FAKULTÄT FÜR INFORMATIK

DER TECHNISCHEN UNIVERSITÄT MÜNCHEN

A Metamodel for Cyber-Physical Systems

Constantin Stefan Scheuermann

FAKULTÄT FÜR INFORMATIK
DER TECHNISCHEN UNIVERSITÄT MÜNCHEN

Forschungs- und Lehreinheit 1
Angewandte Softwaretechnik

A Metamodel for Cyber-Physical Systems

Constantin Stefan Scheuermann

Vollständiger Abdruck der von der Fakultät für Informatik der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat.)

genehmigten Dissertation.

Vorsitzender:	Prof. Dr. Matthias Althoff
Prüfer der Dissertation:	1. Prof. Bernd Brügge, Ph.D.
	2. Prof. Daniel Siewiorek, Ph.D.

Die Dissertation wurde am 04.07.2017 bei der Technischen Universität München eingereicht und durch die Fakultät für Informatik am 25.09.2017 angenommen.

Abstract

Cyber-physical systems (CPS) are complex systems which monitor and control the physical environment and support humans during tasks. CPS are interconnected, heterogeneous systems that combine software and hardware components. Such systems raise challenges, as developers, engineers, and researchers collaborate to design and implement them. Experts from different domains need to understand the system to cooperate, independent from their domain. We propose a cyber-physical system metamodel and a formative research procedure that cyber-physical systems developers, engineers, and researchers can apply, reuse and extend for new cyber-physical system applications. The formative research process allows an iterative extension of the proposed metamodel on M2 of the Meta Object Facility (MOF). Domain experts and developers reuse this metamodel to instantiate a cyber-physical system providing system models on M1, understandable among different domains. The metamodel comprises smart objects as well as persons that are typically part of any cyber-physical system design. It uses a composite pattern to allow aggregates of cyber-physical systems with smart objects as leaf nodes. Defined stereotypes can extend such smart objects. We extended and reused this metamodel during the design and implementation of six prototypical cyber-physical systems applications. Within these applications electrical engineers, smart textile experts and software engineers contributed to build the prototypes in the domains of factory as well as extreme environments. We evaluated the prototypes qualitatively as well as quantitatively with a total of 87 participants. In factory environments, our metamodel-based approach significantly improved the support to humans in real-world workflows. Within extreme environments our approach contributed to improve operational safety for deployed personnel. As a result, a smart textile concept that allows remote health monitoring in combination with a user- and textile interface was developed.

Zusammenfassung

Cyber-physikalische Systeme (CPS) sind komplexe Systeme, welche die physikalische Umgebung überwachen, kontrollieren und Menschen während ihrer Aufgaben unterstützen. CPS sind miteinander verbundene, heterogene Systeme mit Software- und Hardwarekomponenten. Solche Systeme bergen Herausforderungen, da Entwickler, Ingenieure und Forscher zusammenarbeiten, um sie zu entwerfen und umzusetzen. Experten aus verschiedenen Bereichen müssen das System verstehen, um domänenübergreifend zusammenarbeiten zu können. Wir schlagen ein Metamodell für cyber-physikalische Systeme und ein formatives Forschungsverfahren vor, welches von cyber-physikalischen Systementwicklern, Ingenieuren und Forschern angewendet, verwendet und erweitert werden kann. Das formative Forschungsverfahren ermöglicht eine iterative Erweiterung des vorgeschlagenen Metamodells auf M2 der Meta Object Facility (MOF). Domänenexperten und Entwickler können dieses Metamodell wiederverwenden, um ein cyber-physikalisches System zu instanziieren und um Systemmodelle auf M1 domänenübergreifend verständlich zu machen. Das Metamodell umfasst intelligente Objekte sowie Personen, die typischerweise Teil eines cyber-physikalischen Systemdesigns sind. Das Metamodell verwendet ein Composite Pattern, um Aggregate von cyber-physikalischen Systemen mit intelligenten Objekten als Blattknoten zu ermöglichen. Definierte Stereotypen können solche intelligenten Objekte erweitern. Bei der Konzeption und Implementierung von sechs prototypischen cyber-physikalischen Systemen haben wir dieses Metamodell erweitert und wiederverwendet. Elektrotechniker, Smart-Textile Experten und Softwareingenieure trugen dazu bei, die Prototypen in Fabrikumgebungen sowie extremen Umgebungen zu entwickeln. Wir haben die Prototypen qualitativ und quantitativ mit insgesamt 87 Teilnehmern evaluiert. In Fabrikumgebungen hat unser Metamodell-basierter Ansatz die Unterstützung für den Menschen in realen Arbeitsabläufen deutlich verbessert. In extremen Umgebungen hat unser Ansatz zur Verbesserung der Betriebssicherheit für stationierte Mitarbeiter beigetragen. Als Ergebnis wurde ein intelligentes Textilkonzept entwickelt, das eine Ferngesundheitsüberwachung in Kombination mit einer Benutzer- und Textilschnittstelle ermöglicht.

Acknowledgments

This dissertation would not have been possible without the support of many people. A dissertation is not a piece of work that is possible without exchanging ideas and receiving input from others. I appreciate and I am thankful for the help of everybody during this dissertation.
First, I would like to thank Prof. Bernd Brügge and Dr. Stephan Verclas. Prof. Bernd Brügge provided me the opportunity to join his chair. He supported me during my entire dissertation. To me you are a role model of how to motivate and deal with people. You showed me what innovation means and how to deal with uncertainty. This lessons I will never forget. I enjoyed the time during my dissertation and I am grateful that you have done more than just supervising me. Dr. Stephan Verclas provided the scholarship that allowed me to start my dissertation. Moreover, you helped me to establish research projects and always encouraged me to turn my ideas into projects. Both of you offered me a high degree of freedom and trust, that created space for creativity — I would like to express the deepest appreciation to both of you.
Second, I would like to thank Prof. Daniel Siewiorek for your constructive input, feedback and taking over the responsibility of the second reviewer.

Third, I would like to thank all my colleagues, who created a welcoming and positive atmosphere during my time at the chair. In particular, I would like to thank Lukas Alperowitz, Andreas Seitz, Jan Ole Johanssen, Dora Dzvonyar, Jan Knobloch and Stephan Krusche for your support. I will always remember our conversations during lunch, our activities outside university and the constructive feedback you have provided.

I thank all the co-authors of the publications that contributed to the research. Especially, I would like to thank Dr. Raman Tandon and Dr. Andreas Werner for your insights into the textile domain and the cross-domain knowledge transfer. I would like to thank Tarek Ouertani for the successful research cooperation and all my Master and Bachelor students for their contribution.

Finally, I want to express my love to my family. I would like to express my deepest appreciation to my girlfriend Camila for your support and the possibility to talk about everything that occupied me during the dissertation. I owe my parents, Stefan and Cordula, and my brother, Sebastian, a lifelong gratitude for your steady support.

Publication Preface

The contribution of this dissertation is based on the following five first-author publications:

Publication [A]

Constantin Scheuermann, Stephan Verclas and Bernd Bruegge
Agile Factory - An Example of an Industry 4.0 Manufacturing Process
International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)
DOI: 10.1109/CPSNA.2015.17

Publication [B]

Constantin Scheuermann, Bernd Bruegge, Jens Folmer and Stephan Verclas
Incident Localization and Assistance System: A Case Study of a Cyber-Physical Human System
International Conference on Communications (ICCC): International Workshop on Internet of Things
DOI: -

Publication [C]

Constantin Scheuermann, Maximilian Strobel, Bernd Bruegge and Stephan Verclas
Increasing the Support to Humans in Factory Environments using a Smart Glove: An Evaluation
International Conference on Ubiquitous Intelligence & Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People, and Smart World Congress
DOI: 10.1109/UIC-ATC-ScalCom-CBDCom-IoP-SmartWorld.2016.40

Publication [D]

Constantin Scheuermann, Florian Heinz, Bernd Bruegge and Stephan Verclas
Real-Time Support During a Logistic Process Using Smart Gloves

Smart SysTech, European Conference on Smart Objects, Systems and Technologies
ISBN: 978-3-8007-4428-2

Publication [E]

Constantin Scheuermann, Felix Meissgeier, Bernd Bruegge and Stephan Verclas
Mobile Augmented Reality based Annotation System: A Cyber-Physical Human System
Augmented Reality, Virtual Reality, and Computer Graphics
DOI: 10.1007/978-3-319-40621-3 20

Contents

List of Figures

List of Tables

Chapter 1

Introduction

> The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.
>
> Mark Weiser

Cyber-physical systems (CPS) are complex systems which monitor and control the physical environment and support humans during tasks. They are interconnected, heterogeneous systems that combine software and hardware components. CPS make use of latest technology and developers must deal with constant technological change. Technical improvements over the last years enable us to seamlessly integrate smaller and smaller computer systems into objects such as textiles or wearable devices. Quantities such as hardware size, computational power, energy consumption as well as the communication bandwidth improved over the last decades. For example, the supercomputer Cray-1, released in 1976 [Nor+10], weighted around 5.5 tons and was installed in a dedicated room. The Intel Edison™ of 2014, a single board computer, weights about 1.100.000 times less than the Cray-1 and has the dimension of a coin. As opposed to the first mass produced computer of Apple Computer's, the Apple II, released in 1977, quantities such as weight, size, performance and price further improved. The Intel Edison™ weights about 1.004 times less than the Apple II and size decreased by a factor of 27. Concerning data transmission rates, the computers of the 1980s used modems that followed the Bell 202 protocol supporting 300 Bit/s to transfer data wire-based. The Raspberry PI 3[1] offers a wireless radio that is half the size of a 1 cent

[1]Raspberry PI 3: `https://www.raspberrypi.org/`

coin and a Bluetooth Low Energy (BLE) support that consumes less energy. Moreover, sensors that transmit the body core temperature are available such as the CorTemp Sensor[2] that can be swallowed to transmit the core body temperature wireless at 262kHz or 300kHz. It consists of a sensor, an antenna, printed circuits and a battery. All components fit in a silicon coated pill. Interactivewear[3] offers a sensor concept where sensors are connected with conductive yarns and are directly integrated into textiles. Sensors can be combined and distributed within textiles. Those sensors are able to resist strain during washing procedures and become a part of the textile design.

These technology enhancements allow developers to create interconnected and integrated systems that monitor and control the physical environment [RLSS10] such as cyber-physical systems. CPS have recently appeared in different domains such as Transportation, Health/Medical, Manufacturing and Military. Our hypothesis is that these – at first glance – unrelated systems, share common abstractions that can be reused for the development of new CPS.
Two major enabling technologies of cyber-physical systems are 'Embedded Systems' and 'Sensor Networks'. The term 'Embedded System' describes a system that is invisibly integrated into the physical environment. It consists of a processing core, is connected to sensors and actuators, controls the environment, offers processed information and is dedicated to a certain application [Mar10]. Compared to personal computers end-users do not administrate embedded systems [Hea02]. Moreover, embedded systems do not use typical input and output devices such as keyboards, computer mice and/or large computer monitors as Human-Machine Interfaces (HMIs) [Mar10]. Noergaard defines an embedded system to have a dedicated function, limited hardware and software capabilities and a higher reliability than normal computer systems [Noe12].
We define a system model of embedded systems to identify major system components (Figure 1.1). An Embedded System consists of Interaction Devices that comprise Sensors and Actuators. Examples for Sensors are devices that can measure a temperature or humidity levels. Typical Actuators are servos that operate valves. A major enabler for embedded systems was the replacement of discrete logic-based circuits with microprocessors that started in the 1970s (Appendix Figure C.1a) [Hea02]. Such microprocessors offered the possibility to change software instead of creating an entire new circuit that will meet new requirements.
Embedded systems incorporate technology such as microcontrollers that possess a CPU with a fixed amount of RAM or ROM. These microcontrollers, combined with sensors and actuators, are key components of an embedded system. With the introduction of

[2]CorTemp Sensor: `http://www.hqinc.net/cortemp-sensor-2/`
[3]Interactivewear `www.interactive-wear.de`.

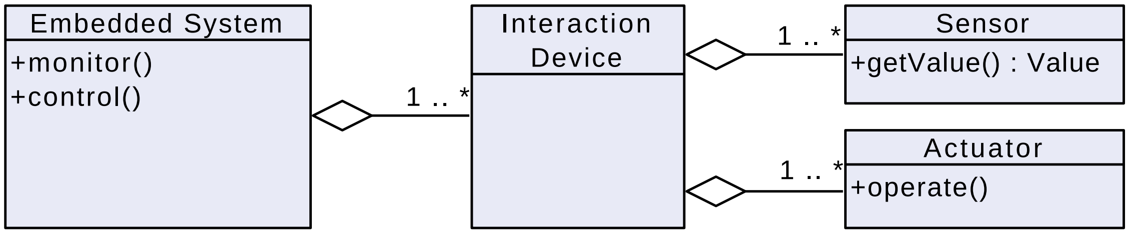


Figure 1.1: **Embedded Systems Model:** an Embedded System comprises one or more Interaction Devices. Such an Interaction Device consists of one or more Sensors and Actuators.

standards such as IEEE 802.3 and CAN BUS 2.0 in the 1980s and 1990s respectively, embedded systems made a breakthrough as 'boxed' systems. Embedded systems are found in everyday objects as washing machines, network switches or cars.
Sensor Networks (SN), consist of thousands of nodes ('motes') that are connected to each other. Such motes form small networks to monitor building structures [Xu+04] or form regional area networks to monitor geological activities [WA+06]. A mote is typically divided into different subsystems: the sensor and actuator-, the processor-, the communication-, the memory- and the power-subsystem. Motes interact with the physical environment. The sensor and actuator subsystem monitors as well as controls the physical environment. It can measure quantities such as a room's temperature or its humidity and control such values using deployed actuators. The processor, communication and memory subsystem run efficient operating systems such as TinyOS and use communication protocols focusing on challenges such as ad-hoc connectivity like IEEE 802.15.4. Concerning the power subsystems, they are equipped with small, powerful, durable and robust batteries, that allow motes to operate for years.
A sensor network is a closed network using domain specific protocols supporting different topologies, such as star, tree or mesh. Based on this interconnection the sensor network makes use of sensor fusion to gather information about the environment. A (wireless) sensor network is equipped with a Base Station (BS) connected to the Internet where all the information of the motes converges [ZG04] [DP10].
As motes are typically distributed, small and operating independently, each mote faces several limitations such as battery lifetime [KKP99], limited network communication bandwidth and limited memory size. Moreover, motes typically need to overcome extreme environmental conditions such as varying weather and physical attacks. In many cases the physical accessibility of single motes is difficult or up to impossible. They might be deployed in dangerous areas such as of active volcanoes or might be attached to animals that are moving and therefore are, difficult to reach. Consequently, a sensor network is aware of component failure and possesses decentralized decision

making [DP10].
Sensor networks cover domains such as industrial control and monitoring, home automation and consumer electronics applications, security and military sensing, asset tracking, supply chain management, intelligent agriculture, environmental sensing and health monitoring [Cal03]. At the Golden Gate Bridge in San Francisco, a monitoring system is installed that controls the bridge's vibrations to guarantee operational safety [Kim+07]. Looking at the military domain a sniper detection system was developed, in which each soldier represents an actual sonic sensor [Sim+04]. An overview of wireless sensor networks history and example applications can be found in [AV10].
Figure 1.2 shows a model of sensor networks. It emphasizes the commonalities of embedded systems and sensor networks. The Mote package within the model contains the embedded system model. Each Sensor Network consists of one or more Motes. A

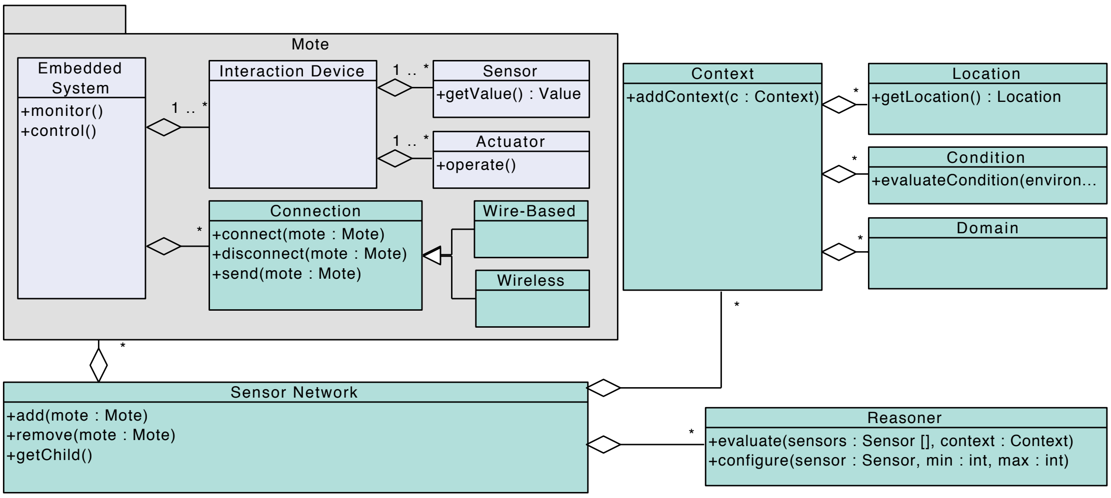


Figure 1.2: **Sensor Network Model:** each Mote consists of one or more Embedded Systems and can connect to other Motes. Each Sensor Network operates in a Context and utilizes a Reasoner. The Connection can be realized wire-based or wireless.

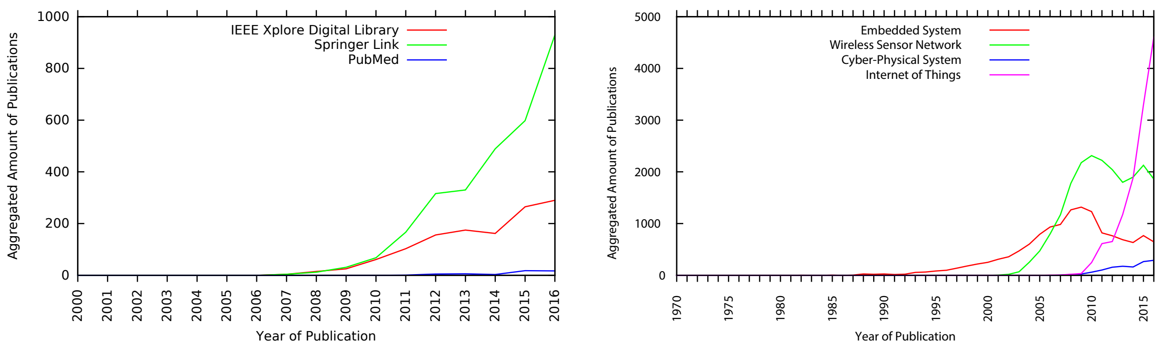
Sensor Network consists of Context defined by a Location, the Condition and an application Domain. A location is defined by latitude and longitude, can also be defined by indoor positioning systems or by semantic locations such as a position at the human body. A Condition can be the link quality, battery levels or reliability estimations. A Domain helps to identify what the Sensor Network is responsible for. The Sensor Network does not necessarily make use of a Wireless Connection. The Connection can also be Wire-based on the physical layer like in body sensor networks that measure health quantities such as heart-rate. A Reasoner evaluates the environmental as well as the system condition based on the measured quantities gathered from the Sensors.

Sensor networks start to bridge the digital and physical environment and can monitor and control it – a requirement to build cyber-physical systems.
Other areas are 'Ubiquitous Computing' [Wei93], also called 'Pervasive Computing' [Sat01] and 'Ambient Intelligence' (AmI) [Aar04]. They represent research areas where embedded systems and sensor networks interact. Mark Weiser defined the goal of ubiquitous computing as 'the nonintrusive availability of computers throughout the physical environment, virtually, if not effectively, invisible to the user' [Wei93]. Ubiquitous computer systems are highly embedded, and usually invisible to their environment. Ubiquitous computing systems combine sensors and actuators to monitor and control the physical environment, like sensor networks. With the development of small, cheap and energy efficient systems and low cost sensor technology the idea of Ubiquitous Computing becomes feasible. Over the last ten years more than 70 single board computers such as Arduino™, Raspberry PI™, BeagleBone™, Intel Edison™ or Intel's newly released Intel Curie™ became available for the consumer market and for an expanding research community. They enable researchers and industries to create small and highly utilitarian ubiquitous systems that can support everyday lives.
The terms ubiquitous computing and pervasive computing are often used synonymously. According to Lyytinen et. al. pervasive computing offers a high level of embeddedness such as ubiquitous computing but the latter offers a higher level of mobility compared to pervasive computing [LY02].
Ambient Intelligence deals with 'sensitive, adaptive electronic environments that respond to the actions of persons and objects and cater for their needs' [AW09]. It includes objects as well as human beings and the necessary interaction between them [AW09]. AmI benefits from the advances of sensor and actuator technology with the goal to create flexible and adaptive surroundings. [CAJ09] summarizes various requirements of AmI such as sensitivity, responsiveness, adaptability, transparency, being ubiquitous and intelligent. Industry 4.0[4] does apply such requirements.

Industry 4.0 deals with the digitization of industrial processes where systems are interconnected. The term Industry 4.0 is often used as synonym for Industrial Internet. According to Hermann et. al. Industry 4.0 follows four design principles, namely technical assistance, decentralized decisions, interconnection and information transparency [HPO16].
Technical assistance focuses on the support to humans within factory environments. The goal to facilitate the decision-making process in terms of efficiency and time saving is a typical example. Decentralized decisions should be based on the interconnection of

[4] A German governmental initiative dealing with the fourth industrial revolution and the digitization of industries.

objects and humans. Based on the information humans receive from an interconnected cyber-physical environment should enable them to make decisions autonomously.
Wireless technologies allow an 'interconnection' of systems and contribute to the Industry 4.0 initiative. Communication standards, security and ubiquitous Internet access, and collaboration are fields of research [HPO16]. Research within information transparency deals with the context aware information and the convergence of the cyber and physical environment. Virtual clones that make use of sensor data from a representation of existing physical objects are prominent design principles. [HPO16]
Industry 4.0 is part of the Internet of Things (IoT). The term Internet of Things was first mentioned around 2003 (Figure 2.1b) to summarize technologies, standards and current research efforts. IoT refers not only to businesses and factory environments but includes and affects all objects such as chairs or textiles. IoT uses technologies



(a) Cyber-Physical System

(b) Merged Plot

Figure 1.3: **Publications Containing the Terms Cyber-Physical Systems and Connected Keywords:** total amount of publications containing the term 'Cyber-Physical System' aggregated by year (Figure 2.1a). A merged plot in Figure 2.1b was created to illustrate the total amount of publications containing the terms 'Embedded System', 'Wireless Sensor Network', 'Cyber-Physical System' and 'Internet of Things'. Data source for the merged plot was the IEEE Xplore Digital Library. Data acquisition in May 2017.

such as embedded systems and (wireless) sensor networks connected to the Internet. IoT[5] systems are interoperable and provide a seamless communication between heterogeneous devices [MPPT12].
The term 'smart' summarizes IoT systems ranging from large scale like 'Smart Cities', 'Smart Buildings' and 'Smart Factories' down to a small scale like 'Smartphones',

[5]The IoT includes topics and research fields such as the Cloud-of-Things, Smart Cities, Sensing as a Service (SaaS), Things as a Service (TaaS), Sensing-and Actuation-as-a-Service (SAaaS), Smart Cities [SLF11] [Nap+11] [MPPT12], Ubiquitous Cities [SK10], Digital Cities [SLF11], Smart Grids, Smart Enterprises and Smart Planet. These terms are not focus of this dissertation but are mentioned for the sake of completeness.

'Smartglasses', 'Smarttextiles' or 'Smart Thermostats'. Figure 1.4 shows the taxonomy of Smart Objects. The idea of the IoT is that every object can be turned into a Smart Object if it possesses sensors, actuators and is interconnected.

