement of the users in the system: does he need to wear anything or can it be kept on a no-disturbing distance? For the reason that these innovations have some elements of technology push, the needs and perceptions of people involved need to be identified

Devices and software. The required number and variety of the sensors and detectors that have to communicate, including for example motion detectors, smoke detectors, cameras, and magnetic door contacts. Intelligent software to interpret and analyse the sensor signals continuously, to control the functioning of the devices, and draw conclusions. Analysis of the consequences of incorrect conclusions: something is detected but did not take place; or it took place but was not detected.

Profits. It is difficult to show the profits of a system, to identify and account the assets and liabilities. Besides there are other values than financial profits.

Installation. The correct installation impacts the well-functioning too. For example sensors must be mounted at the right place in the right direction. Sensors and detectors may detect elements that disturb the normal functioning, such as a cat. A prototype has been built and installed and has been incrementally improved based on real life experiments and tests. The system is flexibly extendable by adding more devices. And it is movable: the system installation takes one day and removal a few hours.

Case 2

The design and application of interactive tangible products as extension of existing social media has been explored. For example, in [28] an awareness system for home use has been described that collects snippets of sound and is connected to Facebook. This case serves as an example of a cyber-physical augmentation applied on a cyber-based product. The authors address both the iterations that led to the prototype and the obtained design insights.

They explored the possibilities and user experiences of connecting a physical awareness system to an online social network service. The resulted design of the awareness system was inspired by considering Facebook a venue for mediated sharing (liking, commenting and posting) and exploring (finding, viewing and browsing). The first version of the prototype, called Facebook Listener, enabled recording and sharing a short (5s) sound sample with Facebook friends, or automatically record and share samples at a fixed interval. Sound was considered to be more pervasive than a visual interface, which would require visual attention. To address privacy issues, users could choose to scramble the sample by adjusting the noise added to the sample. Exploring was supported by enabling playback of samples shared by other members of the social network. The device was designed to easily blend in the natural user environment, both in terms of interaction and appearance in colour and material. Besides voice message, sound samples could contain contextual cues such as environmental sound or tone of voice. This is an extension to the type of media that are usually shared on Facebook. The physical design had two elements; a base and a glass as a metaphor of using a glass to listen through a wall.

More cases

Besides the two cases described here, more cases in literature have been explored to extend the findings for cyber-physical augmentation. For example [29] report about the results of Octopus, an industry-as-laboratory project in the context of the development of high-end adaptive professional printing systems, thereby developing a model-based approach. One of their main lines of attention contribute to our analysis for cyber-physical augmentation: System-level reasoning and design: the development and application of multidisciplinary design methods and tools, to allow design trade-offs across disciplines, such as hardware, software, and mechatronics, in order to make better use of all available design options while managing the increased complexity.

3.3. Analysis of the cases in literature

This paragraph lists the main results of the analysis of cases described in literature. Although obviously the analysis has not been exhaustive, relevant items, needs to know, and needs for methods approaches and techniques in the field of cyber-physical augmentation have been qualitatively explored.

- To determine the configuration of roles and responsibilities in ad hoc, hybrid social support structures, as in the case of ordinary citizens and professionals working together.
- To define what an involved human needs to know for proper functioning of the system.
- To consider user experiences of all users involved.
- To identify and realize access control to the system, user authentication, and to transmit reliable, and timely information. Security, data confidentiality, integrity and data freshness, network availability
- To foster trust and privacy, in an ad hoc network with nodes entering and exiting.
- Address issues of data validity, accuracy and reliability. To realize interoperability and to provide dynamically updatable and sharable information and back-up procedures.
- The development of interactions needs to be carefully designed, accounting for privacy, feedback, and preferred modalities of interaction.
- System level reasoning and design.

4. SPECIFIC CPSs AND RELATED NEEDS TO KNOW

Descriptions and definitions of cyber-physical and related systems like embedded systems, and advanced mechatronic systems present some specific characteristics of these systems and therewith identify potential focus areas for industrial design engineers working on CPA. Embedded systems are not visible but have a big role because they bring intelligence to objects, devices and other artefacts [30]. Advanced mechatronics systems integrate mechanical, electronics, computing, control and situated reasoning components, and these are typically implemented as closed, predefined, controlled, and deterministic systems [6]. For that reason a number of descriptions and definitions have been analysed.