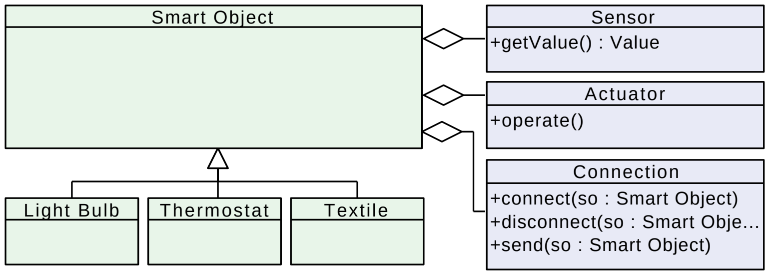


Figure 1.4: **Smart Objects:** consist of sensors and actuators and are interconnected. Examples of such objects are smart light bulbs (www.meethue.com), smart thermostats (www.tado.com), or smart textiles (www.ambiotex.com).

Embedded systems, sensor networks and smart objects share common abstractions and are the core components of CPS. We use these common abstractions to define a CPS base-metamodel that can be reused and extended by CPS developers. The problem within the domain of CPS is that CPS developers start from scratch designing and implementing a new CPS application. Our hypothesis is that cyber-physical systems share commonalities that can be reused for the design and implementation of new CPS independent from their domain. To further extract and extend the CPS base-metamodel we apply a formative research process.

1.1 Research Process

We apply a formative approach[6] to extend the CPS base-metamodel. To demonstrate the extensibility of the CPS base-metamodel we design and implement CPS from two different application domains, namely manufacturing and extreme environments. During this process, we identify additional abstractions to be included in the base-metamodel (Figure 1.5).

Developers of cyber-physical system applications from other domains, such as transportation or medicine, can use this approach to extend the base-metamodel with their abstractions. This reuse speeds up the design process, and forms a guideline for stakeholders within new CPS applications.

[6]We do not elicit metamodel abstractions by observing the actual application and its users. Robert E. Stake summarizes this in a succinct phrase: 'When the cook tastes the soup, that's formative; when the guests taste the soup, that's summative.' [Sta04].

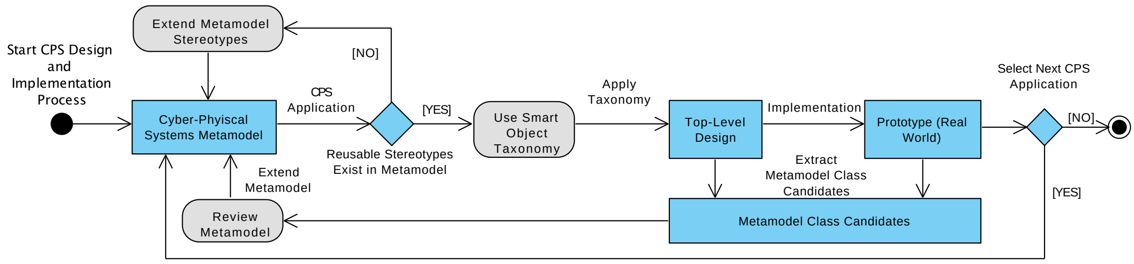


Figure 1.5: **Formative Process:** the cyber-physical system metamodel is defined, extended and reused within different domains following this process.

1.2 Outline

Chapter 2 defines the term CPS more formally as it is used throughout the remainder of the dissertation (Section 2.1). Section 2.2 covers an introduction to the Meta Object Facility and the UML stereotype mechanism. Section 2.3 describes the cyber-physical system metamodel, which is the result of the formative process (Figure 1.1) applied in two different domains, designing and implementing six prototypical CPS applications. Section 2.4 introduces the metamodel extensions and the system model for each CPS application.

Chapter 3 summarizes the dissertation and provides threads to validity in Section 3.1) and future work in Section 3.2 for each CPS application as well as for the metamodel.

Chapter 4 lists the five first-author publications this dissertation is based on. A forecast summarizes the publications and provides the contribution to the dissertation.

The Appendix contains the textual description of two selected CPS applications within the domain of extreme environments and their results. It contains additional results such as figures created during the literature review and the summary of all publications that have been part of the literature review.

Chapter 2

Cyber-Physical Systems

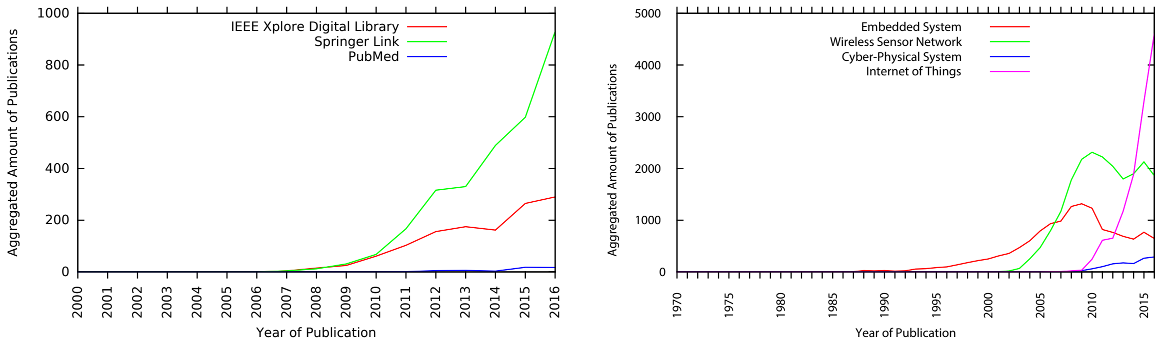
In the new era, thought itself will be transmitted by radio.

Guglielmo Marconi

This chapter provides the definition of cyber-physical systems (CPS) in Section 2.1 used for the remainder of this dissertation. Section 2.2 describes the concept of the Meta Object Facility from the Object Management Group (OMG) as foundation of the cyber-physical system metamodel. Section 2.3 defines the metamodel for cyber-physical systems and describes the methodology for building new CPS. We have designed and implemented CPS applications in two different domains, namely within manufacturing and extreme environments, to show the extensibility and reusability of the base-metamodel. We selected these domains opportunistically, as we had ongoing research projects with experts in these domains. Altogether we selected six applications: Agile Assembly (Section 2.4.1), Incident Management (Section 2.4.2), Smart Logistics (Section 2.4.3), Augmented Maintenance (Section 2.4.4), the Remote Health Monitoring (Section 2.4.5) and Health Data Visualization (Section 2.4.6). Details about the applications are provided in the corresponding publications and in the appendix.

2.1 Definition

The term 'Cyber-Physical System' (CPS) was first mentioned in the literature between 2005 and 2006. The following years the amount of publications at Springer Link exponentially increased in the research community (Figure 2.1a). As depicted in Figure 2.1b the total amount of publications about 'Cyber-Physical Systems' is low compared to the publication amount of 'Embedded System' and 'Wireless Sensor Network'. It might



(a) Cyber-Physical System

(b) Merged Plot

Figure 2.1: **Publication Containing the Terms Cyber-Physical Systems and Connected Keywords:** total amount of publications containing the term 'Cyber-Physical System' aggregated by year (Figure 2.1a). A merged plot in Figure 2.1b was created to illustrate the total amount of publications containing the terms 'Embedded System', 'Wireless Sensor Network', 'Cyber-Physical System' and 'Internet of Things'. Data source for the merged plot was IEEE Xplore Digital Library. Data acquisition in May 2017.

indicate that this research field will grow in the next few years as it was the case for 'Embedded System'. It is interesting to mention that the publication rates for 'Embedded System' and 'Wireless Sensor Network' start to decline in 2011 whereas the amount of publications concerning 'Internet of Things' and 'Cyber-Physical System' start to increase. The number of publications that contain the term 'Internet of Things' exceeded 4600 articles at IEEE Xplore Digital Library in 2016 (Figure 2.1b). The amount of publications for the remaining terms in Figure 2.1b equals about half this publication amount. The term 'Internet of Things' (IoT) includes technologies such as embedded systems and (wireless) sensor networks, where cyber-physical systems are

one of the protagonists of the IoT.
The term CPS is a mashup of the terms, *Cyber*, *Physical* and *System*. In this dissertation, we use the term *cyber* as an equivalent to the Internet. Web protocols such as the Hypertext Transfer Protocol (HTTP), the File Transfer Protocol (FTP) or email protocols such as the Post Office Protocol (POP) allow data exchange via the Internet. A key characteristic of cyber environments is, that their users form and influence it and it is under frequent change [Sha14]. It is a human-created, artificial environment. CPS make use of that environment. Raj et al. claim that CPS typically possess a computing and communication core being interconnected with other CPS and the Internet [RLSS10].
The term *Physical* refers to the actual device that one can see and touch. CPS are physical and engineered systems, which can monitor and control the physical environment [RLSS10]. They bridge the physical and the digital environment offering a communication channel to interact with the physical environment in various domains [RLSS10]. CPS can create physical signals such as the emission of light or radio waves and/or influence physical values such as a room's temperature. Marwedel states that CPS are based on embedded systems focusing more on the physical aspect. They comprise embedded systems emphasizing the connection to physics and the environment. [Mar10] A CPS can also form physical shapes such as spheres or actual physical objects [KH08]. In literature, the formation of shapes using programmable components is called programmable matter. Such components can range from meter to submillimetre scale such as Claytronics. Claytronics consists of catoms that can form meta-materials. Each catom possesses a processor unit, memory, network and communication capabilities. The CPS consisting of catoms form shapes as a direct result of its calculation and information offered by other CPS. [CGM06]
Finally, physical can implicitly refer to the physical environment such as weather conditions and to some unreliable environmental influences [Moh14] such as accessibility, security and safety. According to Edward Lee CPS are 'integrations of computation with physical processes' [Lee08].
System in this context refers to the composition of a CPS. In case one decomposes a CPS into its subsystems it typically possesses a sensor and actuator subsystem. It possesses a powerful, energy saving computational-, one or more communication-, a power-, storage-, and memory-subsystem. According to Wan et al. CPS have to deal with high heterogeneity concerning memory, sensors, actuators, topology and network bandwidth. Additionally, they have to deal with unreliable networking conditions, limited bandwidth, unpredictable and uncertain network behaviour such as in wireless sensor networks and high mobility. To deal with these conditions such systems often use protocols such as IEEE 802.15.4, use GSM-based communication that can suffer

from a high packet loss or low bandwidth. [WMH10]
Crenshaw et al. claim that CPS are deployed in critical infrastructures such as automobiles, manufacturing plants and health-management. They have to face real-time aspects with hard deadlines and need to deal with unreliable sensor and third party component data information.
Based on the literature review (Appendix C) we summarize the key aspects of CPS as follows: a CPS includes hardware, software and communication protocols, controls and monitors its physical environment through sensors and actuators. Sensors are generally sensing physical phenomena whereas actuators transform energy into motion to control or move a system. It is robust against unpredictable situations and environmental influences. Its scale can differ from meter scale down to nanometer scale, it is flexible in system and software design, connected to the Internet, interconnected to other CPS and open to end-users. CPS include heterogeneous devices that can themselves represent CPS.
CPS exist in various domains, such as transportation, health-care, manufacturing, agriculture, energy, defense, aerospace, buildings and more general public environments [RLSS10] [Lee08]. Domain specific CPS add the domain name to the term CPS such as in Cyber-Physical Medical Systems [Che08] [LS10], Cyber-Physical Energy Systems [IXKM08] [Mor+09] [KA10] [MQMN11] [KM13], Cyber-Physical Social Systems [Liu+11] or Cyber-Physical Vehicular/Automotive Systems [WBJ08] [BR12] [JL14] [Zen+14]. As a result of the literature review an overview of domains has been extracted offering some typical CPS examples based on [MC14][Zha+09][PSKW12] [KA10][ZBMM10]:

- Transportation: Air traffic control and transportation management systems such as highway and urban traffic coordination systems [Zha+09].
- Health, Medical: Medical devices, patient monitoring systems, tele-robotic surgery systems, body sensor networks, brain-computer interfaces or pervasive health care systems [Che08] [LS10].
- Manufacturing: Automobiles, aircrafts, factory automation systems, chemical processes monitoring and control, autonomous robotic spaces and industry networks.
- Environmental: Environmental science systems, agriculture, environmental and geological systems.
- Energy: Power grids, electric grid management, smart grids, oil refineries, data centers, zero-net energy buildings, hydro-power management, CPS power management and battery management systems or cooling systems for nuclear reactors.

- Military: Military intrusion detection systems, enemy detection in battlefield, generally military applications and systems to protect society at a national and international level.
- Aerospace: Turbine fuel control systems, space exploration systems and Unmanned Air Vehicles (UAVs).
- Buildings: Everyday life assisted living and smart spaces.
- Public Environment: Disaster recovery, autonomous search and rescue systems, disaster management, Intelligent Water Distribution Networks.
- Mobility, Automotive: Car-2-Car-, Car-2-Infrastructure-, Car-2-Pedestrian applications.
- Cyber-Physical Social Systems: are CPS that additionally take human knowledge, metal capabilities and sociocultural elements into account [Liu+11].

The next section introduces the Meta-Object Facility, followed by the introduction of a base-metamodel for cyber-physical systems. The base-metamodel contains the abstractions of embedded systems, sensor networks and smart objects. It also describes the mechanism to extract stereotypes from new CPS applications to extend Smart Objects. Moreover, each CPS application is modeled as top-level design.

2.2 Meta Object Facility

The Object Management Group (OMG) defines the Meta Object Facility (MOF)[1] as a 'platform-independent metadata management framework and associated set of metadata services to enable the development and interoperability of model and metadata driven systems'. In other words, MOF is an 'extensible [...] framework for defining, manipulating and integrating metadata and data in a platform independent manner' [Ain10]. MOF applies object modeling techniques to describe any kind of metadata. It is often associated to UML but is totally independent from UML [Com+16]. UML represents one possible modeling language that conforms to the MOF such as the Common Warehouse Metamodel (CWM), the Software Process Engineering Metamodel (SPEM) or the UML Profile for Enterprise Distributed Object Computing (EDOC).
Figure 2.2 illustrates how we apply the MOF to CPS. On the M3 layer a meta-metamodel is defined — MOF. This meta-metamodel is used to create the CPS metamodel, which specifies the concepts of the domain, in our case, the cyber-physical

[1] Core Specification Meta Object Facility (MOF) Version 2.5.1 `http://www.omg.org/spec/MOF/`

M3	Meta-Metamodel	MOF (2.0)
M2	Metamodel	Cyber-Physical Metamodel (Figure 2.3)
M1	System Model	Top-Level Design (Section 2.4)
M0	Real World Application	Publications/Appendix

Figure 2.2: **Meta Object Facility:** the cyber-physical system metamodel in this dissertation is defined at M2 (Section 2.3). At M1 six system models as top-level designs are described (Section 2.4). The real world is implemented as CPS application at M0 (Chapter 4, Appendix A and Appendix B).

system metamodel as UML class diagram. A CPS profile is the aggregate of stereotypes, interfaces and constraints that are dedicated to the application of cyber-physical systems.[2]

We make use of the stereotype mechanism of UML to define and extend Smart Objects on the CPS metamodel. The metamodel serves as basis to extend and reuse classes defined on M1. Those classes are used to represent a system or application. On M1 we define the application design as top-level design. Our top-level designs are technology independent, abstract and with the goal to be understandable to all stakeholders within a project. The top-level design represents the blueprint to instantiate the CPS application within the M0 layer. M0 contains the real-world objects that are part of the application. The next section introduces the CPS metamodel.

2.3 Metamodel for Cyber-Physical Systems

Based on the definition of cyber-physical systems we extracted commonalities and created a base-metamodel applicable to all cyber-physical systems (Figure 2.3) at layer M2 of the MOF[5]. This metamodel is extensible and reusable. Extensibility allows

[2]An example of a profile that extends the UML language is the U2TP (UML 2 Testing Profile). It offers an abstraction to create understandable test models for all participating stakeholders in a project. Those test models can automatically generate test cases that are executable. Another example is the UML profile for Software Development Processes[3] that offers models applicable for different stages of a development process. It defines stereotypes such as 'UseCaseModel' derived from the base class model that specifies services that users of a system can use. The OMG Systems Modeling Language (SysML)[4] is another extension that uses the stereotype mechanism of UML. It reuses UML 2.0 models and also extends models within the SysML profiles that apply the defined stereotypes.

[5]The abstractions Peters proposed as classes at M1 for Instrumented and Smart Environments influenced the cyber-physical system metamodel [Pet16].

developers to add new abstractions to the metamodel and to add new stereotypes. Reusability offers existing abstractions that can be used on the M1 layer of the MOF. Top-level designs use the metamodel definition on the M1 layer and describe the system on an abstract level. Each implementation is an instantiation of the top-level design on the M0 layer of the MOF. The metamodel shown in Figure 2.3 is based on the models of embedded systems, sensor networks and smart objects.

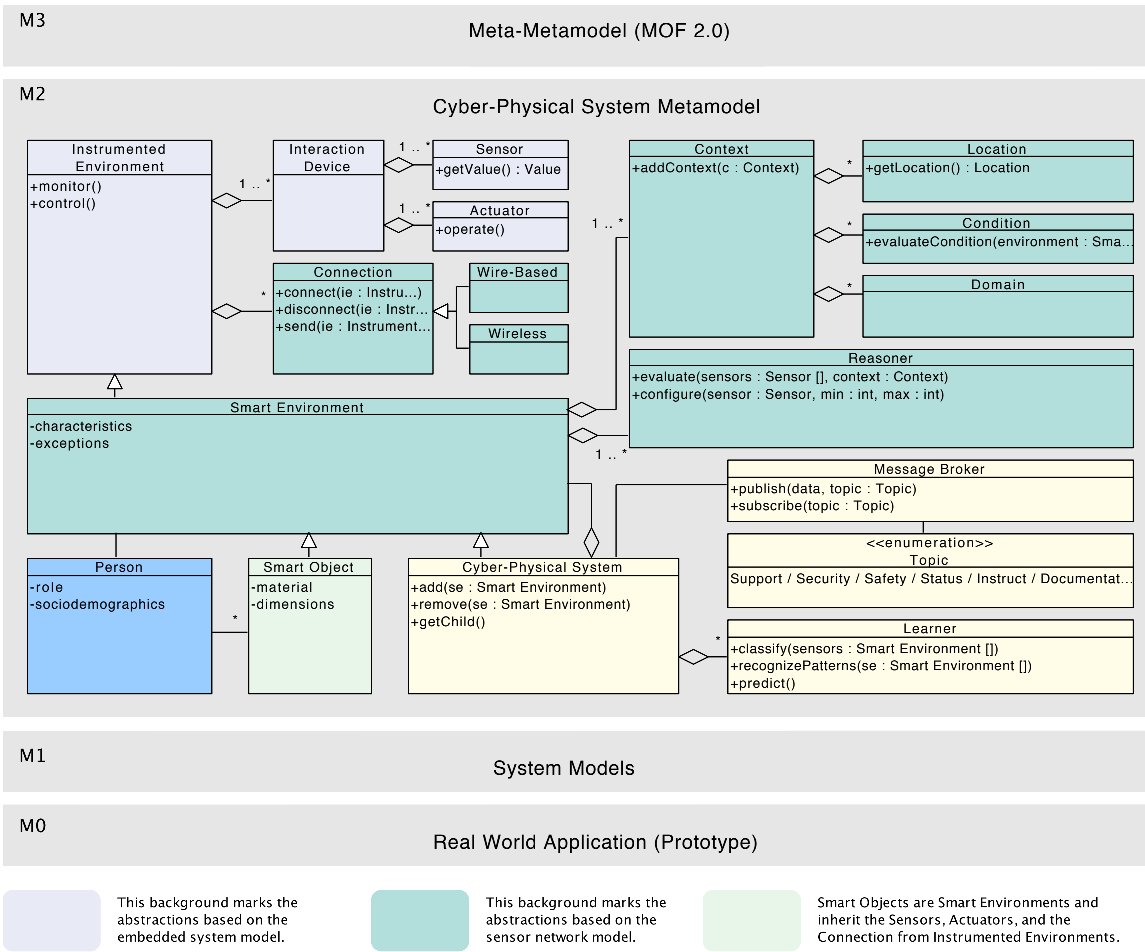


Figure 2.3: **Metamodel of a Cyber-Physical System:** a Cyber-Physical System is a composite of several Cyber-Physical Systems with Smart Objects as leaf nodes. Each Smart Environment can contain Persons that are part or use the Smart Environment.

Embedded systems (Figure 1.1) can be seen as an instance of an Instrumented Environment that can consist of one or more Interaction Devices. Each Interaction Device is a composite of Sensors and Actuators. Each Interaction Device can access the method getValue() to receive sensor values from the Sensors or can access the operate() method to trigger physical actions at the Actuator. All Instrumented Environments possess one or more Connections. Such Connections can be used to connect to, disconnect from, or

send information to other Instrumented Environments. Instrumented Environments can monitor and control an environment that they are deployed in.
An example of an Instrumented Environment could be an airbag system within a car. The system can sense a crash of the car. As soon as it detects such an abnormal behaviour it triggers an inflation process that fills the bag with air. This Instrumented Environment might be connected to other Instrumented Environments within the car, to trigger an action to automatically trigger the hazard lights.

With the miniaturization of hardware, the improvements concerning calculation power, storage capacities, transmission protocols as well as battery lifetime, Smart Environments could be established. The basis of the Smart Environments was the model of sensor networks. Ubiquitous computing influenced the definition of Smart Environment as they make use of Smart Objects. A Smart Environment extends Instrumented Environments. A Smart Environment consists of Contexts. A Smart Environment consists of Contexts such as Location, Condition or a Domain. A Location is an indoor position or a geo-position such as latitude and longitude. Each Context receives the location and calls the method getLocation(). Each Context possesses one or more Conditions. Such Conditions represent the integrity of the Smart Environment. Battery levels or connection reliability are examples. Each Context provides a Domain. If a Smart Environment measures driving behaviour of a diver it might be assigned to the domain of transportation or automotive. Typically, Smart Environments include Reasoners with defined thresholds such as min and max values. The Smart Environment configures such values. Moreover, a Reasoner evaluates the Smart Environment given the specified Sensors and a Context. As Smart Environments are Instrumented Environments they collect Sensor values, that are considered by the Reasoner. Each Smart Environment defines characteristics that describe it and defines exceptions that are triggered in case the Reasoner evaluates the Smart Environment and predefined thresholds are exceeded. An autonomous cruise control (ACC) system of a car can be modeled as Smart Environment. It possesses several sensors that measure the distance to a car in-front of it. The car configures a Resoner, which defines thresholds when a distance is too short and the car must be slowed down. The Reasoner also defines the minimum velocity to activate the ACC. The Smart Environment evaluates the situation during the driving process. An additional Context defines where the car is driving and how the overall condition of the ACC is evaluated. As soon as the distance is too short the cars' velocity is adjusted and the distance is adjusted. In case the car in-front breaks unexpectedly strong, an actuator triggers an additional warning signal. The transition between an Instrumented Environment and a Smart Environment is smooth [Pet16]. Therefore, the Smart Environment on the M1 layer is typically represented by its extension such as

Smart Objects or Cyber-Physical Systems.

A Cyber-Physical System extends Smart Environments and uses a composite pattern to allow aggregates of Smart Environments. A Cyber-Physical System can add() and remove() Smart Environments. Moreover, it can getChild() nodes namely Smart Objects, which are themselves Smart Environments. Therefore each Smart Object is an instance of an Instrumented Environment and inherits all properties and associations from it. The composite patterns allows a Cyber-Physical System to be a composite of Smart Environments that are instances of Instrumented Environments with leaf nodes of Smart Objects.

Each Instrumented Environment makes use of a Connection to another Instrumented Environment. The Instrumented Environment has to be known, to establish the connection as it must provide a parameter to the connect method. To allow information exchange with unknown systems a Cyber-Physical System makes use of a Message Broker. It provides publish() and subscribe() methods that provide data on a specified topic. A Topic is a string-based, human-readable identifier that assigns the data to this identifier. Other systems that are unknown to the Cyber-Physical System make use of published information without the necessity of a direct connection.

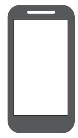
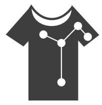
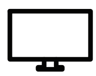
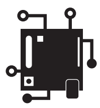
A Learner that can classify(), recognizePattern()s in sensor data or can predict() situations based on the gathered sensor data can be part of the Cyber-Physical System.