Embedded humans in the system. A vehicle can be considered a cyber-physical augmentation since it has developed from a physical system to a sophisticated CPS. Work et al [31] discuss the limitations of automotive CPSs with embedded humans who are the primary consumers for traditional transportation infrastructure information, such as travel times and route navigation. Embedded humans perform three tasks: (i) they can sense; (ii) decide, and (iii) assess. Work et al state that a poorly designed CPS will require the human to actively participate in information acquisition instead of having the system automatically integrate sensed information. Humans are exposed to a wide variety of human-centric systems. As new human centric features appear in other CPSs ranging from mass transit to mobile devices such as cell phones, the utility of the automotive CPS will depend on its ability to adapt and integrate similar features.

Synergy. The level of synergy is a quality measure of the cooperative actions of the components of CPSs. The most important drivers for synergy according to [32] are: emergence of truly synergic technologies, proliferation of sophisticated abstraction models, model-driven system specification, and platform-based function realization. The major obstacles for synergy are: different mental models and vocabularies, lack of multilevel informatics, the limitations in handling non-hierarchical complexities, managing emergent intelligence and autonomous operation, and the premature state of informing science.

Components. The inherent complexity of the creation of large scale, widely distributed, heterogeneous networked embedded systems that interoperate and adapt to their environments must be simplified if the full potential for networked embedded systems is to be realized [33]. Components provide many benefits: They are well-defined entities that can be replaced without affecting the rest of the systems, they can be developed and tested separately and integrated later, and they are reusable.

Integration, predictability of system behaviour [34] System integration is currently the largest obstacle to effective CPS design, which is primarily due to a lack of a solid scientific theoretical foundation for the subject, caused by its complexity. As CPS-based solutions become ubiquitous, the need for theories, methods, and tools to ensure predictability of system behaviour has significantly increased and expanded to most engineering systems.

Spatio-temporal correctness. Tan et al. stated that CPSs are envisioned to integrate computation, communication and control with the physical world

[35]. That is why CPSs require close interactions between cyber and physical worlds both in time and space.

Interaction. [36] It is not sufficient to separately understand the physical components and the computational components of a CPS, instead their interaction must be understood. Therefore, a key element in CPS is an ICT component as a communication medium, which connects the computing and physical elements by information exchange.

Communications. [37] A major difference between a CPS and a regular control system or an embedded system is the use of communications, which adds reconfigurability and scalability as well as complexity and potential instability. Furthermore, CPS has significantly more intelligence in sensors and actuators.

5. FINDINGS OF THE EXPLORATION

5.1. Knowledge and design aspects

Both the students' and the literature cases demonstrate that specific design aspects need to be addressed by design engineers applying cyber-physical augmentation. Many keywords, characteristics and issues have been raised in the previous sections. These have been combined into design aspect clusters that are specifically relevant when applying cyber-physical augmentation:

User, stakeholders roles

- System interacts with and impact the user in the cognitive domain;
- The involvement of the users in the system: does he need to wear something or can it be kept on a no-disturbing distance?
- The configuration of roles and responsibilities in ad hoc, hybrid social networks;
- To define what an involved human needs to know for proper functioning of the system.
- Consider user experiences of all users involved.
- The human role in the system: actively participate in information acquisition or having the system automatically integrate sensed information.
- Obstacles for synergy are: different mental models and vocabularies, lack of multilevel informatics, the limitations in handling non-hierarchical complexities, managing emergent intelligence and autonomous operation, and the premature state of informing science.

Communication, reasoning and adaptation

- A cooperating cluster of entities that may be embedded in host artefacts or environments;
- Smart reasoning and adaptive information processing based on sensing, mining and communication;
- A variety of sensors and detectors have to communicate. Intelligent software to interpret and analyse the sensor signals continuously, to control the functioning of the devices, and draw conclusions.
- History, situation, user and context awareness.

Space and time

- Close interactions between cyber and physical worlds both in time and space. An ICT component as a communication medium, which connects the computing and physical elements by information exchange.
- Presence in terms of functional availability in space, ultimately omnipresence;
- Alertness of the system: either or not permanently ready for operation in time;
- Predictability of system behaviour over time.

Reliability, privacy, trust

- Reliability of the system: consequences of incorrect decisions; correct installation;
- Access control to the system, user authentication. Security, data confidentiality, integrity and data freshness, network availability
- Trust, privacy, safety and cyber-security of the information involved in an ad hoc network with nodes entering and exiting.
- Data path design.
- Data validity, accuracy and reliability. To realize interoperability and to provide dynamically updatable and sharable information and back-up procedures.
- Interactions needs to be carefully designed, accounting for privacy, feedback, and preferred modalities of interaction.
- Components provide many benefits, they are well-defined entities that can be replaced without affecting the rest of the systems, they can be developed and tested separately and integrated later, and they are reusable.