In case a car is modeled as Cyber-Physical System it would consist of several Smart Objects. It combines Smart Objects to use a Learner that might be able to classify a driver, to predict dangerous situations or to recognize different driving patterns. Other Cyber-Physical Systems within the car or outside of the car might subscribe to defined Topics to use information one Cyber-Physical System provides. The Cyber-Physical System metamodel allows aggregates of Smart Objects that provide object specific methods. A Smart Environment defines methods that a Cyber-Physical System as well as a Smart Object has to implement. As a Cyber-Physical System is an aggregate of Smart Objects it calls those methods for each object as a composite pattern is used.

Each of the Smart Objects can be extended by stereotypes. In Table 2.1 those stereotypes are listed. Each stereotype defines a graphical icon that can be used instead of the stereotype name shown in guillemets. The defined stereotypes are used in each CPS application - and are extended if necessary - to instantiate the metamodel on the M1 level.

A Person is part of a Cyber-Physical System. The taxonomy of a Person is shown in Figure 2.4. A Person is the superclass of a Worker, a Customer, a Manager or Mission Personnel. We further distinguish Workers into Maintenance, Warehouse or Factory workers. For Mission Personnel we further define Deployed Personnel, Medical Advisor and Mission Commander.

Table 2.1: **Smart Object Stereotypes:** the table lists a non-exhaustive list of possible stereotypes that are used to instantiate Smart Objects.

Stereotype	**Description**	**Graphical Icon**
«wearable»	A wearable is a Smart Object that is attached to a human body or a body of an animal. It is not integrated into a textile rather than attached to it. The stereotype was applied in Section 2.4.2, 2.4.3 and 2.4.5.	
«smartphone»	A mobile device that offers a user interface, comprises sensors and actuators. A Person typically uses such a device. The stereotype was applied in Section 2.4.1, 2.4.2 and 2.4.5.	
«smarttextile»	Sometimes referred to as e-textile, smart clothing are textiles that can "sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in the textile structure. The stimulus and response can have an electrical, thermal, chemical, magnetic or other origin" [VLH04]. The stereotype was applied in Section 2.4.2, 2.4.3 and 2.4.5.	
«identificationdevice»	A device that is capable to wirelessly transmit and advertise identifiers that a sensor is able to sense, such as beacons. The stereotype was applied in Section 2.4.1 and 2.4.2.	
«tablet»	A device that possesses greater dimensions than a smartphone to provide a large screen. The device comprises sensors and actuators. A Person uses such a device. The stereotype was applied in Section 2.4.1, 2.4.4, 2.4.5 and 2.4.6.	
«computer»	A device that is stationary deployed in an environment. It offers a user interface to a Person. The stereotype was applied in Section 2.4.2 and 2.4.3	
«microcontroller»	A device that is stationary deployed in an environment. The stereotype was applied in Section 2.4.3.	

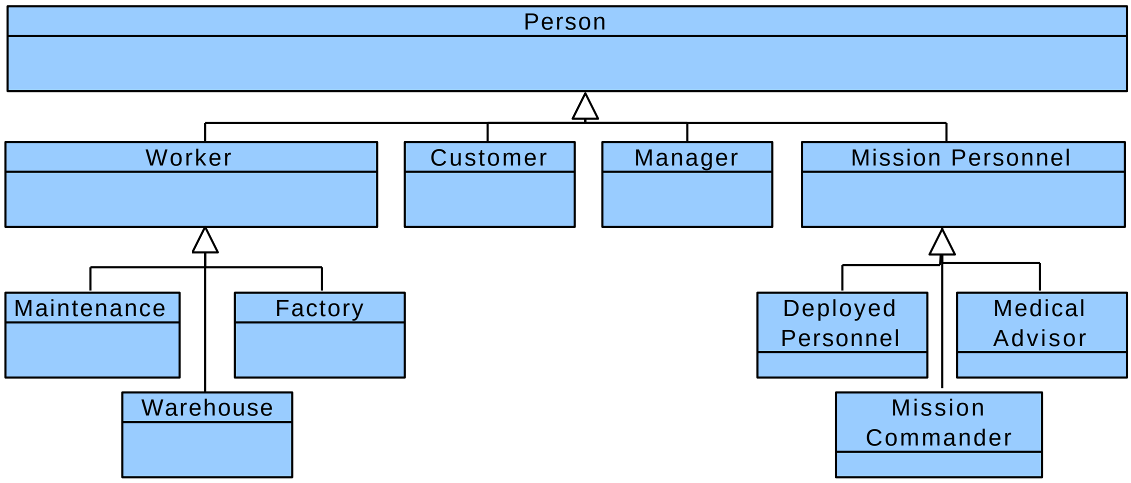


Figure 2.4: **Person Taxonomy:** the UML diagram shows the taxonomy of Persons on M2 of the MOF. The taxonomy is reused at M1 to instantiate the top-level designs for each CPS application.

In the following we describe the extensions of the metamodel for the Agile Assembly, Incident Management, Smart Logistics, Augmented Maintenance, Remote Health Monitoring as well as Health Data Visualization. Each top-level design of the CPS application follows a graphical notation that is given beforehand.

Graphical Notation

This section summarizes the notation for each instance of the metamodel. Each instance is illustrated as top-level design on the M1 layer of the MOF. It shows the system on a top level, technology independent and abstract [ASFB17]. The color scheme of those models follows that of the metamodel (Figure 2.3) in Section 2.3.

Within the top-level design, cyber-physical systems conform to this notation: **[name] : Cyber-Physical System**. The cyber-physical system name is followed by the type declaration, which is denoted with underlined, bold-face font. Each cyber-physical system is surrounded by a box with a dashed border.
The notation for smart objects follows this pattern: [functional name] (abbreviation) [Stereotype]: Smart Object. Each smart object reuses the graphical icon of the defined stereotypes (Section 2.3). Such a graphical icon helps the reader to imagine how the smart object could look like within the CPS application on the M0 layer. Right next to each smart object the offered methods are shown as list.
Arrows visualize information exchange, connections and data flows. Dashed lines indicate a wireless connection, solid lines any other connection.

Persons are illustrated with an icon. Each person possesses an assigned name. This name is followed by the [Person Taxonomy] : Person.
For clarity reasons, the overall cyber-physical system is not illustrated. Each section describes a CPS application, which represents the overall cyber-physical system. The notation includes UML 2.0 conform notations.
In the following we refer to the metamodel as base-metamodel as we extended it throughout the CPS application based on the proposed formative research process.

2.4 Base-Metamodel Extensions

We designed and implemented interdisciplinary CPS applications (Figure 2.5) to extended the Smart Object taxonomy, to mine for new stereotypes and to collect metamodel class candidates to review and adapt the base-metamodel.

We applied the formative research process introduced in Section 1.1. Each Smart

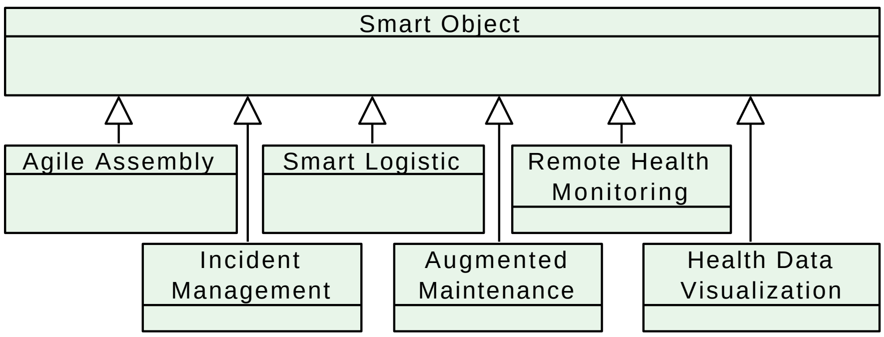


Figure 2.5: **Smart Object Taxonomy:** based on the formative research process (Section 1.1) we selected the following six applications to mine for potential subclasses for the Smart Object class at M2: Agile Assembly Application (Section 2.4.1), the Incident Management Application (Section 2.4.2), the Smart Logistics Application (Section 2.4.3), the Augmented Maintenance Application (Section 2.4.4), the Remote Health Monitoring Application (Section 2.4.5) and the Health Data Visualization Application (Section 2.4.6).

Object contains the methods and uses corresponding stereotypes that extend M2. The defined top-level designs at M1 as well as the prototypes at M0 help us to collect metamodel class candidates. The following subsections describe the extensions and reuse of the metamodel for each CPS application.

2.4.1 Agile Assembly

The agile assembly CPS application is a part of an agile factory and represents a vertical prototype that addresses two problems: the inflexible arrangement of shop floor workstations and non-hands-free interaction with user interfaces. Therefore, the agile assembly enriches workstations with context and enables smart devices to display context-aware information to factory workers. The published work can be found in Section 4.1. The next section defines the Smart Object taxonomy extension.

Smart Object Taxonomy Extension

The agile assembly CPS application extends the **Smart Object** taxonomy with four new objects: the Order Device, the Worker Assistance Application, the Beacon Scanning Application and the Smart Workstation (Figure 2.7). Moreover, three new stereotypes have been elicited during the design process, the smartphone, the tablet and the identificationdevice.

The Order Device uses the smartphone stereotype and provides methods that enable a

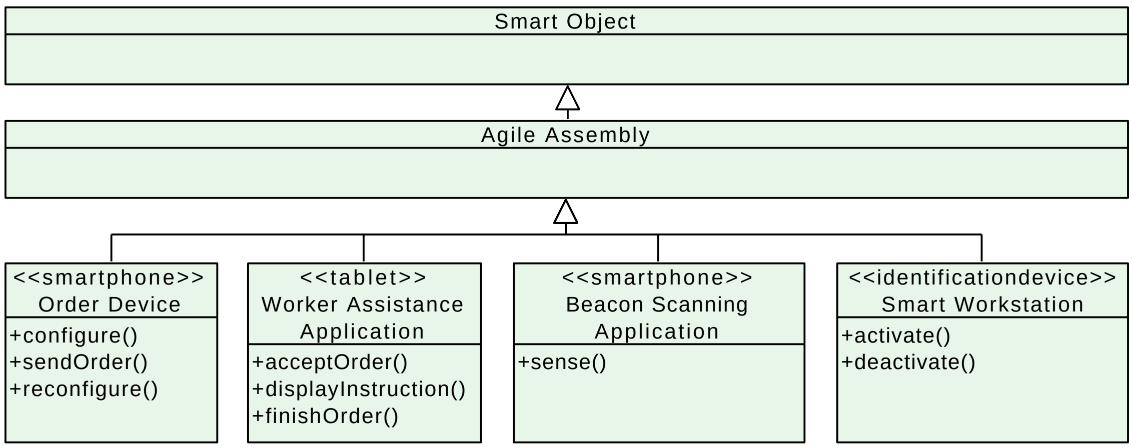


Figure 2.6: **Agile Assembly Taxonomy Extension:** this taxonomy extends the Smart Object taxonomy as shown in Table 2.1 with three new stereotypes.

Person to configure() a product, sendOrder() of a product and reconfigure() a product. The Worker Assistance Application applies the tablet stereotype and offers methods such as acceptOrder(), displayInstruction() and finishOrder(). It is mounted on a mobile worktable to allow hands-free operation. The Beacon Scanning Application uses the smartphone stereotype and can sense() Smart Workstations. The Smart Workstation is a factory hardware table that is equipped with an identificationdevice that is continuously sending identifiers that the Beacon Scanning Application senses. To send those identifiers the Smart Workstation offers an activate() method. To turn off the identification

mechanism the deactivate() method is called.
In the next section, the top-level design of the agile assembly CPS application uses the graphical icons for each Smart Object and defines the system on the M1 layer of the MOF.

Top-Level Design

The agile assembly CPS application uses a commercially available software framework[6]. The agile assembly CPS application consists of three CPS shown in Figure 2.7: the Customer Space, the Factory Shop Floor and the Factory Support System.
The Customer Space defines a Customer of type Person who uses an Order Device. The Customer configures his or her order, sends the order and reconfigures the order (Figure 2.3).
The Order Device sends an order of a product, receives status changes and sends change requests.
The Factory Shop Floor can be a manufacturing environment, that provides necessary

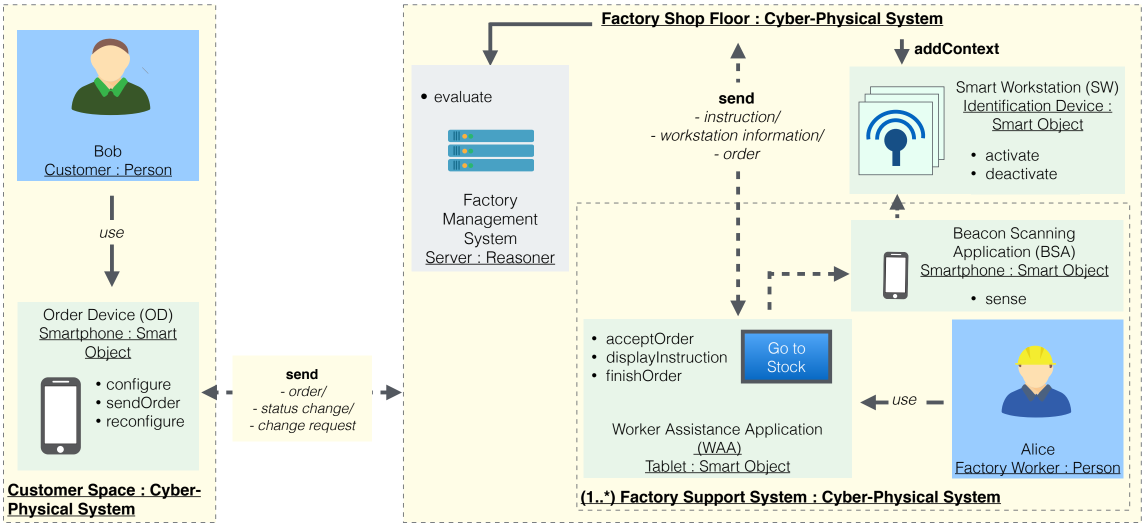


Figure 2.7: **Top-Level Design:** the Agile Assembly CPS application consists of three cyber-physical systems Customer Space, a Factory Shop Floor and the Smart Factory Support System which themselves are CPS.

material and equipment to process an order and to build the desired product the Customer ordered. The Factory Management System from type Reasoner evaluates the Factory Shop Floor according to the given Context. It determines which status an ordered product has, or evaluates in which process step a Factory Worker currently is. The Factory Shop Floor adds Context information to each Smart Workstation of the type

[6]Manufacturing Execution System: DE software & control GmbH

Smart Object. Examples of such pieces of context information are: where the Smart Workstation is located, what kind of process steps can be conducted at this Smart Workstation as well as which halo-radius it defines to trigger automatic instructions to the Factory Worker. Moreover, the Factory Shop Floor activates the Smart Workstation, to send the wireless beacon identifiers. To stop broadcasting such an identification the Smart Workstation offers a deactivate() function. A Smart Workstation typically is a table equipped with special tools or materials that are necessary to conduct a certain process step.

As soon as an order arrives at the Factory Shop Floor the Factory Management System evaluates the Factory Shop Floor. Based on that evaluation the Factory Shop Floor sends instructions, workstation information as well as the order information to an available Worker Assistance Application within the Factory Support System of the type Cyber-Physical System. It contains a Worker Assistance Application of type Smart Object, which is able to display requests that represent the order of the Customer. A Factory Worker uses the Worker Assistance Application and accepts the order, follows the displayed instructions and finishes an order. The Worker Assistance Application guides the Factory Worker through the process. It displays instructions that are automatically triggered as soon as the Factory Worker is near a certain Smart Workstation. Based on the defined Context the Worker Assistance Application provides instructions to the Factory Worker, context-aware. The Worker Assistance Application connects to a Beacon Scanning Application, which senses the wireless identifiers of nearby Smart Workstations. Both the Beacon Scanning Application and the Worker Assistance Application are attached to a mobile worktable (Section 4.1). In this top-level design, the mobile worktables are left out due to space constraints.

The Factory Worker follows the automatically triggered instructions. As soon as the Factory Worker finishes an assembly step, an instruction to which Smart Workstation the Factory Worker has to go next is displayed on the Worker Assistance Application. As soon as the Factory Worker approaches the next corresponding Smart Workstation new instructions are provided and a status change back to the Order Device is sent. This flow of events repeats until the ordered product is finished or no changes from the Customer had to be processed during the assembly process.

The Customer is able to reconfigure the order during the assembly process. In case this happens a change request is sent to the Factory Shop Floor. The Worker Assistance Application updates the instructions that the Factory Worker can process the change request.

The instantiation on level M0 of the application be found in the publication reprinted in Section 4.1. It is summarized and reprinted with permission of the IEEE Digital Library.

2.4.2 Incident Management

In factory environments, an incident is a situation that impedes the manufacturing process. A malfunctioning machine or worn out parts of a production line can cause such incidents.
We implemented an Incident Localization and Assistance System (ILAS), which helps factory workers to localize and document incidents. ILAS transfers process oriented incident management knowledge from IT Service Management (ITSM) to the domain of manufacturing. It enables the factory management to monitor the incident process in real-time. The system equips factory workers with wearables, provides incident analysis support and knowledge sharing capabilities within and among different production sites. As wearables, it integrates technologies into mandatory protective textiles such as gloves. In case a detailed incident analysis is necessary a smartphone supports the factory worker. The worker documents the new incident and browses through relevant incidents that have already happened. Incidents are sharable with colleagues or the factory management as they are digitized.

Smart Object Taxonomy Extension

The incident management CPS application extends the Smart Object taxonomy from Figure 2.5 with four new Smart Objects, namely the Mobile Documentation Device, the Wearable Incident Device, the Production Line Sector and the Documentation Manager (Figure 2.8). During the design, we added the three new stereotypes smarttextile, wearable and computer.

The Mobile Documentation Device uses the stereotype smartphone and offers methods to locate() and document() an incident as well as takePictures() of, and add text() to an incident. Moreover, it is able to calculate() the distance to an incident. We reused the stereotype as we defined it within the Agile Assembly application (Section 2.4.1). For the Wearable Incident Device we extended the base-metamodel and added two new stereotypes, smarttextile and wearable. The Wearable Incident Device offers methods to locate() an incident, and to document() the incident. Moreover, it provides a scan() method that triggers a barcode reader to scan and decode a barcode. The Production Line Sector provides methods to activate() as well as deactivate() the Production Line Sector identification. We reused the existing stereotype smartphone. The Documentation Manager is a browser-based application that allows to show existing incidents, to create new incidents and to assign incidents. For this Smart Object we defined the stereotype computer and assigned it to the object.
Based on the defined extensions we design the system on the M1 layer at the MOF as top-level design in the next section.

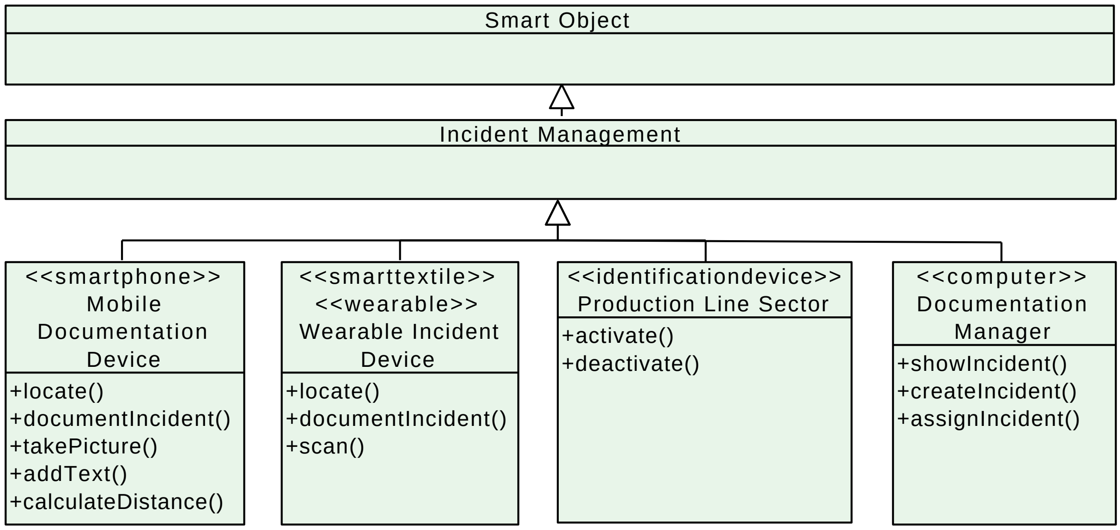


Figure 2.8: **Incident Management Taxonomy:** this taxonomy extends the Smart Object taxonomy as shown in Table 2.1 with three new stereotypes, smarttextile, wearable and computer.

Top-Level Design

The incident management CPS application consists of five cyber-physical systems: the Factory Shop Floor Environment, which contains one to many Factory Workers, a Manufacturing Execution System, and a Factory Administration Environment that contains a Factory Management Environment (Figure 2.9). During the design of the application we extracted two metamodel class candidates for layer M2: Message Broker and Topic. We added those classes to the base-metamodel and reused the classes in the remaining CPS applications.

The Factory Shop Floor Environment comprises one to many Production Line Sectors of type IdentificationDevice. Production Line Sectors are Smart Objects. The Manufacturing Execution System provides information about each component of the production line, such as if a certain sensor is working or not. A Factory Worker consists of a Maintenance Worker that uses a Mobile Documentation Device as well as a Wearable Incident Device. The Mobile Documentation Device provides methods to locate and document an incident, take a picture of the incident and add text to an incident. To localize the incident the Mobile Documentation Device is able to establish a wireless connection to the Production Line Sector (PLS). At the PLS a visual feedback device is activated to support the Maintenance Worker during the localization process. Additionally, to the visual feedback, the Mobile Documentation Device displays the calculated distance to the PLS.

The Wearable Incident Device is a slim version of the Mobile Documentation Device.

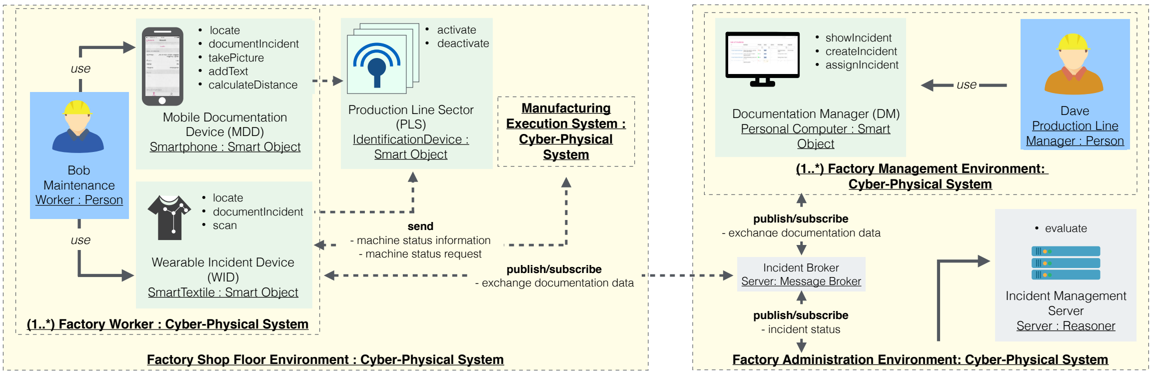


Figure 2.9: **Top-Level Design:** the ILAS enables maintenance workers to localize and document incidents in factory environments. The top-level design uses the extended base-metamodel.

It also locates an incident and establishes a wireless connection to the PLS. As soon as the Maintenance Worker reached the affected PLS, a potentially malfunctioning sensor equipped with a barcode can be scanned. The Wearable Incident Device sends a machine information request to the Manufacturing Execution System. It will receive machine status information such as if this part is functioning or not. The Wearable Incident Device indicates such information with a green or red LED. To exchange documentation data the Factory Worker and the Factory Administration Environment use a publish/subscribe mechanism. They use an Incident Broker located at the Factory Administration Environment. A Incident Management Server evaluates incidents and manages the incidents. To exchange data with the Factory Management Environment the same publish/subscribe mechanism is used. The Factory Management Environment possesses a Documentation Manager (DM) of the type Smart Object. A Production Line Manager uses the DM to show, create and assign incidents.
The top-level design focuses on the localization and documentation workflow of incidents. Section 4.2 provides the instantiation of the system on the M0 layer of the MOF and provides details about the incident management workflow.

2.4.3 Smart Logistics

The term logistics derives from the military domain. Its definition was extended to the business and factory domain in the late 1980s [LKV01]. The Council of Logistics Management (CLM) defines logistics management as "the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods, and related information flow from point-of-origin to point-of-consumption for the purpose of conforming to customer requirements." [LMU99]. Within factory environments logistic process help to deliver

materials and products when and where they are needed. Logistic processes cover stock management, commissioning of parts and packages as well as the documentation of all process steps.
Mistakes within single logistic steps influence deferred process steps. Mistakes are typically not noticed when they occur but in later steps. Parts can be missing, have been commissioned in a wrong order or the wrong part have been commissioned. This causes delays, monetary drop and misunderstandings. To reduce the probability of mistakes we developed and evaluated several prototypes that support factory workers during logistic processes.

Smart Object Taxonomy Extension

During the design of the smart logistic CPS application we extended the Smart Object taxonomy with five new Smart Objects: the Barcode Data Receiver, the Warehouse Workstation, the Scanning Glove, the Commissioning Assistance System and the Logistics Management System (Figure 2.10).
We extended the base-metamodel introducing a new stereotype microcontroller. The

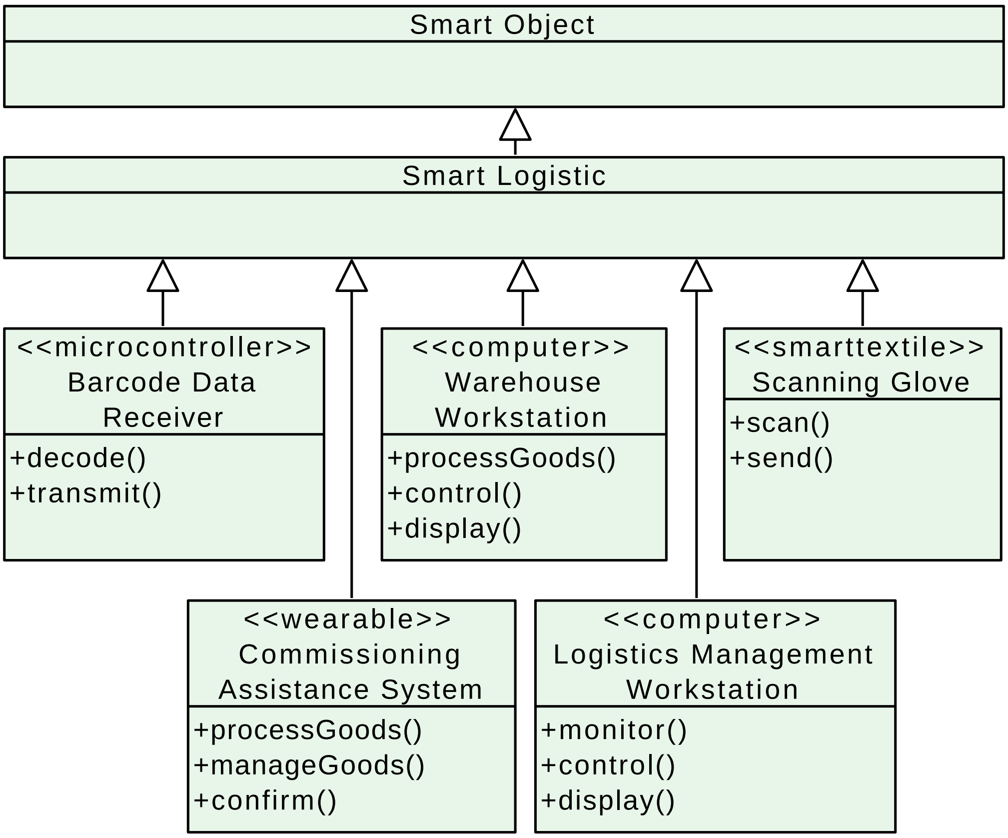


Figure 2.10: **Smart Logistic Taxonomy:** this taxonomy extends the Smart Object taxonomy as shown in Table 2.1 with one new stereotype, microcontroller.

Barcode Data Receiver uses this new stereotype and offers methods to decode and transmit barcode information. For the remaining Smart Objects we reused existing stereotypes. The Warehouse Workstation applies the computer stereotype and offers methods to processGoods, control and to display the inventory. The Scanning Glove is a smarttextile that can scan and send barcode information. The Commissioning Assistance System is assigned to the wearable stereotype and can process and manageGoods as well as confirm process steps. Finally, the Logistics Management System is also assigned to the stereotype computer and can monitor, control and display the warehouse inventory. All of the Smart Objects are instantiated and described in detail in the next section with the help of the top-level design.

Top-Level Design

The smart logistics CPS application comprises four cyber-physical systems: the Warehouse Environment, one to many Warehouse Worker, one to many Warehouse Controller and a Warehouse Administration Environment (Figure 2.11).

The Warehouse Environment possesses a Warehouse Broker that handles inventory updates and contains an Inventory Manager to evaluate inventory updates. The Inventory Manager is connected to the Warehouse Environment.

The Warehouse Worker is part of the Warehouse Environment and comprises a Warehouse Worker, a Scanning Glove and a Commissioning Assistance System. The Warehouse Worker uses both Smart Objects to scan, process and manage goods. The Scanning Glove is a smart textile with an integrated scanning unit. It is supplemented with the Commissioning Assistance System, which is a wearable device attached to the wrist of the Person. It supports the Person during the logistic processes and offers information to the Warehouse Worker. The Commissioning Assistance System publishes and subscribes to inventory updates and decoded barcode information. The Scanning Glove decodes barcodes and send it to the Barcode Data Receiver. It is part of the Warehouse Controller, which can be represented by a stationary workstation of a Warehouse Worker. It is equipped with a Warehouse Workstation that displays information and offers additional interaction devices. The Warehouse Workstation publishes and subscribes to inventory updates and distributes decoded barcode information.

The Warehouse Administration Environment consists of a Warehouse Manager from type Person and a Logistics Management Workstation. The Warehouse Worker uses the Logistics Management Workstation to monitor the warehouse inventory, to control and display it. It is subscribed to inventory updates and also publishes such updates. Figure 2.12 shows a detailed model of the Scanning Glove together with the Commissioning Assistance System introduced in Figure 2.11. Both Smart Objects define a Context, which in this case is the right hand of the warehouse worker. The Scanning Glove

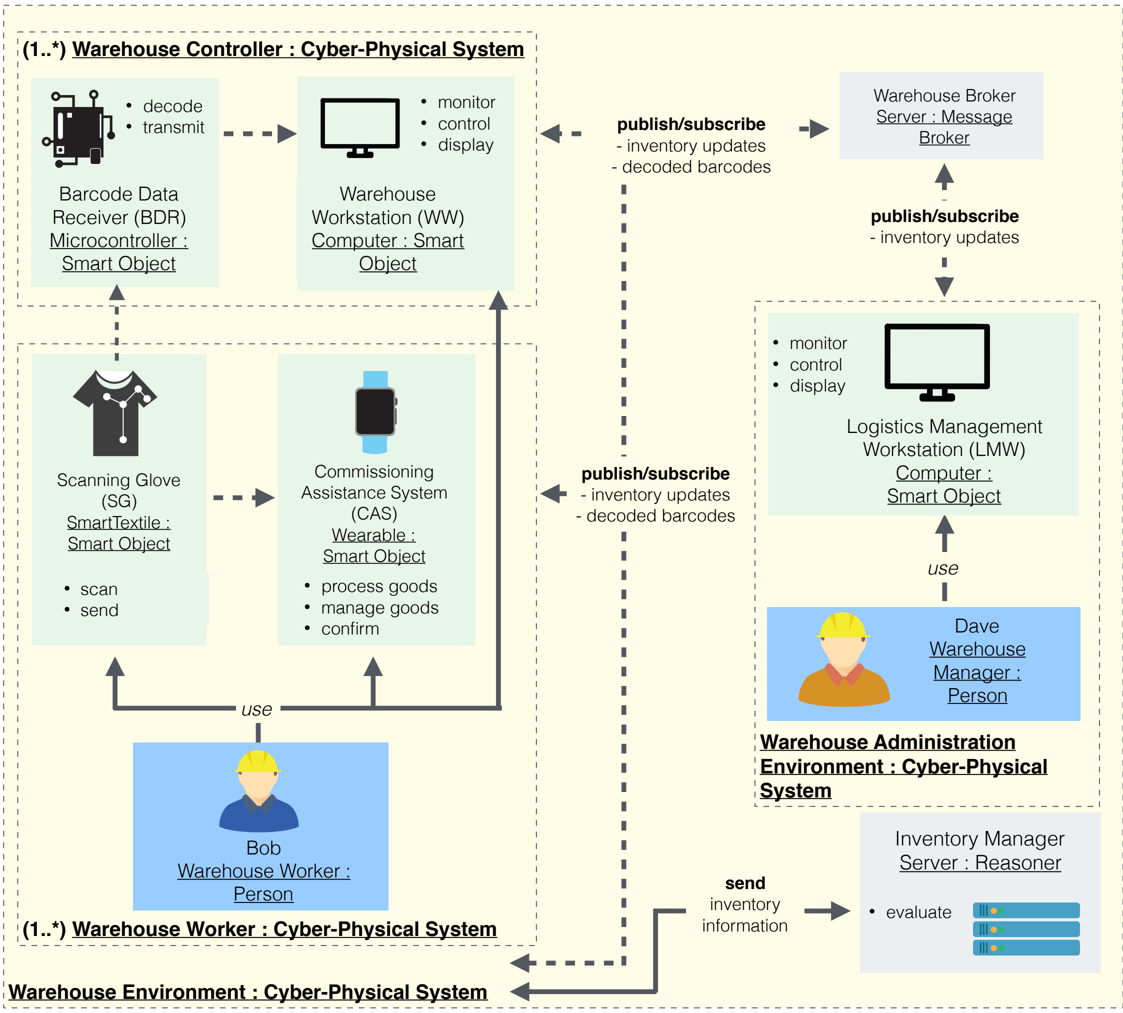


Figure 2.11: **Smart Logistics Top-Level Design:** the figure illustrates the four cyber-physical systems within the smart logistics CPS application, the Warehouse Environment that consists of the Warehouse Worker, the Warehouse Controller and the Warehouse Administration Environment.

consists of three sensors: the Scan Trigger, the Confirmation Button and the Barcode Reader. The Scan Trigger is a textile integrated button that allows the Warehouse Worker to trigger the Barcode Reader. The Barcode Reader is able to scan barcodes such as the EAN barcode or Quick Response Codes (QR-Codes). It is a battery driven, modular system that can be attached and removed to the Scanning Glove. Section 4.4 provides details about the system. The Confirmation Trigger helps the Warehouse Worker to navigate through the application that is installed at the Commissioning Assistance System. The trigger is integrated into the textile and can be pushed with the thumb. The Scan Trigger is wired to the Barcode Reader, the Confirmation Trigger is wired to the Bluetooth Gamepad.

Figure 2.12: **Top-Level Design of Scanning Glove and Commissioning Assistance System:** the figure shows two Smart Object extensions for the Smart Logistics application. Both use abstractions of the base-metamodel. The Scanning Glove uses Sensors, Connections, whereas the Commissioning Assistance System uses a Connection, an Interaction Device and a Reasoner.

The Commissioning Assistance System is able to receive inventory updates and confirmations via the WLAN/Bluetooth Module. A Capacitive Display handles user input. The Commissioning Guidance from type Reasoner is able to process user input and select the corresponding information the warehouse worker needs.

Both top-level designs reuse the base-metamodel and the Smart Object taxonomy on M2 of the MOF. The instantiation of M0 of the MOF can be found in Section 4.4 and Section 4.3.

2.4.4 Augmented Maintenance

In this section, we describe the augmented maintenance CPS application that deals with information sharing within and among peers in one production site.
Incidents in industries and production sites influence the production negatively. Down-

times cause economical damage to companies[7] and are a huge cost driver for industries. Severe incidents lead to economic losses, environmental damage or the loss of life [Jaa+09]. Therefore, down-times in production lines should be minimized to keep negative consequences at a minimum.

In case an incident causes a production down-time, incident or maintenance management helps to deal with the problem in a structured way. Incident management requires maintenance actors, such as technicians, to access knowledge from other experts as well as being able to share knowledge among experts [RKFN13]. Knowledge and the analysis that contributed to create that knowledge should be digitized and sharable to facilitate collaboration among experts.

To contribute to the area of augmented remote maintenance we will introduce our Smart Object taxonomy, followed by the top-level design.

Smart Object Taxonomy Extension

During the design of the augmented maintenance application we defined one new Smart Object. We instantiated a Mobile Annotation System that is able to scan real world objects, annotate them and exchange annotations. The Mobile Annotation System reuses the tablet stereotype. We define the top-level design in the next section.

Top-Level Design

Figure 2.13 shows the top-level design of the augmented maintenance CPS application. It consists of three cyber-physical systems: the Factory Environment and two Factory Workers. The Factory Environment possesses a Factory Broker of type Message Broker that enables the exchange of annotations.

One Factory Environment contains one to many Factory Worker. In the top-level design those cyber-physical systems appear twice to illustrate the exchange of annotations.

A Worker uses a Mobile Annotation System to scan objects, to annotate the scanned objects and to finally exchange the digital annotations.

Section 4.5 defines the instantiation on M0 of the MOF for this CPS application. No new metamodel class candidates were necessary to model the system.

2.4.5 Remote Health Monitoring

The remote health monitoring application takes place in extreme environments. It support humans during deployment with the goal to increase operational safety. To achieve this goal smart textiles measure health quantities of the deployed persons, that

[7] `http://news.thomasnet.com/companystory/downtime-costs-auto-industry-22k-minute-survey-481017`, accessed on 28.06.2017

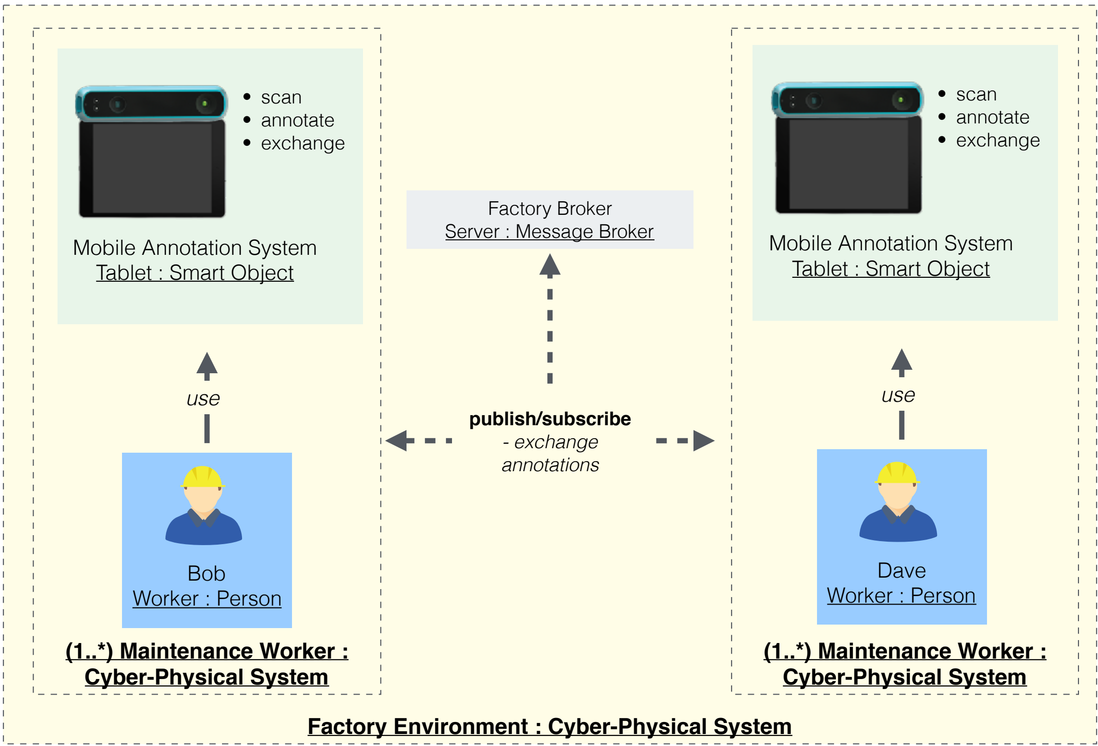


Figure 2.13: **Top-Level Design of Augmented Maintenance:** the figure shows the three cyber-physical systems, the Factory Environment and the two Factory Workers. Both are able to share Annotations.

a medical advisor analyses remotely. The system allows mission personnel to create and plan, as well as monitor missions.
The following section describes the Smart Object taxonomy as it builds the foundation for the top-level design.

Smart Object Taxonomy Extension

The remote health monitoring application extends the base-metamodel with five new Smart Objects within the Remote Health Monitoring CPS application: an Instruction Receiver, a Sensor Garments, a Medical Advisor Application, a Secure Data Collector and a Commander Application (Figure 2.14).
The Instruction Receiver is able to display instructions to a deployed worker. It uses a stereotype wearable. The Sensor Garment is a smarttextile that monitor()s health data quantities such as temperature or heart rate. The Medical Advisor Application is a tablet application that enables medical advisors to create advises that are sent to the mission commander. Moreover, a medical advisor selects deployed workers to receive detailed information about them. For each deployed worker, a physiological fingerprint can be

shown. The Secure Data Collector of type smartphone is able to collect data, to send instructions, to assign suits to a deployed worker using the createSuitmapping method and to offer a setup process. With the Commander Application a mission commander is able to instruct a deployed worker. Mission Details are accessible as well as a selection of a specific deployed worker is possible.

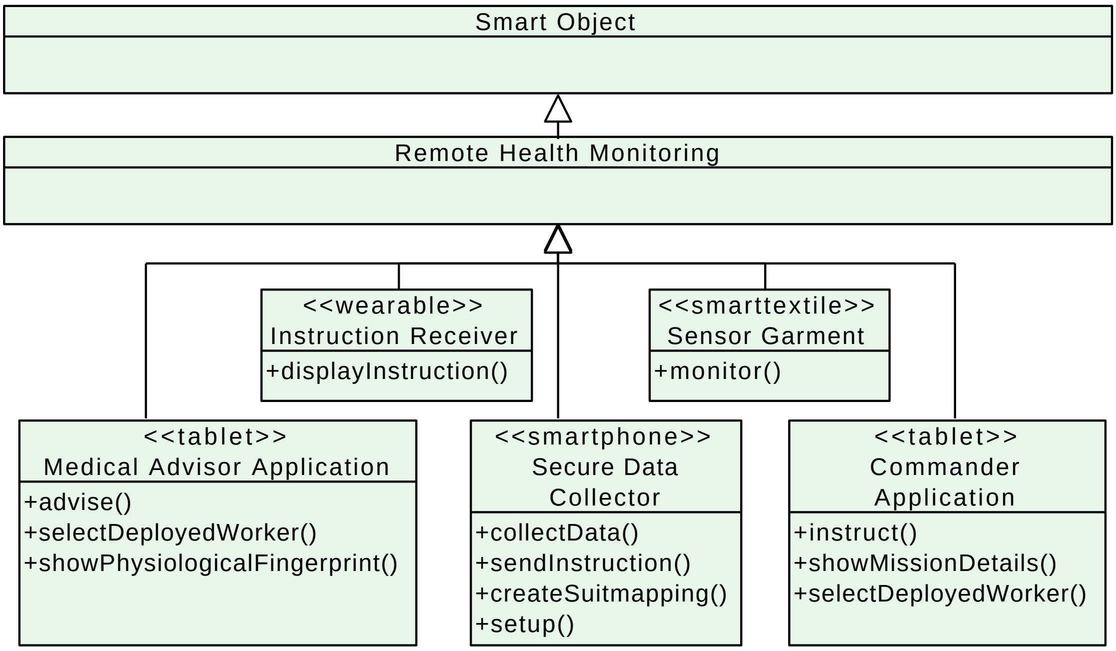


Figure 2.14: **Smart Object Extension:** this taxonomy extends the Smart Object taxonomy as shown in Table 2.1 and reuses the already defined stereotypes.

Top-Level Design

The top-level design of the remote health monitoring CPS application is shown in Figure 2.15. We defined six cyber-physical systems. Two main cyber-physical systems define the Danger- and Secure Zone. Within the Danger Zone one to many Deployed Worker exist. Each of the Deployed Worker possesses a Protective Suit. The Secure Zone contains one to many Health Monitoring Systems and one to many Mission Monitoring Systems.

The cyber-physical system of the Deployed Worker contains a Deployed Worker from type Person. Such a Person uses the Protective Suit and uses the Secure Data Collector to setup the cyber-physical system. Moreover, the Secure Data Collector is able to collect data from the Protective Suit, to send instructions to the Instruction Receiver and to create the suit mapping which is necessary to assign the measured data to the corresponding Deployed Worker.

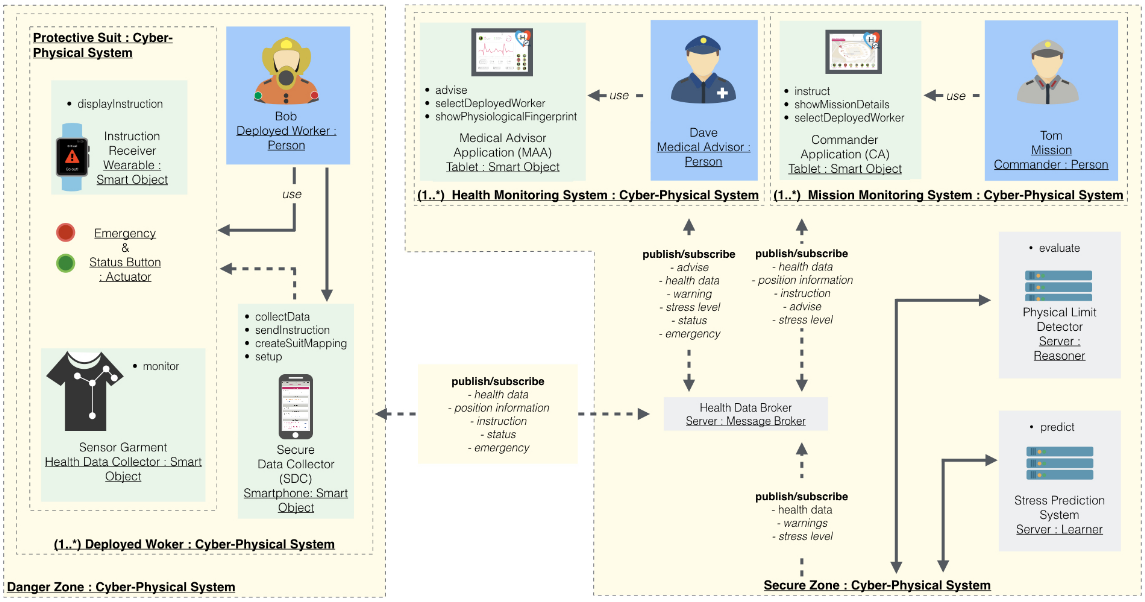


Figure 2.15: **Top-Level Design:** the top-level design divides the system in two major cyber-physical systems, the Danger Zone and the Secure Zone. The Danger Zone contains two other cyber-physical systems, one or more Deployed Workers and a Protective Suit. The Secure Zone consists of one-to-many Health Monitoring Systems and Mission Monitoring Systems.

The Protective Suit contains a Sensor Garment that monitors health quantities of a Deployed Worker, such as heart rate and body core temperature. Moreover, the Protective Suit provides an Emergency- and a Status Button. Both are attached to the Protective Suit. An Instruction Receiver is a wearable device that is able to display instructions, which a Mission Commander sends.

Within the Secure Zone a Health Data Broker is able to handle all data flows within the remote health monitoring CPS application. It processes health data, position information, instruction(s), status information and emergency requests, advise(s), warning(s) and stress level(s). To evaluate health data a Physical Limit Detector of type Reasoner is implemented. To predict stress levels a Stress Prediction System is deployed.