Trade off, integrative approach

- Cost trade off (e.g. the costs for a sensor in a product can prevent major costs somewhere else). It is difficult to show the profits of a system, to identify and account the assets and liabilities.

Besides there are other values than financial profits;

- Energy consumption at many entities. The use of energy has to be balanced with other design criteria such as robustness, security and costs and the physical aspects of weight and volume;
- Based on our analyses, we have observed that on the application of cyber-physical augmentation, the design aspects need to be considered on two or more levels: on system level on middle levels and at nodes-level.

The new design aspects for cyber-physical augmentation that have been uncovered can be added to a frequently used tool by design engineers when making up the list of requirements, or the design specifications in order to strive for completeness in the list of requirements, being a checklist of design aspects, e.g. [38]. An extended design aspects checklist can be a helpful instrument for designers applying cyber-physical augmentation.

Obviously the identified design aspects point to knowledge fields that are relevant for industrial design engineers working on cyber-physical augmentation, such as: Factual knowledge about available ubiquitous technologies and their affordances, about systems design and about complexity control and about the new design aspects [10]. And knowledge about the energy consumption and provision for these kind of products and systems.

5.2. Design principles

From the above findings, design principles have been derived for cyber-physical augmentation:

1) Due to the individual adaptations of cyber-physical system and its frequent interactions with the context and users, the human user can be seen as a part of the system to be developed.
    a. Determine the expected behaviour and mental models of the users.
    b. Determine the role of the user in the system: either active or passive or any position within these two user roles.
2) Design the data, information and knowledge in the cyber-physical system and all of its properties, characteristics and behaviours, such as; trustworthiness, data security, privacy, accessibility, authorization control, selection of existing data- or knowledge bases, or generate knowledge on the fly or generate new information bases: sensing, mining or communication.
3) Include in the process tree, which reflects the future product life, the intended behaviour of the product in various contexts and for different users.
4) Keep an eye on the downside of adaptive capabilities, mining and sensing. Consider ethical aspects and protect people against unaware data capturing and too active systems. Make the product attentive, not too pro-active or even intrusive.
5) The increased complexity of the products calls for measures to increase the reliability and the maintainability, for instance with modularity or redundancy.
6) Reason and design at system level and apply multi-, inter-, intra-, and/or transdisciplinary [39[, [40] design methods and tools, to allow design trade-offs across disciplines, such as hardware, software, and mechatronics.

5.3. Methods and techniques

Most of the derived design principles call for new or adapted methods and techniques to support the design engineers. Some of the required methods and techniques for the novel types of innovations have already been developed, such as the abstract prototype technique [13], [14], and a framing of existing creativity techniques [11]. Others require further investigations to develop appropriate design methods and techniques to support design engineers in the new aspects and opportunities provided by the application of cyber-physical augmentation, see Figure 4.

- Data, information and knowledge functions constructions and development method. Supporting decisions on sensing, mining or communication and the diverse knowledge properties.
- Methods and techniques for forecasting the product adaptations in the use phase.
- Complexity and reliability evaluation method.
- And of course an integrated user-centred system level development method incorporating the newly identified aspects, principles and techniques.

6. DISCUSSION

The physical part of cyber-physical products is a relatively familiar field for design engineers. Enhancing cyber products to cyber-physical products resembles more the conventional design engineering than the augmentation the other way round. The involved data, information, knowledge and the