A Medical Advisor is part of one Health Monitoring System. The Medical Advisor uses the Medical Advisor Application to advise the Mission Commander, to select a deployed worker and to show the physiological fingerprint. Within the Mission Monitoring System a Mission Commander uses the Commander Application to instruct a Deployed Worker, to show mission details and to also select a Deployed Worker.

Figure 2.16 shows the realized implementation of the Sensor Garment. It uses a Core Temperature Sensor, two Humidity Sensors, three ECG Electrodes and four Temperature Sensors for the wrist and ankle temperature. The Sensor Garment uses litz wires and cable fabric to connect the sensors to the Data Device of type Reasoner. Details about

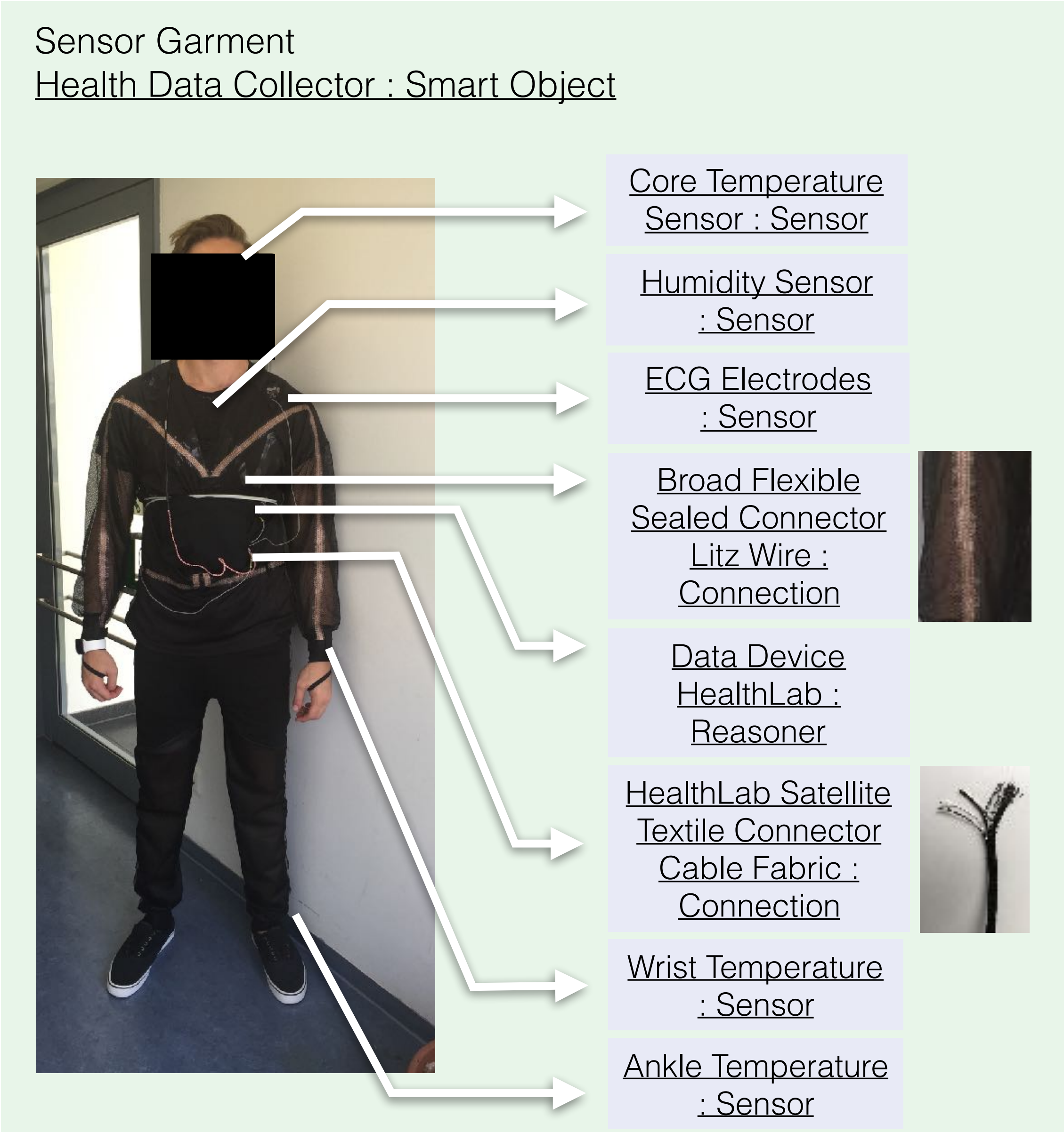


Figure 2.16: **Smart Object Sensor Garment:** the figure shows the Sensor Garment, which consists of objects reused from the base-metamodel (Figure 2.3). It comprises different kinds of Sensors, two Connections and one Reasoner.

the CPS application on layer M0 of the MOF can be found in the Appendix B, as the results are currently being published.

2.4.6 Health Data Visualization

The health data visualization application focuses on the evaluation of the user interface design of the medical advisor within the remote health monitoring application intro-

duced in Section 2.4.5. During the implementation of the remote health monitoring CPS application we figured out that little research about user interface design for medical advisors in professional work environments exists. User interfaces exist but evaluations and guidelines are missing. The same applies for mission commander user interfaces.
The following section describes the Smart Object taxonomy.

Smart Object Taxonomy Extension

During the design and implementation of this CPS application we reused the Smart Objects Medical Advisor Application and the Commander Application (Figure 2.14). No new stereotypes had to be identified.

Top-Level Design

To evaluate the Health Data Visualization we reused the two cyber-physical systems Health Monitoring System and the Mission Monitoring System introduced in Section 2.4.5. Both are part of the Simulation Environment. The Simulation Environment consists of a Scenario Simulator that publishes health data and position information to the Health Data Broker. The Stress Prediction System and the Notification System supply the Simulation Environment with stress level estimations and warnings. Both, the Health Monitoring and the Mission Monitoring System operate as described in the CPS application in Section 2.4.5. The difference for evaluation purposes is that all health data is generated to keep the evaluation environment stable and to conduct a controlled experiment.

Details about the instantiation on the M0 layer of the MOF can be found in the Appendix Chapter B, as the results are currently being published.

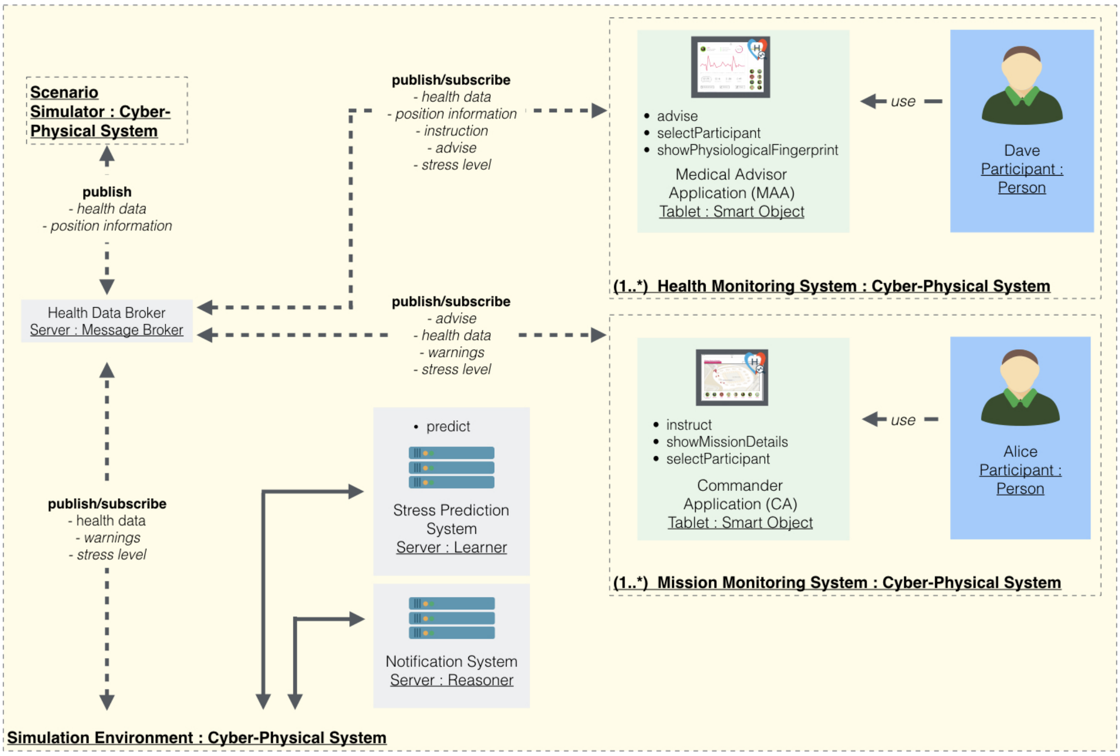


Figure 2.17: **Top-Level Design of the Simulation Environment:** the cyber-physical system of the Danger Zone in Figure 2.15 has been replaced by a reasoner that simulates the evaluation scenarios.

Chapter 3
Conclusion

> New capabilities emerge just by virtue of having smart people with access to state-of-the-art technology.
>
> Robert E. Kahn

This chapter concludes the dissertation and discusses threats to validity and summarizes future work.

This dissertation proposed and followed a formative research approach which includes the definition of a metamodel for cyber-physical systems that has been instantiated within six CPS application prototypes. The metamodel is based on the proposed taxonomy of embedded systems and wireless sensor networks and has been iteratively refined during the design and implementation of the CPS applications. We apply a composite pattern which defines cyber-physical systems as an aggregate of Smart Environments of type Instrumented Environment. The leaf nodes of the composite represent Smart Objects. Persons are part of a Smart Environment that use Smart Objects (Section 2.3).

We defined Smart Object stereotypes that allow us to apply graphical icons within an instance of the metamodel. The goal of the metamodel is to facilitate interdisciplinary cooperation especially at an early stage of the system design. It allows developers to reuse and extend the metamodel for cyber-physical system applications. It provides a guideline for project stakeholders and developers of how to design cyber-physical systems. Moreover, the instances of the metamodel on M1 allow stakeholders to understand the system, independently from their domain.

Our metamodel-based approach improved the support to humans in factory and extreme environments [SSBV16], [SHBV17], [SBFV15], [SVB15], [SMBV16]. Using the metamodel we could offer top-level designs, which facilitated the communication between all stakeholders of a CPS application.

The contribution and the conclusion of the CPS-application-specific results can be found in the publications the dissertation is based on in Chapter 4. For the CPS applications within extreme environments the results have not been published yet and can be found within the Appendix A and B. The next sections summarize the threats to validity and future work for each CPS application as well as for the metamodel.

3.1 Threats to Validity

This section provides threats to validity for each CPS application. It concludes with threats to validity of the developed metamodel. All publications the dissertation is based on can be found in Chapter 4.

Agile Assembly

The Agile Assembly CPS application shows the technical feasibility of context-aware user interfaces in combination with a flexible shop floor management. It has not been evaluated in industrial environments, therefore external validity of the results is limited. The ISM band which we used to communicate is prohibited in many factory environments. Communication ranges can be challenging in real factories due to the topology of the shop floors. A wireless technology evaluation in real factory environments was not part of the research.

Incident Management

Within the incident management CPS application, we implemented a smart glove application. Our conducted foresight about the potential of smart textiles is based on a sample with over 300 participants. However, due to the sample technique of the prognosis market it is non-representative. The CPS application we implemented has been shown to our research partners and has led to a follow up research project, namely the smart logistic CPS application. Yet, the application of ILAS has not been evaluated in-field.

Smart Logistics

The smart logistics CPS application and its smartglove prototypes have been evaluated within two lab experiments. The total sample included 57 participants and was a convenience sample. We evaluated an existing process in a lab environment to keep external influence factors at a minimum. External validity is limited as we conducted lab experiments but the results are applicable to improve the prototypes.

Augmented Reality

This CPS application has been evaluated on an algorithmic level. Based on our results we selected an appropriate ICP algorithm that has been used for the CPS application. An in-field test of the application was not the focus of the research as we focused on the algorithm and the system design, rather that on a user evaluation.

Remote Health Monitoring

The focus of this CPS application was to implement a prototype that solves textile integration challenges of sensors and defines an applicable software system architecture. It provides textile- as well as software-based user interfaces for deployed personnel, mission commanders and medical advisors. We did not evaluate wearing comfort following a structured evaluation. We did not focus on rugged system components. We have anecdotal evidence that the system is applicable in extreme environments, based on expert feedback.

Health Data Visualization

The evaluation of the user interface design was based on a sample of 30 participants. It is a non-representative sample, but we conducted the user study at three different locations, two of which did not take place at the university. The user interface designs have been elicited in cooperation with a medical advisor experienced in extreme environments.

Metamodel

The metamodel has been instantiated for six CPS application prototypes in different areas of application. The areas have been selected based on the research possibilities that have been established. We followed an opportunistic selection approach of CPS domains. Therefore, the sample of domains is not representative.

3.2 Future Work

This section follows the structure of Section 3.1. For each CPS application future work is discussed. The future work for the metamodel concludes this section.

Agile Assembly

Within the agile assembly CPS application future work could focus on identification technologies. We used the ISM band at 2.4 GHz that is commonly used by smartphones and other commercial devices. Frequencies located in the UHF band solve issues such as range and interference, as they are not typically used by such devices. The integration of technologies into applicable rugged cases is subject to future work. Moreover, the definition of the halo around a workstation is an open issue. Currently, only trial and error for such a halo setup is possible. Each topology of a new environment may be different and might need readjustments. A method to estimate such halo settings is subject to future work.

Incident Management

Further effort is needed concerning textile-based and textile-controlled user interfaces. Evaluations that address the textile-software co-design are of major interest. Guidelines that help developers from both domains are yet to be established.
We are currently working on speech input for use-cases such as the description of incidents. Such a description typically requires a touch interaction with a device that can impede a workflow. The applied identification technology needs to be switched to a frequency band that is applicable for factory environments.

Smart Logistics

Incident documentation is also necessary in the logistics domain. We are currently addressing speech input for single process steps within the logistics domain. Moreover, we believe that alternative input and button locations are of interest. Several concepts for the button location must exist that can be selected according to the use case. In addition, modular designs that offer re-positioning of devices depending on the use cases offer research potential.

Augmented Reality

For the augmented reality application future work should substitute hand-held devices such as the developed tablet solution. Hands-free operations offer the potential to reduce motion waste but bare challenges with occlusion of the hands within augmented reality applications. Mesh alignments are calculation-intensive and consume additional energy on mobile, battery-driven devices. A cloud or fog-based solution that outsources calculation efforts into nearby powerful workstations could be part of the future work.

Remote Health Monitoring

We are currently miniaturizing the hardware that we used in the proposed textile prototype with the goal to increase user comfort. Moreover, textile comfort and textile design that increases user acceptance are part of our current work. The usage of machine learning for stress estimation is another issue we are currently trying to address. The setup of the suit concerning the software application as well as the textile has to be evaluated with users. The usage of rugged devices needs to be further impelled.

Health Data Visualization

An opportunity for future work is to implement the proposed redesign of the user interface and evaluate it within an in-field experiment. We considered alternative concepts to include augmented reality that could facilitate data visualization especially for complex and huge data sets.

Metamodel

After six iterations within factory and extreme environments we have reached a state where we could not further identify new class candidates for the CPS metamodel. In the current state, other CPS domains such as cyber-physical energy, vehicular or social systems could be designed and implemented following our proposed formative research procedure. Those applications allow developers to further mine for stereotypes and metamodel class candidates. Moreover, the mechanism of the candidate class selection needs to be formalized.
Concerning the metamodel itself, common methods have to be extracted that Smart Objects might share. The extension of the composite pattern to a decorator pattern could be helpful to override methods in domain-specific cyber-physical systems. The proposed stereotypes have to be extended to devices that might be usable in other, new cyber-physical systems applications. Smart glasses for example have not been used within this dissertation and are a possible example to further extend the stereotypes. An evaluation about the quantifiable benefit within cyber-physical system software projects is part of future work.

Chapter 4
Publications

> To get to know, to discover, to publish — this is the destiny of a scientist.
>
> François Arago

In this chapter, we are presenting the publications the dissertation is based on. Each publication is summarized before the actual reprint of a publication. Reprints are only included in case the paper has already been published or the reprint was granted. Each summary covers the *goal*, the *approach*, the *results* and the *Metamodel Contribution*.
All included papers are first-author papers where the author claims the full contribution of the idea and approach, the design of the software system and its architecture, the design and conduction of the evaluations as well as writing the publications.

4.1 Agile Factory - An Example of an Industry 4.0 Manufacturing Process

This publication (Publication [A]) proposes a novel approach to manage factory floors and processes in factory environments.

Conference: International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)
Number of Pages: 5
Type: Full Paper
Review: Peer Reviewed (3 Reviewers)

The author of this dissertation designed the approach of the modular factory hardware. He designed the concept of the agile factory, which includes the context-aware interfaces, the feedback channel between the customer and the worker as well as the BLE beacon-based approach. He created and coordinated the cooperation with DE Software & Control GmbH and created a new concept that transfers agile software development knowledge to the domain of manufacturing. Furthermore, the author conducted the literature review, defined the problem statement and created the architectural software design for the extension necessary for this prototype. Finally, the author conducted the demonstrations of the prototype within workshops that contributed to the findings of this publication.

Goal

Our goal was to use and integrate tracking technology into equipment of the factory floor, namely the factory hardware. Therefore, we are able to control user interface of mobile devices according to the context to avoid motion waste. The context to us is the location of the worker within the factory environment. Utilizing the knowledge about the worker's location in combination with the associated product request, we could establish a feedback channel between the customer and the worker. This channel allows us to change the product request during runtime and to send detailed information about the status of the product. We created a human-centric cyber-physical system that supports humans during assembly tasks. We used a commercially available Manufacturing Execution System (MES) to implement and show the technical feasibility of our approach.

Approach

Our approach is a conceptual implementation resulting in a vertical prototype. The approach suggests applying a BLE (Bluetooth Low Energy) beacon technology, that allows us to identify factory hardware. Additionally, I have designed a new factory hardware that allows the worker to enter each workstation with his or her mobile worktable.

Results

Our vertical prototype was shown to our project partners from industry and research. It received positive feedback according to the context-aware control of user interfaces and created room for discussions. We could show that the approach is feasible for manufacturing environments. We could show the decomposition of linear factory environments and transferred agile software engineering knowledge to the domain of manufacturing.

Metamodel Contribution

During the design process of the CPS application the formative research process supported interdisciplinary cooperation. It was our first CPS application in the domain of manufacturing and we extended our stereotypes as it was necessary to create the system models. We built and instantiated a cyber-physical system and the metamodel helped all included stakeholders to understand the system in an early stage of the project.

2015 IEEE 3rd International Conference on Cyber-Physical Systems, Networks, and Applications

Agile Factory - An Example of an Industry 4.0 Manufacturing Process

Constantin Scheuermann
Department of Computer Science, Technische Universitaet Muenchen
constantin.scheuermann@in.tum.de

Stephan Verclas
T-Systems International GmbH
stephan.verclas@t-systems.com

Bernd Bruegge
Department of Computer Science, Technische Universitaet Muenchen
bruegge@in.tum.de

***Abstract*—Since the late 90s the idea of mass customization in industry is present. The main goal is to handle the consumer demand for customized products. Recent developments in research, engineering and technology enable industries to move from profitable linear assembly lines to profitable non-linear, dynamic assembly lines to satisfy such a demand. Industry 4.0, a German governmental initiative, encourages industries to use interconnected Cyber-Physical Systems (CPSs) to create context-sensitive and decentralized factory environments. CPSs in combination with tracking technologies and a component based assembly line can create a factory environment that allows customers to change their requirements during assembly-time. Such change is typically not considered in the domain of manufacturing. In modern software engineering projects, agile techniques allow customer change during the entire development phase. Such change results in customer oriented, customized software products.**

In this paper we describe the development of an Agile Factory prototype. The developed Agile Factory prototype transfers agile software engineering techniques to the domain of manufacturing. It explores the impact and feasibility of customer changes during assembly-time using a commercially available software framework. The assembly line of the Agile Factory is component based, using trackable mobile worktables in combination with stationary workstations. Therefore, each product with its associated request is trackable during assembly-time which enables us to implement a customer feedback loop. The feedback loop allows change requests during assembly-time. Without the integration of such tracking techniques a customer feedback loop is very difficult up to impossible to implement. We created a Cyber-Physical Human System (CPHS) using smart factory-hardware in combination with an accepted manufacturing software framework. We bridge the virtual and physical world enabling the customer and the factory worker to communicate with actual physical objects.

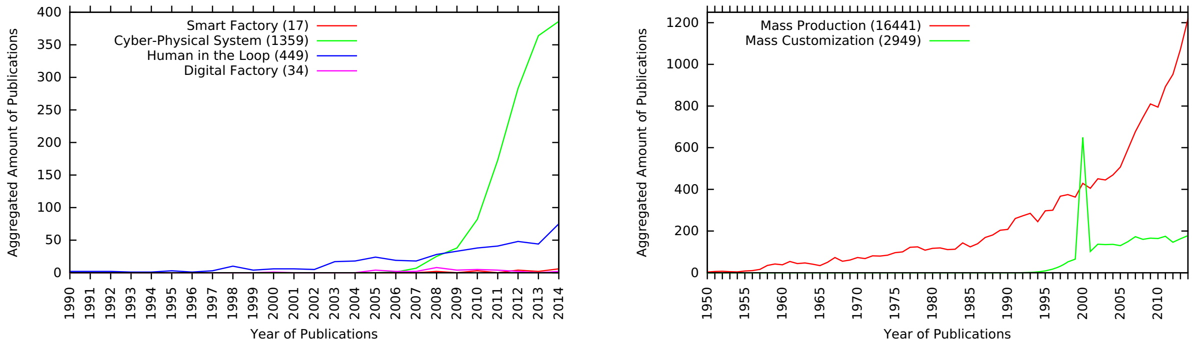
I. Introduction

Markets are facing an increasing need for individualized products [1]. Within research this need has been noticed since the late 90s claming the need to switch from mass production to mass customization (compare Figure 1b). Mass production is creating standardized products everybody can afford whereas mass customization claims that customers can find what they really want. Both production paradigms have the goal to be cost-effective during their production cycle [2]. The application of new management methods and the integration of new technology can enable the paradigm shift from mass production towards mass customization as Pine et. al. define it [3]. We claim that the idea of interconnected Cyber-Physical Systems that bridge the virtual and physical world, enabling us to communicate with actual physical objects, are key enabler for that paradigm shift. As Mark Weiser created the idea of information everywhere and anytime [4] we transfer this idea to the domain of manufacturing allowing change everywhere anytime. Such changes can be located outside a factory boundary such as the change of a product configuration or inside the factory boundary such as the rearrangement of the assembly line. We define such change as human triggered feedback. As such change serves as input for other processes and systems it can be defined as closed loop feedback [5]. The Agile Factory is implemented as Cyber-Physical Human System (CPHS). It covers the cyber domain by using the accepted manufacturing framework DESC and covers the physical domain including actual physical, smart objects into the assembly process. Finally, the Agile Factory is user centric as the worker and the customer serve as sensors and actuators. Moreover, the customer can influence the assembly process during runtime and receives detailed status updates (compare section II).

In software engineering customer requirement changes can be faced through modular software designs being flexible to meet customer expectations. The modular design can be realized by following the principle of product lines [6]. Such product lines use core assets for a software product assembly utilizing modularity, already shown 1996 at Carnegie Mellon University [7]. In addition, agile methods often decompose the software development process into sprints allowing customer feedback loops. This leads to customer oriented software solutions. In the area of software engineering it is common to deal with changing requirements from customers during the implementation phase (compare SCRUM agile method). The idea of agile software engineering concepts will be transferred to the manufacturing domain using low cost tracking technologies to establish a bidirectional customer-factory feedback channel. To integrate this feedback a prototype called Agile Factory was implemented. It uses the commercially available software framework from *DE software & control GmbH* called DESC[1]. To estimate the position of a worker, a low cost tracking technology based on Bluetooth Low Energy (BLE) was integrated into the DESC framework. This technology is used to extend

[1]DESC is an EN 62264-1:2008 (Enterprise-control system integration - Part 1: Models and terminology), EN 62264-2:2008 (Enterprise-control system integration - Part 2: Object model attributes), EN 62264-3:2007 (Enterprise-control system integration - Part 3: Activity models of manufacturing operations management) compliant software framework used in manufacturing environments.

978-1-4673-7785-0/15 $31.00 © 2015 IEEE
DOI 10.1109/CPSNA.2015.17



(a) Amount of publications at IEEE Digital Library aggregated by year.

(b) Amount of publications from IEEE Digital Library and Springer Link aggregated and averaged by year using the term: 'Mass Production' and 'Mass Customization'.

Fig. 1: Showing the amount of publications for the selected search terms. All data was acquired during March 2015.

the existing worker assistance system offered by DESC with automatic event triggering using BLE. Each part of the Agile Factory is equipped with an unique identifiable BLE device, creating a halo around each part. Such halos can be sensed and used to track the worker and offer context aware assistance services. A halo is as big as the transmission range of a BLE device. The idea of the halos was inspired by the idea of auras [8] and can also be defined as a certain region around the BLE device.

This paper is structured as follows: First the term Cyber-Physical Human System is explained in Section II. Section III describes the problem statement of the project followed by a detailed description of the prototype and the system design in section IV and V. Section VI offers our findings. Section VII summarizes the paper and its contribution.

II. Cyber-Physical Human Systems in Manufacturing

A CPS is capable of monitoring and controlling physical processes, bridging between the virtual and physical world offering new communication channels [9]. Moreover, CPSs are interconnected and can process feedback [10]. CPSs are highly cross-functional and therefore cover many different domains, such as transportation, health-care, manufacturing, agriculture, energy, defense, aerospace, buildings and more general public environments [11]. In this paper we focus on the domain of manufacturing including human feedback as a central part of a CPS - we name it Cyber-Physical Human System (CPHS).

In literature other factory types beside our *Agile Factory* have been defined focusing on different aspects in modern production sites. The *Smart Factory* can be defined as where “the research focuses clearly on the use of innovative information and communication technologies in automated systems and on the resulting challenges in the design of such systems” [12]. The *Ubiquitous Factory* [13] focuses on information transparency, autonomous control and sustainable manufacturing. The *Factory of Things* ”is context aware and assists people and machines in their task execution by using calm-systems that are operating in background” [14]. The *Real-Time-Factory* utilizes RFID tracking during production in real-time reporting errors that may occur [15]. The *Agile Factory* as designed in this paper is combining aspects of the *Smart Factory* and the *Factory of Things*. Moreover, we integrate humans as a feedback source that have direct impact on processes within the *Agile Factory*. We define the *Agile Factory* as a Cyber-Physical Human System as it covers all three design spaces: the *Cyber*, the *Physical* and the *Human* space. The *Cyber* space is covered by using commercially available production software. The *Physical* space is covered by using actual physical objects such as worktables and workstations as an information source being able to communicate with the *Cyber* and *Human* space. The *Human* space is covered by the creation of a feedback loop between the worker and the customer as well as a feedback channel within the boundaries of the *Agile Factory*.

To get an impression about ongoing research, we have examined different data sources (compare Figure 1). As shown in Figure 1a the aggregated amount of publications concerning the terms Smart Factory, Cyber-Physical System, Human in the Loop and Digital Factory are shown over time. The publication rates for the terms CPS and Human in the Loop are increasing, yet the publication rates concerning Smart and Digital Factory are relatively low. We claim the research field of Cyber-Physical Systems has strong impact on the domain of manufacturing and that modern factory systems as the *Agile Factory* can be seen as a CP(H)S. Figure 1b shows the amount of publications for the two terms 'Mass Production' and 'Mass Customization'. As the term mass production has been present since the early 50s the term mass customization starts to gain interest in the late 90s. Since the last 10 years both terms are used more frequently in publications. In the year 2000 the term mass customization had a peak followed by a linear growth afterwards. We claim that the transformation of a factory into an interconnected CPHS makes mass customization feasible.

III. Problem Statement

The integration of new technologies can improve efficiency, productivity, workflows, operational safety and security in factory environments. In a workshop such an integration was discussed before implementing this prototype as well as after the prototype was finished with experts from *DE software & control GmbH* and with experts specialized in the field of

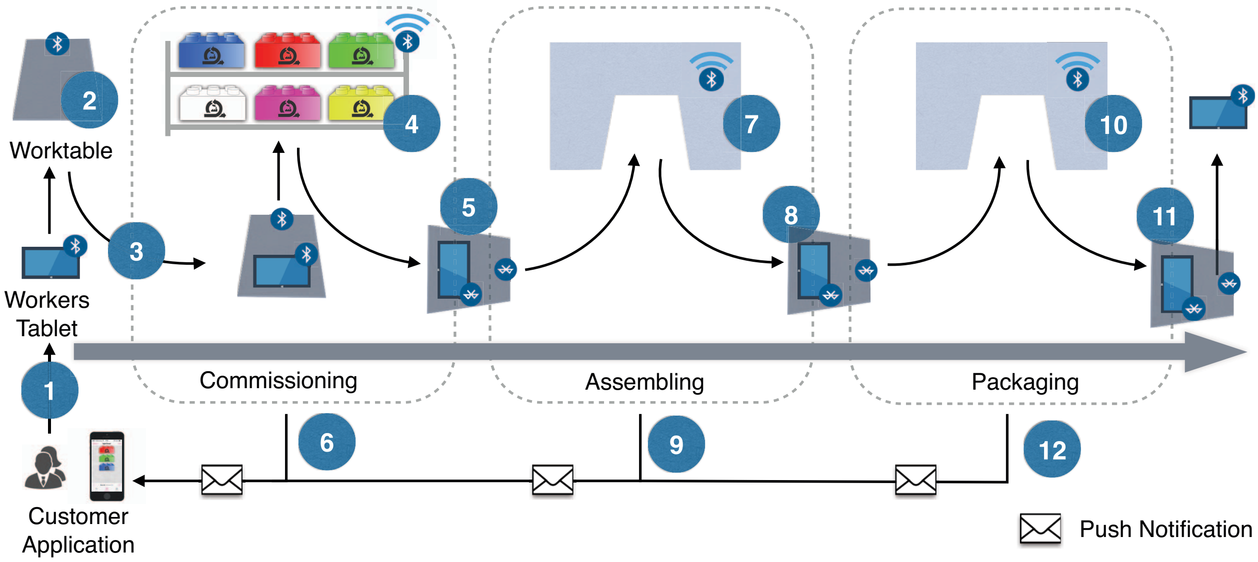


Fig. 2: Design of the Agile Factory with mobile worktables, a tablet and halos around the stationary workstations. The customer receives automatic status updates via push notifications and can reconfigure the product during assembly-time. In case this happens the worker will receive instructions accordingly on his tablet and may go back to the Commissioning station. Due to readability reasons, the feedback channel in case a customer changes the product during assembly is left out.

Industry 4.0[2] at T-Systems International GmbH.
As a result of the performed workshops main problems and challenges have been identified. The automation of events such as the trigger when a specific task starts and ends is of great interest. Such automation improves horizontal and vertical monitoring, the reliability of data and offers a detailed insight into factory efficiency. Each worker at a stationary workstation normally triggers such events manually. In case the worker is wearing gloves, is using tools, is carrying something or simply forgets to trigger the event can interfere with the workflow and the monitoring process. Additionally, the tracking and localization of a request (product order) and the mapping to the mobile working table is challenging, especially in case the assembled product is not produced in a sequence but with interruptions. Another finding was the lack of detailed assembly line status updates that can be realized using applicable tracking technology. Automated assistance of the worker, navigation tasks as well as the localization of each worker are additional challenges to be faced.
As a result of the discussions a problem statement has been created describing the functional and nonfunctional requirements for the Agile Factory prototype. To explore the defined problems we intended to implement the prototype using a commercially available software framework to profit from know-how of experts in their domain. The integration of BLE devices to automatically trigger events will improve the existing worker assistance system. Therefore, we defined a simple product, which will be assembled in the Agile Factory to minimize the product cycle complexity. With the design of mobile worktables that fit in the stationary workstations we redesigned the classic mapping of worker and workstation.

[2] A German governmental initiative dealing with the forth industrial revolution.

IV. Agile Factory - A Cyber-Physical Human System

The prototype was planned and implemented during a 6 months project. The extension of the software framework was implemented with the support of a software engineer of *DE software & control GmbH*. Students, under the supervision of one project leader from T-Systems International GmbH and a coach following the Tornado Model [16], have implemented the Agile Factory as well as the customer application. The hardware setup of the factory has been designed from scratch and custom-build, covering three production steps each represented by a stationary workstation: Commissioning, Assembling and Packaging (compare Figure 2 (4), (7), (10)). Each workstation is equipped with a BLE device. As the BLE device is continuously sending out beacons it is defining a halo around it (compare Figure 2 dashed line). The workstations have been designed in such a way that the mobile worktable can easily fit into each stationary workstation (trapezial-design). Each worktable is also equipped with a BLE device. The following two paragraphs describe the product definition and customer application as well as the assembly line in detail.

Product Definition and Customer Application: In the Agile Factory a customized colored Duplo™ Tower can be ordered (compare Stones in Figure 2 (4)). The Duplo™ Tower is assembled in the desired order and colors of the customer. To place a product order the customer uses the implemented iOS application. The customer can configure a Duplo™ Tower in the desired colors. As soon as the customer finishes the configuration and sends the product order to the Agile Factory backend server, the corresponding worker receives the request on his Worker Device. As the worker starts to follow the instructions diplayed on his worker device the customer receives instant status updates via push notifications and can monitor the progress of his product. In case the customer changes the product definition during assembly-time the worker receives a push notification and gets instructions about the next steps.

Assembly Line: After the factory-hardware- and product-setup, the workflow for the worker in the factory was defined in detail. As soon as a request is ready for assembly (1) the worker selects an available worktable from the stock. As each worktable is equipped with a BLE device the tablet of the worker can sense available worktables. The tablet will automatically connect the selected request with the mobile working table in case the signal strength is greater or equal the configured threshold. After that, the worker receives seamlessly the first instruction: Go to the Commissioning workstation (2). As soon as the worker enters the halo of the Commissioning workstation the next instructions are displayed on the tablet (3). Typically, the required amount of material is displayed. As soon as the worker has picked all needed material he can manually set the task to the status finished, or in case he forgets it, this will automatically be triggered in case he leaves the halo of the Commissioning workstation (5). Steps (7), (8) and (10) work accordingly. During all tasks the customer is automatically informed about the status of his product ((6), (9) and (12)). As soon as the entire process has finished the worker can unpair the mobile worktable with the tablet (11) and the process can start at (1) again. At any point the customer can modify his order according to his desires. In case this happens, the worker receives instantly a push notification that the customer has changed the product request.

V. SUBSYSTEM DECOMPOSITION

The `Mobile Customer Application` (compare Figure 3) encapsulates the mobile applications to create, monitor and manipulate an order. The customer can create a new order for a Duplo™ Tower. The product definition and maximum parts allowed are stored in the `BACKBONE.DE`. The `Mobile Customer Application` loads the definition dynamically as well as the images and description of the parts. Additionally, the customer can manipulate the product order in an extra view. The customer can add, delete and reorder each part according to his wishes. Finally, the subsystem offers a monitor screen in which the customer can find detailed information about the status of his product. In this case study an iOS Application was implemented that is using RESTful services offered by the `Webserver`. As a persistence component a `MS SQL Server` is used. The backend of the Agile Factory is the `BACKBONE.DE` from the DESC software framework. The data model of the DESC system, called 'MetaModel', can be configured with a .xsd file and is deployed to the database offering high flexibility concerning the factory setup. The 'MetaModel' defines the factory products and the assembly process of the product. For this purpose the DESC system provides a basic business object structure, which has to be used. The `BACKBONE.DE` maps the 'MetaModel' to the database. `BACKBONE.DE` loads the MetaModel as soon as its process gets started and provides it to the DESIGNER.DE and the `VIEWER.DE`. The DESIGNER.DE is used to configure the User Interface of the `VIEWER.DE` and is not mentioned in the deployment diagram due to space reasons. The `Worker Device` is subdivided

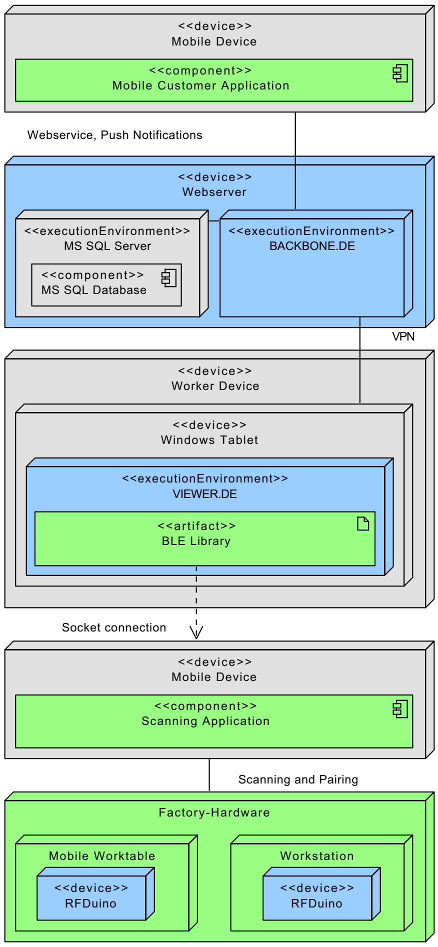


Fig. 3: Deployment diagram of the Agile Factory. Green components have been developed and designed from scratch, blue components have been adapted and extended, gray components existed and have been used.

due to current interface limitations. The BLE scanning is handled by an additional `Mobile Device` that does the BLE scanning. The received averaged signal strengths of each visible BLE device are send via socket connection to the `Windows Tablet` using JSON Objects. On the `Windows Tablet` the `VIEWER.DE` is running. It offers the worker detailed information about each step that needs to be done within one workstation (e.g. take 2 blue, 1 yellow and 1 red stone out of the commissioning shelf). The `VIEWER.DE` is using the developed `BLE Library`. It contains the pairing logic and receives the Received Signal Strength Indication (RSSI) thresholds which define the actual halo expansion of each `Factory-Hardware` from the `BACKBONE.DE`. These thresholds can be changed during runtime according to the topology of the Agile Factory. The `Factory-Hardware` consists of three `Worktable` and three `Workstations` which are all equipped with battery driven RFDuinos.

VI. FINDINGS

The Agile Factory is a successful proof of concept. After the prototype was implemented, it was demonstrated in a workshop to experts from university and industry and received great feedback. All findings are presented in this section.
The BACKBONE.DE needs to offer interfaces to integrate mobile devices in a convenient way. The need for mobility and the integration of wearables as a comfortable alternative to the currently used worker tablet have been pointed out. The implementation of a customer feedback loop was successfully demonstrated and gained great acceptance and created room for discussions. Especially constant order changes have a huge impact on logistics and the factory management layer the Agile Factory concept is not applicable for some use cases, but the shipbuilding industry or rapid prototyping scenarios are imaginable scenarios for steady customer requirements changes. The big challenge is to define product lines that are able to handle such customer demands supported by tracking and tracing technologies.
Additionally, the need for evaluations concerning channel interference and parallel operation of devices that share the 2,4 GHz ISM band are missing. The guarantee of Quality of Service (QoS) is an open issue and important in such a CPHS. The halo threshold estimation has been done manually and can be supported by machine learning techniques to automatically estimate an appropriate value. In case even the workstations are getting mobile this issue needs to be solved.
The prototype did not focus on the ruggedized integration of the hardware. The rationale for applicable BLE devices is missing. Generally the integration of halos into the manufacturing domain received a positive feedback from our industrial partners and is a great proof of the integration of consumer technology into the domain of manufacturing. An integration of consumer hardware into the domain of manufacturing is, according to our experts, not common. The potential and benefit of such hardware has been demonstrated in our prototype and experts claim that such an integration is inevitable to improve factory environments. The next section summarizes our paper.

VII. CONCLUSION

In the planning phase of the Agile Factory prototype, workshops with experts at T-Systems International GmbH and DE software & control GmbH have been conducted to discuss current problems and to find out needs in the domain of manufacturing. As a result of those workshops the Agile Factory project has been set up. In this paper we described the prototype Agile Factory, the used technology and its implementation. The prototype transfers agile software engineering techniques to the domain of manufacturing. To the best of our knowledge, such a transfer connected with BLE tracking technologies has not been implemented yet. The Agile Factory offers an automatic event triggering mechanism based on BLE in connection with mobile worktables and stationary workstations. Additionally, a bidirectional feedback channel between the customer and the Agile Factory has been implemented to offer the possibility of product order modification during assembly-time. The prototype has successfully been demonstrated to representatives at university and industry. The Agile Factory successfully proved the applicability of a customer feedback loop and it showed the potential of integrating consumer technologies into the domain of manufacturing. The authors claim that consumer technologies have a huge potential in the domain of manufacturing in future. Moreover, the approach to use an accepted manufacturing software framework such as DESC turned out to work much better than expected by all included parties. The prototype is part of innovation workshops with industrial partners and the next project phase with the aim to extend the Agile Factory is currently in progress.

ACKNOWLEDGMENTS

The authors would like to thank Friedrich Steininger and Richard Hierlmeier for their support during the development of this prototype as well as Sara El-Shinnawi, Christian Fruehauf, Alexander Galtsev, Magnus Jahnen, Michael King, Martin Schwoerer and Maximilian Strobel for their great effort during the project phase.

REFERENCES

[1] K. Moser, *Mass Customization Strategies: Development of a Competence-based Framework for Identifying Different Mass Customization Strategies*. Lulu.com, 2007.

[2] C. Chandra and A. Kamrani, *Mass Customization: A Supply Chain Approach*. Springer US, 2004.

[3] B. Pine and S. Davis, *Mass Customization: The New Frontier in Business Competition*. Harvard Business School Press, 1999.

[4] M. Weiser, "Ubiquitous computing," 1993.

[5] K. Aström and R. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, 2010.

[6] K. Pohl, G. Böckle, and F. J. v. d. Linden, *Software Product Line Engineering: Foundations, Principles and Techniques*. Secaucus, NJ, USA: Springer-Verlag New York, Inc., 2005.

[7] L. Brownsword and P. Clements, "A case study in successful product line development," 1996. [Online]. Available: http://sunner.cn/courses/SA/Case%20Study%20in%20Successful%20Product%20Line%20Development.pdf

[8] D. Garlan, D. Siewiorek, A. Smailagic, and P. Steenkiste, "Project aura: Toward distraction-free pervasive computing," *IEEE Pervasive Computing*, vol. 1, no. 2, pp. 22–31, Apr. 2002. [Online]. Available: http://dx.doi.org/10.1109/MPRV.2002.1012334

[9] R. Raj, I. Lee, and J. Stankovic, "Cyber-Physical Systems : The Next Computing Revolution," pp. 731–736, 2010.

[10] E. Lee, "Cyber physical systems: Design challenges," in *Object Oriented Real-Time Distributed Computing (ISORC), 2008 11th IEEE International Symposium on*, May 2008, pp. 363–369.

[11] I. Lee, L. Sha, and J. Stankovic, "Cyber-physical systems: The next computing revolution," 2010. [Online]. Available: http://www.cse.psu.edu/~xydong/files/proceedings/DAC2010/data/papers/2010/44.1.pdf

[12] D. Zuehlke, "SmartFactorytowards a factory-of-things," *Annual Reviews in Control*, vol. 34, no. 1, pp. 129–138, 2010. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1367578810000143

[13] J.-S. Yoon, S.-J. Shin, and S.-H. Suh, "A conceptual framework for the ubiquitous factory," *International Journal of Production Research*, vol. 50, no. 8, pp. 2174–2189, 2012. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/00207543.2011.562563

[14] D. Lucke, C. Constantinescu, and E. Westkmper, "Smart factory - a step towards the next generation of manufacturing," in *Manufacturing Systems and Technologies for the New Frontier*, M. Mitsuishi, K. Ueda, and F. Kimura, Eds. Springer London, 2008, pp. 115–118. [Online]. Available: http://dx.doi.org/10.1007/978-1-84800-267-8_23

[15] B. Hameed, F. Durr, and K. Rothermel, "Rfid based complex event processing in a smart real-time factory," *Expert discussion: Distributed Systems in Smart Spaces*, 2011.

[16] B. Bruegge, S. Krusche, and M. Wagner, "Teaching tornado: from communication models to releases," in *Proceedings of the 8th edition of the Educators' Symposium*. ACM, 2012, pp. 5–12.

Reprint Permission

Copyright Clearance Center RightsLink®

Home | Create Account | Help

IEEE
Requesting permission to reuse content from an IEEE publication

Title: Agile Factory - An Example of an Industry 4.0 Manufacturing Process

Conference Proceedings: Cyber-Physical Systems, Networks, and Applications (CPSNA), 2015 IEEE 3rd International Conference on

Author: Constantin Scheuermann; Stephan Verclas; Bernd Bruegge

Publisher: IEEE

Date: 19-21 Aug. 2015

LOGIN

If you're a copyright.com user, you can login to RightsLink using your copyright.com credentials. Already **a RightsLink user** or want to learn more?

Thesis / Dissertation Reuse

The IEEE does not require individuals working on a thesis to obtain a formal reuse license, however, you may print out this statement to be used as a permission grant:

Requirements to be followed when using any portion (e.g., figure, graph, table, or textual material) of an IEEE copyrighted paper in a thesis:

1) In the case of textual material (e.g., using short quotes or referring to the work within these papers) users must give full credit to the original source (author, paper, publication) followed by the IEEE copyright line � 2011 IEEE.
2) In the case of illustrations or tabular material, we require that the copyright line � [Year of original publication] IEEE appear prominently with each reprinted figure and/or table.
3) If a substantial portion of the original paper is to be used, and if you are not the senior author, also obtain the senior author�s approval.

Requirements to be followed when using an entire IEEE copyrighted paper in a thesis:

1) The following IEEE copyright/ credit notice should be placed prominently in the references: � [year of original publication] IEEE. Reprinted, with permission, from [author names, paper title, IEEE publication title, and month/year of publication]
2) Only the accepted version of an IEEE copyrighted paper can be used when posting the paper or your thesis on-line.
3) In placing the thesis on the author's university website, please display the following message in a prominent place on the website: In reference to IEEE copyrighted material which is used with permission in this thesis, the IEEE does not endorse any of [university/educational entity's name goes here]'s products or services. Internal or personal use of this material is permitted. If interested in reprinting/republishing IEEE copyrighted material for advertising or promotional purposes or for creating new collective works for resale or redistribution, please go to http://www.ieee.org/publications_standards/publications/rights/rights_link.html to learn how to obtain a License from RightsLink.

If applicable, University Microfilms and/or ProQuest Library, or the Archives of Canada may supply single copies of the dissertation.

BACK ��� CLOSE WINDOW

4.2 ILAS: A Case Study of a Cyber-Physical Human System

This publication (Publication [B]) combines a smart textile with a wearable solution to support humans during maintenance processes. We propose the Incident Localization and Assistance System (ILAS) that is capable to handle typical maintenance processes. It transfers incident management knowledge to the domain of manufacturing.

Conference: International Conference on Communications (ICCC): International Workshop on Internet of Things
Number of Pages: 5
Type: Full Paper at Workshop
Review: Peer Reviewed (3 Reviewers)

The author of this dissertation designed the approach of the Incident Localization and Assistance System (ILAS) and created the connected Incident Management Lifecycle (IML). He designed the concept of the ILAS, which includes the BLE-beacon-based approach in combination with a smartphone application and a smart glove. The author claims the major contribution of the item creation used within the conducted survey. The author designed the system architecture and selected the necessary protocols.

Goal

ILAS uses a smart glove with an intelligent wrist band. The maintenance worker can locate incidents in a production line. The maintenance worker can check the functionality of sensors in a production line using the smart glove. LEDs on the wrist band display the result of the functionality check. Each conducted step during this workflow is instantly documented and stored at an application server. An additional mobile device allows the worker to add and access multimedia content such as images, text and sound, which is necessary to document and understand the incident.