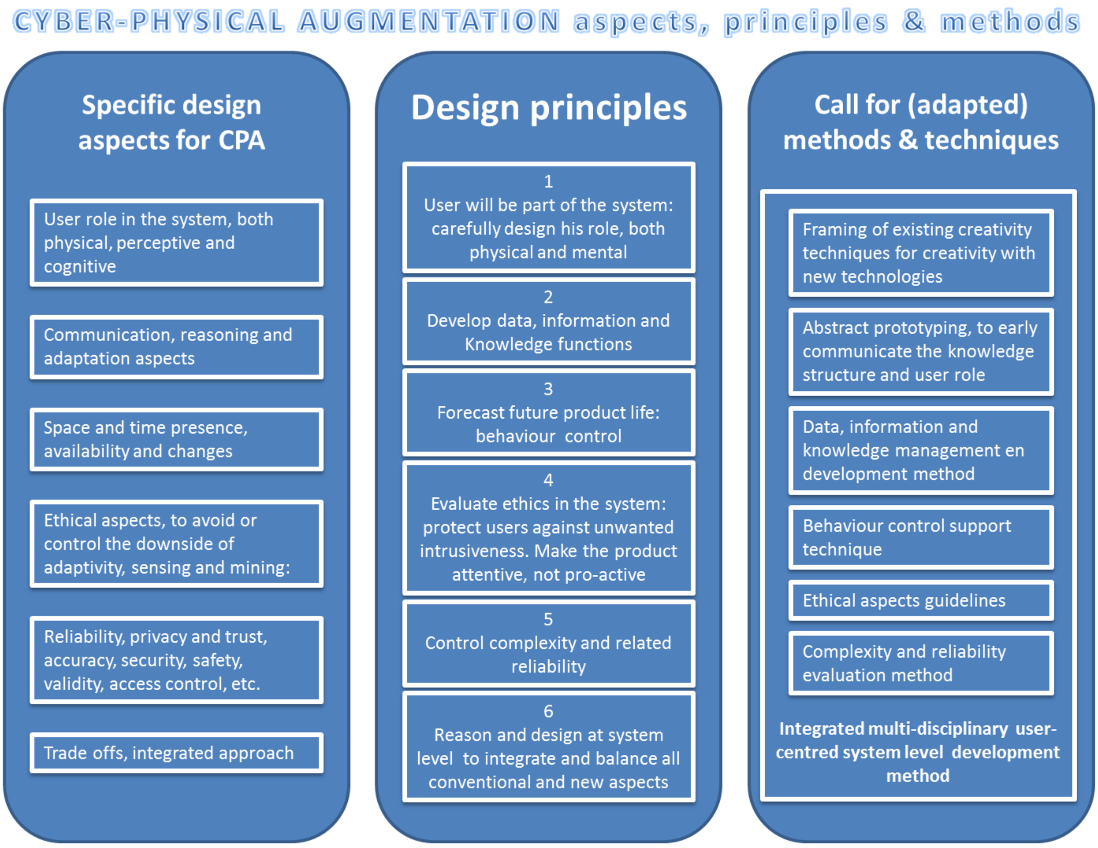

Figure 4 Cyber-physical augmentation aspects, principles and call for methods

conversions herein, and the communications are relatively new. Hence systematic analysis and development of the role of data, information and knowledge in the new products and systems is needed for a satisfactory design result

More knowledge and useful or even indispensable techniques will be discovered in future explorations and analyses, not only because the current exploration has not been exhaustive, but also because new developments in the field will also raise new issues. A first initiation towards a more comprehensive approach of cyber-physical augmentation is given in Figure 4, combining design aspects, design principles and new methods and techniques.

The methods and techniques that will be valuable for cyber-physical augmentation applications, need additional studies. Some of the new methods could be based on existing methods in adjacent disciplines or on other new methods that are currently under development (e.g. [41]). For example system engineering principles could possibly be adjusted towards user-centred system design.

For the method to be developed for designing the data, information, knowledge and communication in a user-centred cyber-physical system, we will develop a method that will support the designer in the inventory of the data, information and knowledge needs in the system, both in places and in time. And also to assign characteristics to these data, information and knowledge, such as availability, authorization, reliability, actuality, and privacy-sensitivity and also whether to sense, mine or communicate these items. All these aspects need to be considered relatedly. The new method under development will be first tested in students' design projects.

7. CONCLUSIONS

An analysis of students' design work and reported cases on cyber-physical augmentation have led to the conclusion that the skills required for designing conventional physical products and mechatronic systems need to be extended with specific skills for designing cyber-physical systems. Designers need to adopt new knowledge and procedures regarding ubiquitous technologies, complexity control, knowledge management, prototyping techniques, user participation in cyber-physical systems and controlling the changing state of designed product in the use phase.

The opportunity to create adaptive cyber-physical systems results in system behaviour that is not fully predictable especially when self-learning capabilities will be included. The added design challenge of systems of interactive products includes designing behaviour of the system taking in account the behaviour of its human users. This behaviour will not be static or predictable, but dynamic, adaptive and self-learning. To design such behaviour calls for new approaches and theory.

To make a start in this field we have analysed case studies in which the design space for systems with cyber-physical functionality has been explored and described. We have found reflective comments in the cases and brought these to a more general level. We concluded with suggestions for the development of new guidelines, methods and techniques.

The identified design aspects and design principles (Section 5) can be used in future cyber-physical augmentation to more systematically integrate the aspects that emerge when applying ubiquitous technologies for creating adaptive user-centred cyber-physical systems. The identified methods and techniques to support these augmentation actions have not all been developed yet. The method to construct and develop the data, information and knowledge functionalities in CPSs is one of our current and future research topic.

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