Approach

We implemented a vertical prototype using a smart glove from our research partner ProGlove. We conducted a conceptual implementation, which builds the foundation for our further CPS applications in the publications C and D. We gathered knowledge about how to use and integrate such a smart glove into professional work environments.

Results

We defined an incident management workflow for production sites that includes a smart glove in combination with a wearable device. We successfully demonstrated the advantage of such a system to our project partners. We used one of the first prototypes from ProGlove and extended it while embedding it into a professional workflow.

Metamodel Contribution

We could instantiate the cyber-physical system metamodel to support interdisciplinary cooperation. We could extended our stereotypes and introduced smarttextiles, wearables, computers as new stereotypes. The composite pattern helped us to model the used MES as separate cyber-physical system and offered an abstraction that helped us to understand the system.

In Publishing Process

IEEE/CIC ICCC15
2-4 November 2015, SHENZHEN, CHINA

IEEE/CIC International Conference on Communications in China

Prof. Qinyu Zhang
C210, Communication Engineering Research Center
School of Electronic and Information Engineering
Harbin Institute of Technology Shenzhen Graduate School
University Town of Shenzhen
Shenzhen, Guangdong, P.R. China
Telephone: +86-755-26033786
Email: zqy@hit.edu.cn

May. 18, 2017

Dear Mr. Constantin Scheuermann,

On behalf of the organizing committee of **IEEE/CIC International Conference on Communications in China (ICCC) 2015**, I would like to extend our sincere gratitude for your kind support to this event. Your paper '**Incident Localization and Assistance System: A Case Study of a Cyber-Physical Human System**' has been accepted by 2015 IEEE/CIC International Conference on Communications in China: 2015 IEEE/CIC ICCC IoT Workshop.

The fourth IEEE/CIC International Conference on Communications in China (ICCC 2015) and its workshops have been held in the magnificent city of **Shenzhen**, Guangdong, China, **2-4 November**, 2015. ICCC 2015 aimed at addressing a key theme on "Intelligent Communications for a Connected Cyberspace". This conference featured world-class plenary speakers, major technical symposia, industry and academic panels, tutorials and workshops.

This letter is to claim that you have presented your accepted paper in ICCC'15. Due to several issues, we are still trying our best to publish workshop papers in IEEE. You will be notified if we have any update regarding the publication issue.

The IEEE Communications Society embraces all aspects of the advancement of the science, engineering, technology and applications for transfer of information between locations by the use of signals. This includes: sources and destinations involving all types of terminals, computers and information processors; all pertinent systems and operations to bring about this transfer; guided and unguided transmission media; switched and unswitched networks; and network layouts, protocols, architectures and implementations.

China Institute of Communications (CIC) is the major academic exchanges and educational platform of information and communications technology in China. CIC is the main force in the popularization of science, the main representative of international and non-governmental scientific and technical exchanges, and the home of information and communication technology workers around the country.

If you have any further questions or concerns that I can address, please feel free to contact me.

Sincerely yours,

Prof. Qinyu Zhang
IEEE/CIC ICCC 2015 Technical Program Chair

4.3 Increasing the Support to Humans in Factory Environments using a Smart Glove: An Evaluation

This publication (Publication [C]) proposes and evaluates a smart glove based approach to support workers to manage warehouses inventories.

Conference: International Conference on Ubiquitous Intelligence & Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People, and Smart World Congress

Number of Pages: 8

Type: Full Paper

Review: Peer Reviewed (4 Reviewers)

The author of this dissertation designed the approach of how a smart glove can be used in combination with a smartwatch to enhance a typical logistic process. He created the concept of how a two-button approach avoids unnecessary interaction with a smartwatch. The author defined the user interface guidelines that lead to a tight connection between software and hardware interface design. The author created the qualitative and quantitative user study design, the categorization of the qualitative items, the item selection as well as the selection of the quantitative measurements. He led the evaluation of the prototypes and conducted the evaluation together with Maximilian Strobel.

Goal

The goal of this CPS application was to further improve our smart glove prototype and to evaluate two versions of the smart glove. We wanted to compare our solution to established devices, such as handheld scanners, within the domain of logistics. Our goal was to evaluate to which extent our prototypes can improve a typical logistic workflow.

Approach

We realized a conceptual implementation of two smart glove prototypes and a handheld scanning device with its corresponding hardware and software. We conducted a controlled lab experiment with a qualitative and quantitative evaluation.

Results

We evaluated two new smart glove prototypes additionally to a smartwatch application. We proposed a scan-based number input method and evaluated it. We added a confirmation button to the smart glove to reduce interaction with the smartwatch. We conducted a lab experiment with 30 participants and could show that error rates using a smart glove can be reduced up to 66%. The smart glove variants excel the handheld variant. Our results show that 63,33% of the participants preferred the two button smart glove variant, 33,33 % the one button smart glove variant and 3,33 % the handheld variant.

Metamodel Contribution

The abstractions of the metamodel helped us to transfer the initial idea of incident management to the domain of logistics. The high level of abstraction enabled us to identify new use cases that we implemented and evaluated within this publication. The formative research procedure supported us to extend the metamodel. We added Persons to the metamodel as part of the Smart Environment and extended the Smart Objects stereotypes with microcontroller.

Increasing the Support to Humans in Factory Environments using a Smart Glove: An Evaluation

Constantin Scheuermann*, Maximilian Strobel¶, Bernd Bruegge**
Department of Computer
Science, Technische
Universitaet Muenchen
*constantin.scheuermann@in.tum.de
¶maximilian.strobel@in.tum.de
** bruegge@in.tum.de

Stephan Verclas
T-Systems International GmbH
stephan.verclas@t-systems.com

Abstract—**Humans are an essential part of the manufacturing domain. In factory environments the support to humans can offer benefits. Such benefits can for example be monetary as processes are accelerated and time can be saved. Benefits can also be ergonomic improvements offering hands-free operations during daily tasks. Hands-free operations are of special interest in case both hands are needed during a task. Lifting heavy parts is a typical scenario during commissioning processes that can impede necessary scanning processes. Currently, handheld scanners are used in many industries during commissioning processes. The disadvantage of such scanners is that during the usage, the worker is left with only one free hand. In this publication we conducted a quantitative and qualitative user study and compared three variants during a typical commissioning process. We used a smart textile that integrates the scanning unit into a glove from our project partner and extended it. We developed two smart glove variants in combination with a smartwatch application. One variant offers a semi and the other one a totally hands-free operation during the commissioning process. We compared it to one of the smallest, commercially available scanning handheld devices. Our results show that the developed approaches offer benefits concerning the support to humans, reduce the physical fatigue of the arms, hands and fingers and increase the user acceptance. We show that the time variance while using the smart glove variants is smaller compared to the handheld variant. Also the amount of errors is reduced by 66% percent. The proposed approaches are promising and we are already in contact with partners from the aviation and automotive domain to further improve our proposed variants.**

I. Introduction

In professional environments support to humans is essential. Such support can focus on ergonomics concerning the working environment, on the optimization of workflows and on increasing efficiency during daily tasks and routines. As in many professional work environments humans are still essential, such support must be human oriented and not technology oriented. User acceptance, the reduction of physical fatigue as well as a good guided user interaction are success factors for the introduction of new technologies and approaches.

During the last decades tiny, energy efficient and powerful hardware devices have been developed. They allow us to connect them to sensors and actuators that are directly integrated into textiles. Such textiles become smart and in combination with wearable devices they offer possibilities to improve the support to humans. This support is not limited to a certain domain but in this paper we focus on the manufacturing and factory domain.

Processes and workflows in factory environments are highly individual and can differ between enterprises even in the same domain. But still industries share some processes that are commonly used. A prominent example is the scan of optical transmission patterns such as barcodes or QR-Codes. Scanning takes place during warehouse management, is used for documentation purposes, to create product histories or is used during commissioning tasks to identify products. As such tasks are common and frequent, optimizing them involves a potential for the enterprises as well as for the involved humans. Human oriented systems should increase the support to humans focusing on user acceptance on an early stage of the development phase. Such systems should consider the motivation of use with the goal to increase efficiency. Especially in factory environments the integration of smart textiles should include accepted, already used or even mandatory protective textiles. In this publication we are focusing on the use of smart gloves in combination with a smartwatch.

Product identification, package handling and the transportation to the storage are typical logistic processes. Hands-free operations can have a positive effect on operational safety, error-rates, ergonomic aspects, efficiency and the motivation of the staff. To increase the support to humans we developed together with our partner ProGlove two new prototype variants that are able to support humans during logistic processes. To evaluate these new variants we conducted a lab experiment to explore the benefits of smart textiles to substitute established handheld scanners. We defined a common workflow, qualitatively and quantitatively explored the benefits of our proposed variants and evaluated the three variants.

This publication is structured as follows. In Section II we summarize related work. Section III describes the addressed problem. In Section IV we provide a detailed description of the developed variants. In Section V we present the underlying workflow for the conducted user study. Section VI illustrates the setup and how we conducted our user study. The results of the user study are shown in Section VII, VIII and IX. Section X concludes our work and provides an outlook.

Fig. 1: **Prototype Variants:** The figure shows our three variants (from left to right): the handheld scanner, the smart glove with one button and smartwatch, and the smart glove with two buttons. The variants simulate a 'hands occupied' scenario (handheld scanner), a 'semi hands-free' scenario (one button) and a 'hands-free' scenario (two buttons). The annotated numbers mark the features of each variant as described in the text.

II. Related Work

Wearables are computational devices of any kind, worn on a (human) body. Wearables have been a prominent research topic in science for decades and cover many domains such as the health domain [1] and the industrial domain [2]. Wearables are used to support humans during their daily tasks. Typical examples for such devices are smartwatches and smart glasses. As the needed hardware has become smaller, more energy efficient and possesses more calculation power and storage, such hardware offers great possibilities to connect and integrate it into textiles.

Smart textiles have integrated sensors or actuators that can react to certain signals or stimuli [3]. Other terms such as 'smart fabrics' or 'intelligent fabrics' exist that slightly differ in terms of the integration of connectors, conductors or microsystems.

Combining wearables and smart textiles is a promising approach to offer support to humans. Monitoring systems such as health monitoring shirts are used for health applications as well as for (professional) sport applications. Such shirts are commercially available[1]. They are used in combination with a technical unit, which is in many cases connected to a smartwatch. In this publication we focus on smart gloves as an accepted textile in industrial environments and combine them with a smartwatch.

Several research concerning smart gloves has been conducted already. Within the health and medical sector smart gloves are used to detect the status of diseases such as Parkinson [4]. Also approaches exist that help patients during their rehabilitation phase using an Intelligent Haptic Robot-Glove [5]. It serves as an exoskeleton to support the human hand. A RFID glove to assist people with memory loss has been developed. The glove can scan RFID tags attached to objects while performing routine tasks. The glove remembers people of a certain task in case they are distracted or have forgotten it. Two use cases have been addressed, a kitchen routine task monitor and a medicine reminder [6]. Another glove prototype tracks the 'activities of daily living' by defining object-touch sequences in combination with a probabilistic system. It senses the environment twice a second and send the results to a wearable computer [7].

In professional environments the combination of smart textiles and wearables can be used to support factory workers during daily tasks. Gloves equipped with RFID readers have been part of research within the manufacturing domain [8] during commissioning processes. Another developed RFID glove supports humans during inventory tasks [9]. A smart glove prototype was implemented that supports factory workers during the incident management process in production lines. A smart glove was used in combination with an intelligent device attached to the wrist of the worker [10]. An extensive overview concerning smart glove prototypes can be found in the survey provided by Laura Dipietro et. al [11]. The authors mention that the applications cover information visualization, robotics, arts and entertainment, sign language understanding, medicine, computers and manufacturing. They categorize the glove applications into classical and recent applications. Within the recent applications the combination with wearbales is mentioned. The introduced smart glove in this publication combines the glove with wearable technology and integrates a certain amount of intelligence and hardware into the textile itself.

III. Problem

Within factory environments lean manufacturing is a common term. It tries to identify and eliminate waste (non value-added activities) [12]. This can be targeted on the actual shop floor organization and workstation management but also on single workflow improvements. Factory environments, logistics and warehouse management can be improved focusing on different aspects. One can focus on the worker's efficiency, the ergonomic arrangement of tools and the connected user comfort, as well as the user's intrinsic motivation to use a

[1] Ambiotex, LiveAtos

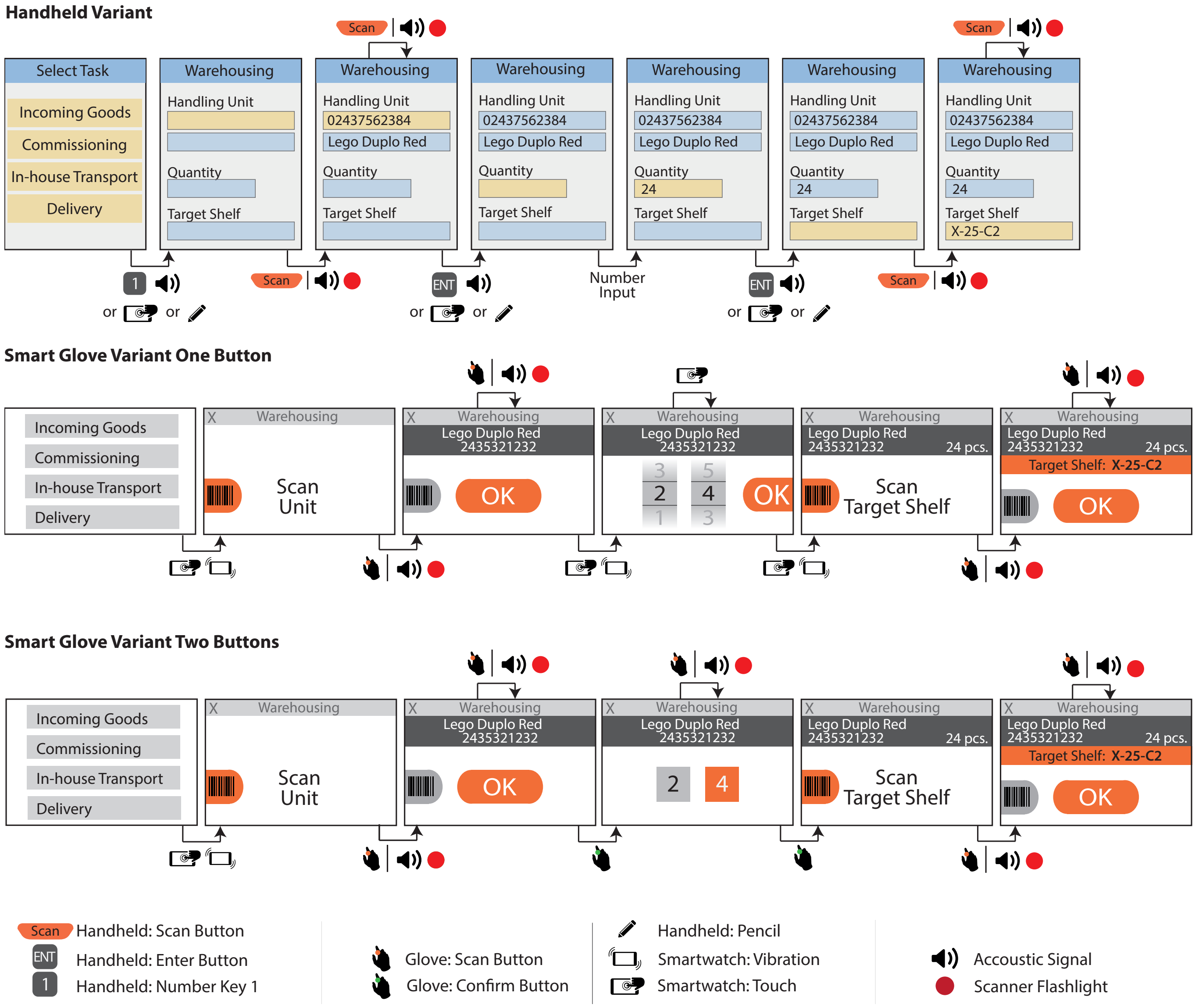


Fig. 2: **User Interfaces of the Three Different Variants:** The figure shows the three different user interfaces for each variant including their segues. The corresponding icons illustrate the user inputs and visual, tactile as well as audio feedback. In the first row the handheld user interface is shown. The second row shows the one button variant and the last row the two buttons variant. All workflows are terminated pressing the enter or OK button on the handheld device, smartwatch or smart glove

certain technology.

In logistics, accurate package handling and the avoidance of mistakes, lapses and slips are essential to keep costs at a minimum. In logistics scanning barcodes is a very common task. This is usually done using handheld scanning devices that occupies at least one hand of the worker. In case heavy packages or products have to be lifted and scanned such devices might not fit into the work environment and are not ergonomically integrated into the workflow. Physiological consequences for the worker due to poorly designed work environments need to be avoided.

If a handheld device impedes the worker in any kind, it can result in a decreasing motivation to use such devices. The offered technological support should intrinsically motivate the worker during daily routines. In the best case such a motivation can be beneficial for the entire workflow and process.

Especially in logistics, time and the correct execution of the workflow is essential for cost efficiency and customer satisfaction. In case the wrong number has been entered, the wrong package has been scanned or the wrong target shelf has been scanned the consequences are connected to avoidable costs.

Operational safety is of special interest as soon as humans are involved. In case one hand or even two hands are occupied with a handheld scanner, risks might appear. We assume that the worker needs to lift a heavy package or needs to commission something. The probability of dropping the package or dropping the handheld scanner increases.

(a) Incoming Goods Station (b) Incoming Goods Station Detailed (c) Commissioning Station

Fig. 3: **Setup of the User Study:** The pictures show our shop floor hardware setup. Picture 3a shows the 'Incoming Goods Station'. It shows the setup for the two buttons variant with the offered digit scan panel. The detailed view in picture 3b of the 'Incoming Goods Station' shows the package and the units (8 duplo® stones). The last picture 3c shows the 'Commissioning Station' with the attached barcode on the target shelf.

To address the mentioned problems we developed three variants that can be used during a typical commissioning process. The variants focus on semi and totally hands-free operations during a simulated commissioning workflow. For the smart glove variants we used a glove with a directly integrated scanning unit. In combination with a smartwatch we tried to substitute handheld scanning devices for the defined workflow. The following chapter introduces the developed variants in detail.

IV. Variants

We use three variants for our evaluation: handheld variant, smart glove one button variant and the smart glove two buttons variant. For the handheld variant we used a commercially available handheld scanner. For the smart glove variants we used one of the first ProGlove prototypes from our project partner and extended them with a smartwatch application and for the two buttons variant we extended the one button variant with an additional button.

Handheld Datalogic: For the handheld variant we used a Datalogic Memor X3 Mobilterminal equipped with a touch screen and a small pen. It is a very small device that is able to scan barcodes and to enter numbers using hardware buttons. It runs on Widnows CE 6.0 and can be programmed using the Microsoft .NET Compact Framework. The navigation can take place in three ways: using the integrated keyboard, using the integrated small pen or just tapping on the display via touch input. The display is as big as the screen of the smartwatch used for the remaining two variants. Fig. 1 shows the handheld variant. (1) shows the scan button in orange and (2) show the enter button used to browse through the input fields.

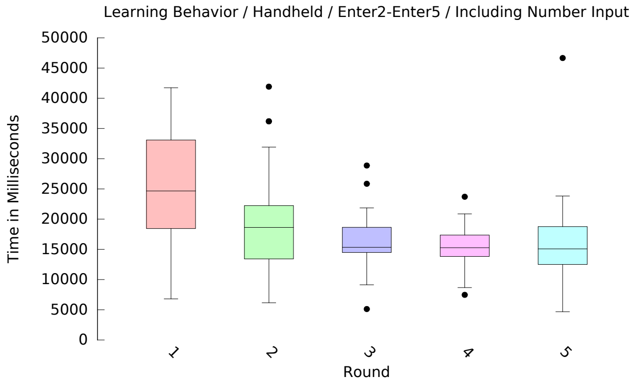
Smart Glove One Button: This variant is equipped with an integrated button (see Fig. 1 (3)). (4) indicates the removable scanning unit. This setup was provided by our project partner. The scanning unit sends the scanned barcodes via 868 MHz to a receiving unit. This unit can be attached to a computer via USB. In our setup the implemented software on the computer receives the scanned and decoded barcode. It then publishes the decoded barcode string to an MQTT Broker following a specified topic scheme. The smartwatch (5) is subscribed to this topic and can receive the barcodes via MQTT and WLAN. We used a Neptune Pine that is able to process touch and swipe gestures.

Smart Glove Two Buttons: for this variant we extended the existing ProGlove prototype and equipped it with two buttons (6) and (7). Button (6) triggers the scanning process as in the previous variant. The second button (7) is a confirm button. It enables the user to jump to the next view or just confirm a step without the need of interacting with the smartwatch. (8) shows the gamepad that was needed to integrate the second button. It supports Bluetooth and is paired to the Neptun Pine smartwatch. The smartwatch can receive the second button input directly as the gamepad is connected as keyboard.

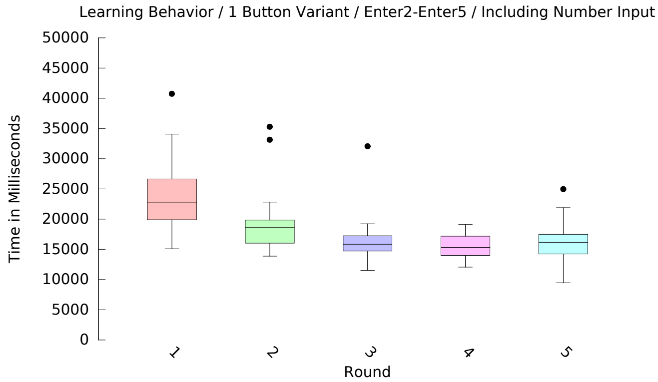
V. Implemented Workflow

For the user study we simulated a typical commissioning workflow that is supported by the previously described variants. For each of the three developed variants we defined a software workflow that helps the participant to fulfill the task. The first screen is the same for all three variants (see Figure 2). The participant needs to select 'Incoming Goods' to start the process. The three other buttons have no attached functionality. For the handheld variant (see Figure 2 first row) the workflow can be processed within a single view. After selecting 'Incoming Goods' the process starts and an acoustic feedback is given. To identify the package, the attached barcode must be scanned. The participant triggers the scan using the orange scan button on the device. The scan is followed by an acoustic signal. By pressing 'ENT' (Enter) or tapping at the next input field (touch or pen) the amount can be entered using the keyboard (number field) on the handheld. Pressing 'ENT' or tapping at the next input field (touch or pen) the target shelf must be scanned and the product must be put into the marked target shelf at the *Commissioning Station*.

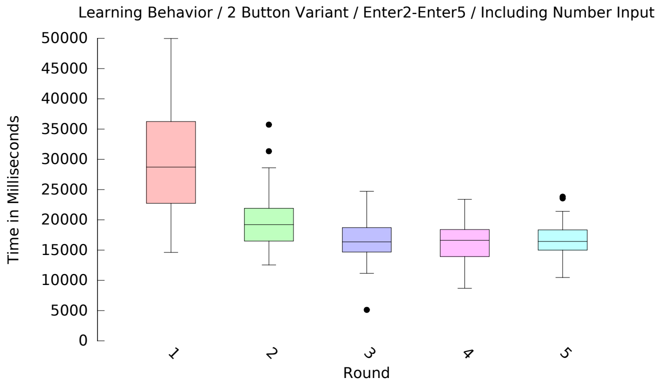
The second workflow is shown in Figure 2 second row. As soon as the 'Incoming Goods' button was pressed the process starts. First the participant needs to scan the barcode attached to the package. Using the one button solution the integrated button in the glove needs to be pushed (see Figure 1 (3)). For the two buttons variant the integrated button needs to be pushed as well (see Figure 1 (6)). After the scan was successful the participant needs to confirm the scan. In case of the one button solution the confirmation is done by pushing the 'OK'



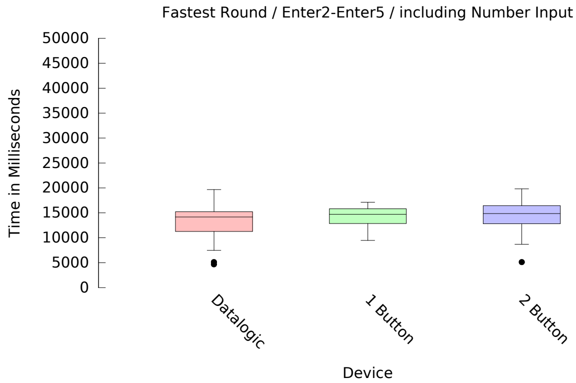
(a) Handheld Variant



(b) 1 Button Variant



(c) 2 Button Variant



(d) Fastest Round

Fig. 4: **Learning Curve:** The learning curves show that in the first round the variance for the handheld and the 2 Button variant is very high. It decreases after each round. Interesting to mention is that the variant increases for the handheld device in the last round.

software button on the smartwatch. For the two buttons variant the integrated hardware button at the smart glove confirms the scan (see Figure 1 (7)). After that step the amount needs to be entered. Using the one button variant, this has to be done using a number slider. For the two buttons variant we offer a digit scan panel, printed and located in front of the participant (detailed description in Section VI). This step needs to be confirmed in the same way as already mentioned, for both solutions. Now the target shelf must be scanned, where the package has to be located. For the one button and two buttons variant the scan is triggered using the integrated hardware button on the smart glove. The last step, the confirmation is done in the same way as the other confirmation processes.

The next section describes our simulation setup for the commissioning process and how we conducted the user study.

VI. Setup and User Study

The experimental setup is illustrated in Fig. 3 and consists of a 'Incoming Goods Station' and a 'Commissioning Station'. The 'Incoming Goods Station' is constructed as follows. It has some direct light from above to guarantee good light conditions for the participants. The incoming goods are located in a small weighted box that contains 8 duplo® stones. To optimize our setup we conducted a pretest with four participants. During the pretest the weight inside the box was increased until the participants had to use both hands to carry the box. Additionally, the amount of stones was increased until the participants needed to use both hands to carry the stones (see Figure 3a and 3b).

The 'Commissioning Station' consists of an industry shelf commonly used in factory environments (see Figure 3c). It is equipped with blue boxes filled with the corresponding colored duplo® stones. The target shelf slot is labeled with a barcode encoding a unique identifier. The participant needs to scan it before the duplo® stones can be put into it. Only the correct target shelf is labeled as we do not want to focus on the optimal position for the target shelf. The focus is strictly on the workflow, namely scanning and hands-free operation, and therefore, support to humans during the task.

Each participant was filmed during the entire experiment. Before a participant starts a task, we introduced the corresponding variant and explained how the participant has to handle it. We let them try each variant but we did not demonstrate how to carry, grasp or commission the duplo® stones. The participant had the choice of optimizing the workflow for each variant, but was not allowed to rearrange the setup. That means that each

participant could choose, if the stones will be carried inside the box, or if they grab the stones as a bulk or each stone individually.
Each participant was asked to execute each workflow 5 times. We evaluated our prototypes quantitatively as well as qualitatively. For the quantitative evaluation we integrated a logging mechanism that allowed us to keep track of the elapsed time for each workflow step. After each variant was used we handed a questionnaire that asked for the favorite preference and asked for sociodemographic data.

VII. Sample and Socio Demographics

Our sample is a convenience sample with a total number of 30 participants. 12 of our participants were female and 18 were male. The average age of the participants was 28 years, while the oldest participant was 56 years old and the youngest 19 years old. 28 participants were right handed 2 were left-handed. 11 participants of our sample were students, 1 an apprentice, 13 employees, and 5 scientific staff members. According to their experience 10 stated that they already had experience within commissioning processes. 20 had no experience within factory environments.

VIII. Quantitative Evaluation

For each round we measured the overall elapsed time to finish the workflow. The learning curve for the handheld device aggregated by the corresponding round, show the following median values: round (1) 24660.50 ms, round (2) 18628.00 ms, round (3) 15335.50 ms, round (4) 15282.50 ms and round (5) 15082.50 ms (see Figure 4a). We calculated the decrease in percentage compared to the first round as follows: round (2) -24.46 %, round (3) -37.81 %, round (4) -38,03 %, round (5) -38,84 %. The results show that after each round the participant performed the task a bit faster. It is noticeable that the variance during the last round (5) increases especially. The one button solution shows the following elapsed times per round: round (1) 22805.50 ms, round (2) 18603.00 ms, round (3) 15835.50 ms, round (4) 15327.50 ms, round (5) 16155.50 ms. Expressed as a percentage with reference to the first round the learning curve looks as follows: round (2) -18.43 %, round (3) -30.56 %, round (4) -32.79 %, round (5) -29.16 % (see Figure 4b). The results show that the elapsed time decreases until round 3 and then slightly increases. In round 5 it decreases again. The variance in round 5 is slightly smaller compared to the handheld variant. Fewer mistakes have been made.
The elapsed time per round for the two button variant is listed in the following: round (1) 28713.00 ms, round (2) 19206.50 ms, round (3) 16364.00 ms, round (4) 16620.50 ms, round (5) 16435.50 ms. Expressed as percentage the elapsed time compared to the first round was: round (2) -33.11%, round (3) -43.01%, round (4) -42.12%, round (5) -42.76% (see Figure 4d). The two buttons variant is the only variant where the variance in the last round decreases and less mistakes have been done.
In all three variants we can observe a positive learning curve over time. An oscillation within the elapsed time between 1% - 2 % is considered as negligible. The learning curve using the two buttons variant is the steepest compared to the other variants. What is important to notice is that the overall variance of the smart glove variants is smaller compared to the variance of the handheld variant. Due to that variance we conducted a video analysis and observed a higher amount of errors within the handheld variant (see Figure 5). We also observed that 50% of the participants that used the handheld variant walked twice to the 'Commissioning Station' as one hand was occupied with the handheld device. Our overall impression while analyzing the videos was, that the workflow felt very smooth as soon as the participants used the two buttons variant. This impression is confirmed by the qualitative evaluation.
We additionally analyzed the fastest round of each participant

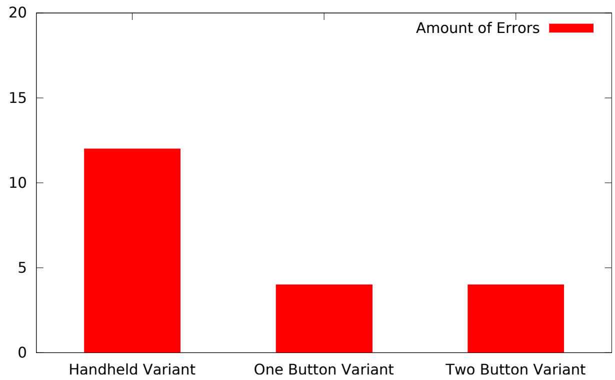


Fig. 5: **Amount of Errors:** Our video analyses showed the following error amount distribution. We dropped 5 participants as we could not analyze the videos. Some parts were not visible or the camera did not capture everything. Using the smart glove variants 66% less mistakes occur.

and aggregated the fastest times. The median of the fastest rounds are: 14176.50 ms (handheld), 14711.50 ms (one button), 14861.50 ms (two buttons). The participants using the one button variant are 0.53 s slower compared to the handheld device. Using the two buttons variant they were 0.68 s slower than using the handheld device. The video analysis let us conclude that the participants using the handheld scanner stated that it looks like a mobile phone and therefore we assume that they are used to handle such devices. Also the scanning direction and the integration into the textile was new to them. The handheld provided a well-known interface comparable to the first mobile phones. They immediately knew how to handle it. Yet, our results show the potential of the smart glove variants concerning the variance. We think that increasing the training period (amount of rounds) would have a beneficial influence on the elapsed time using the smart glove.
Additionally, we selected one of the smallest handheld scanning device we could find on the market. We strongly believe that using a bigger device would change the results to the advantage of the smart glove variants. To conclude we showed that the smart glove could compete with one of the smallest scanning devices available on the market. Concerning time we need to have a closer look at the process, to fully utilize the benefits of hands-free operations.

IX. Qualitative Evaluation

For the qualitative evaluation we asked to complete 4 questionnaires to each participant. One after the usage of each variant and one after conducting the entire experiment

asking for the overall favorite variant, general feedback and sociodemographic data. For the 3 questionnaires of the variant we used a 6 ranged likert-scale. Each item was formulated as a statement where the participant could chose between (1) 'fully applies' and (6) 'does not apply at all'. The items where categorized into 4 categories: support to humans, physical fatigue, user acceptance and user interaction. The category was not visible to the participant and the items where mixed and not grouped by the corresponding category. Depending on how the statement is formulated the selection (1) can be positive for the item or negative. In our results (see Table I, II, III, IV) we indicate this by coloring each cell of the result table, using the following color scheme: dark green, green, yellow, orange, light red and red. Green represents the best and red the worst possible value for the item.
Additionally we asked three open questions providing a text field. We explicitly asked what the participant liked, disliked about each variant and the third text field provided the option to write down any other thoughts about the workflow or variant.

Support to Humans: The items contained in this category are: easiness, hinderness, fun, efficiency and interference (see Table I). Concerning each variant we observed that the handheld received the worst feedback from the participants. The one button variant received very good feedback as well as the two buttons variant. The participants stated that the two buttons variant is more fun to use whereas the one button variant is easier to use. The rest of the items are equally rated.
Physical Fatigue: Table II shows the results for the physical fatigue. The results show that the handheld is slightly more tiring to the arms, hands and fingers. The two buttons variant is slightly tiring to the fingers. Having a look at the text field answers the participants stated that the location of the second button (see Figure 1 (7)) is too close to the thumb. The participants proposed to locate the button more to the front to offer a better accessibility.
User Acceptance: According to the user acceptance (see Table III) the participants stated that the button location on the handheld variant is better than using the one button or the two buttons variant. Concerning the integration into the work environment the participants felt that the handheld is not as well integrated into the work environment as the other variants. All participants thought that all variants feel natural and intuitive.
User Interaction: All items that belong to the User Interaction are shown in Table IV. The readability and the screen size of the handheld as well as the smartwatch received the highest rating possible for all three variants. The one button variant received a relatively bad rating. Our participants did not like the number input (number slider) on the smartwatch. The two button variant and the handheld both achieved the best rating. In addition, we asked if the participants mixed up the buttons of the two buttons variant. Our results show, that they did not mix up the buttons.
To summarize our results of the qualitative evaluation we can state that the support to humans during the commissioning task is better using the smart glove. Both variants show better results than the handheld except for the easiness. We showed a slightly better result concerning the physical fatigue using the smart glove. User Acceptance and User Interaction can be seen almost equal exept of the integration into the work environment (handheld) as well as the number entry for the one button variant.

TABLE I: Items which belong to the category Support to Humans. For each item the table shows the calculated median. The color indicates the manifestation of the item.

Item	Handheld	One Button	Two Buttons
1 Easiness	2	1	2
2 Hindered	2	5	5
10 Fun	3	2	1
11 Efficient	4	2	2
13 Interfered	3	5	5

TABLE II: Items which belong to the category Physical Fatigue. For each item the table shows the calculated median. The color indicates the manifestation of the item.

Item	Handheld	One Button	Two Buttons
4 Tiring (Arms)	5	6	6
5 Tiring (Hands)	5	6	6
6 Tiring (Fingers)	5	6	5

TABLE III: Items which belong to the category User Acceptance. For each item the table shows the calculated median. The color indicates the manifestation of the item.

Item	Handheld	One Button	Two Buttons
14 Button Location	1	2	2
15 Non-Natural	5	5	5
16 Well Integrated	3	2	2
7 Intuitive	2	2	2

TABLE IV: Items which belong to the category User Interaction. For each item the table shows the calculated median. The color indicates the manifestation of the item.

Item	Handheld	One Button	Two Buttons
8 Readable	1	1	1
12 Screensize small	6	6	6
9 Enter Numbers	1	4	1
17 Mixed up Buttons	N/A	N/A	6

X. Conclusion and Future Work

The qualitative analysis shows that the smart glove variants are better than the handheld variant. Concerning support to humans, the physical fatigue and user acceptance, the variants excel the handheld variant. Concerning the User Interface the results show no difference between the variants except for the number entry using the one button variant. The two buttons variant is as good as the handheld variant.
We could show that the variance using the smart glove variant is smaller compared to the handheld device. Our video analysis shows that the error rate during the tasks is lower using the smart glove variants (66% less errors). Concerning the overall elapsed time we could show that we can compete with one of the smallest handheld devices on the market. We strongly believe that using bigger handheld devices will result in much higher task duration especially in scenarios where two hands are needed.
Currently, we are optimizing the button location of the smart glove. We are working on a solution that increases users comfort while pressing the confirmation button. Additionally, we are working on optimizing the number

input method. Concerning the qualitative evaluation results we are identifying workflows where hands-free operation is essential and handheld scanners are not an option. We are corresponding with two partners, located in the aviation and automotive domain, to identify and explore scenarios where the smart glove solution offers benefits.

ACKNOWLEDGMENTS

We would like to thank ProGlove, in particular Jonas Girardet, Paul Guenther and Tarek Ouertani, for their constructive feedback and collaboration. We also would like to thank all participants for spending their time and providing such extensive feedback.

REFERENCES

[1] A. Pantelopoulos and N. G. Bourbakis, "A survey on wearable sensor-based systems for health monitoring and prognosis," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 40, no. 1, pp. 1–12, Jan 2010.

[2] S. Mann, "Wearable computing: A first step toward personal imaging," *Computer*, vol. 30, no. 2, pp. 25–32, 1997.

[3] L. Van Langenhove, *Smart Textiles for Medicine and Healthcare: Materials, Systems and Applications*, ser. Woodhead Publishing Series in Textiles. Elsevier Science, 2007.

[4] K. Niazmand, K. Tonn, A. Kalaras, U. M. Fietzek, J. H. Mehrkens, and T. C. Lueth, "Quantitative evaluation of parkinson's disease using sensor based smart glove," in *Computer-Based Medical Systems (CBMS), 2011 24th International Symposium on*, June 2011, pp. 1–8.

[5] N. Popescu, D. Popescu, M. Poboroniuc, and C. D. Popescu, "Intelligent haptic robotic glove for patients diagnosed with cerebrovascular accidents," in *System Theory, Control and Computing (ICSTCC), 2013 17th International Conference*, Oct 2013, pp. 717–721.

[6] C. Lustig, H. Novatchkov, L. E. Dunne, M. McHugh, and L. Coyle, "Using colocation to support human memory," 2007.

[7] M. Philipose, K. P. Fishkin, M. Perkowitz, D. J. Patterson, D. Fox, H. Kautz, and D. Hähnel, "Inferring activities from interactions with objects," *Pervasive Computing, IEEE*, vol. 3, no. 4, pp. 50–57, 2004.

[8] W. Günthner and M. Wölfle, *Papierlose Produktion und Logistik*, ser. Forschungsbericht / Fml, Lehrstuhl für Fördertechnik Materialfluß Logistik, Technische Universität München. TUM, fml, 2011.

[9] L. Muguira, J. I. Vazquez, A. Arruti, J. R. d. Garibay, I. Mendia, and S. Renteria, "Rfidglove: A wearable rfid reader," in *e-Business Engineering, 2009. ICEBE '09. IEEE International Conference on*, Oct 2009, pp. 475–480.

[10] C. Scheuermann, B. Bruegge, J. Folmer, and S. Verclas, "Incident Localization and Assistance System: A Case Study of a Cyber-Physical Human System," in *2015 IEEE/CIC International Conference on Communications in China: 3rd IEEE ICCC International Workshop on Internet of Things (2015 ICCC IoT Workshop)*, Shenzhen (P.R. China), Nov 2015.

[11] L. Dipietro, A. M. Sabatini, and P. Dario, "A survey of glove-based systems and their applications," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 38, no. 4, pp. 461–482, July 2008.

[12] M. Ayabakan and . Eken, "Creating 5s climate at the shopfloor," in *Management of Engineering Technology (PICMET), 2014 Portland International Conference on*, July 2014, pp. 1907–1928.

Reprint Permission

Copyright Clearance Center RightsLink®

Home | Create Account | Help

IEEE Requesting permission to reuse content from an IEEE publication

Title: Increasing the Support to Humans in Factory Environments Using a Smart Glove: An Evaluation

Conference Proceedings: Ubiquitous Intelligence & Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People, and Smart World Congress (UIC/ATC/ScalCom/CBDCom/IoP/SmartWorld), 2016 Intl IEEE Conferences

Author: Constantin Scheuermann

Publisher: IEEE

Date: July 2016

LOGIN

If you're a copyright.com user, you can login to RightsLink using your copyright.com credentials.
Already **a RightsLink user** or want to learn more?

Thesis / Dissertation Reuse

The IEEE does not require individuals working on a thesis to obtain a formal reuse license, however, you may print out this statement to be used as a permission grant:

Requirements to be followed when using any portion (e.g., figure, graph, table, or textual material) of an IEEE copyrighted paper in a thesis:

1) In the case of textual material (e.g., using short quotes or referring to the work within these papers) users must give full credit to the original source (author, paper, publication) followed by the IEEE copyright line � 2011 IEEE.
2) In the case of illustrations or tabular material, we require that the copyright line � [Year of original publication] IEEE appear prominently with each reprinted figure and/or table.
3) If a substantial portion of the original paper is to be used, and if you are not the senior author, also obtain the senior author�s approval.

Requirements to be followed when using an entire IEEE copyrighted paper in a thesis:

1) The following IEEE copyright/ credit notice should be placed prominently in the references: � [year of original publication] IEEE. Reprinted, with permission, from [author names, paper title, IEEE publication title, and month/year of publication]
2) Only the accepted version of an IEEE copyrighted paper can be used when posting the paper or your thesis on-line.
3) In placing the thesis on the author's university website, please display the following message in a prominent place on the website: In reference to IEEE copyrighted material which is used with permission in this thesis, the IEEE does not endorse any of [university/educational entity's name goes here]'s products or services. Internal or personal use of this material is permitted. If interested in reprinting/republishing IEEE copyrighted material for advertising or promotional purposes or for creating new collective works for resale or redistribution, please go to http://www.ieee.org/publications_standards/publications/rights/rights_link.html to learn how to obtain a License from RightsLink.

If applicable, University Microfilms and/or ProQuest Library, or the Archives of Canada may supply single copies of the dissertation.

4.4 Real-Time Support During a Logistic Process Using Smart Gloves

This publication (Publication [D]) proposes and evaluates a smart glove based approach to support workers during logistic scenarios.

Conference: Smart SysTech, European Conference on Smart Objects, Systems and Technologies
Number of Pages: 8
Type: Full Paper
Review: Peer Reviewed (3 Reviewers)

The author of this dissertation designed the approach of how a smart glove can be used in combination with a smartwatch to enhance an existing logistic process. He defined the processes that have been evaluated and introduced the concept of shape and color coding on the smart gloves. The author created the qualitative and quantitative user study design, the categorization of the qualitative items, the item selection as well as the selection of the quantitative measurements. He led the evaluation of the prototypes and conducted the evaluation together with Florian Heinz.

Goal

The goal of this CPS application is to further improve the smart glove prototypes and integrate them into an existing logistic process of a German truck manufacturer. We want to find out how we can increase process guidance during such a logistic process. Moreover, we want to develop a new smart glove prototype that positions the scan and confirmation button on the right and left glove to reduce cable bending stress. Additionally, we want to reuse the scanning unit mount to attach a button input controller.

Approach

We realized a conceptual implementation of two smart glove prototypes. We conducted a controlled lab experiment with 27 participants and used qualitative and quantitative evaluation techniques. For the evaluation we applied a real-world logistic process from a German truck manufacturer. We compared three workflow variants: a handheld scanner, one glove, and the two glove based variant.

Results

We improved the button location of the one glove variant according to the received qualitative feedback of our previous experiment. We developed a smart glove variant that locates one button on each hand to reduce cable bending stress. We reused the scanning unit holder to locate a button input controller. We could show that 59% of our participants preferred the two glove variant, 41% the one glove variant and none the handheld scanning variant.

Metamodel Contribution

The metamodel abstractions helped us to develop the idea of an abstract button input handler. We could make use of a further abstraction level that enabled us to model the concept of a textile button in a generic way. We further separated the input button and scan trigger button and applied one of the to the left and one of them to the right glove. We reused the metamodel as no extension was necessary for this new CPS application.

Reprint Denied

The reprint of this publication was rejected on open-access platforms. The publication can be found at `https://www.vde-verlag.de`. The details are provided below.

Publication [D]

Constantin Scheuermann, Florian Heinz, Bernd Bruegge and Stephan Verclas
Real-Time Support During a Logistic Process Using Smart Gloves
Smart SysTech, European Conference on Smart Objects, Systems and Technologies
ISBN: 978-3-8007-4428-2

4.5 Mobile Augmented Reality based Annotation System: A Cyber-Physical Human System

This publication (Publication [E]) proposes a novel approach to support humans during maintenance scenarios.

Conference: Augmented Reality, Virtual Reality, and Computer Graphics
Number of Pages: 15
Type: Full Paper
Review: Peer Reviewed (4 Reviewers)

The author of this dissertation designed the MARBAS workflow that allows a virtual annotation of physical objects. He defined the problem statement and defined the user interface design. He designed the evaluation setup and led the evaluation of the MARBAS prototype conducted by Felix Meissgeier. The author of this dissertation selected the evaluation characteristics used within this publication.

Goal

The goal of the conducted research is to improve the support for maintenance workers. Such workers should be able to digitize real world objects using a mobile device. Moreover, a digital annotation of the virtual representation of the objects should be possible. The system should allow information sharing among maintenance workers.

Approach

We conducted a conceptual implementation with a simulation and evaluation of ICP algorithms. We quantitatively evaluated ICP algorithms to elicit an appropriate algorithm for our vertical prototype.

Results

We implemented a vertical prototype that allows digital annotation of real world objects. We conducted a simulation to evaluate the performance of ICP algorithms available for an iPad. Based on our results we selected PCL Non-linear ICP to align our recorded point clouds. We showed that within maintenance scenarios the usage of mobile augmented reality devices is possible and has the potential to improve information sharing among maintenance workers.

Metamodel Contribution

We instantiated the metamodel for cyber-physical systems within the MARBAS prototype. We showed that augmented reality applications can be modeled as cyber-physical system. We could reuse the metamodel and use it to provide an abstract and understandable top-level design.

Reprint Denied

The reprint of this publication was rejected on open-access platforms. The publication can be found at `https://link.springer.com/`. The details are provided below.

Publication [E]

Constantin Scheuermann, Felix Meissgeier, Bernd Bruegge and Stephan Verclas
Mobile Augmented Reality based Annotation System: A Cyber-Physical Human System
Augmented Reality, Virtual Reality, and Computer Graphics
DOI: 10.1007/978-3-319-40621-3 20

Appendices

Appendix A

Remote Health Monitoring

In this chapter we describe the problem statement, the functional and nonfunctional requirements as well as the contribution for the remote health monitoring application.

A.1 Problem Statement

Hazardous, harsh or dangerous environments might require protective textiles. In case of an Ebola decontamination scenario workers need to wear suits that are sealed off from the environment. Such suits protect workers against external threats such as contentious material or organisms. As these suits are sealed off from the environment heat exposure and strain can influence professionals during deployment in a negative way. Heat exposure increases heart-rate, dehydrates, and has negative influences on the overall performance of professionals and can even cause long-term health conditions [GSDL15] [Gli+15]. When the muscles of the worker produce heat during the deployment, it further complicates this situation. The temperature within the protective textiles rises to a level where the worker starts to perspirate. Assuming a workload of 120 Watt, a worker in a CNBR suit evaporates/perspirates up to 0.5 l of sweat in one hour. Those liquids accumulates inside the suit and can cause swollen, soft finger and toe tips that might cause injuries or impede a proper task completion. An experiment conducted by Glitz et. al. showed that taking a break would stop muscle heat production but has no significant effect on the thermoregulation of the wearer, since the CBRN suit is impermeable. Active cooling mechanisms reduce the heat stress within suits during physical workouts [Gli+15].
Frequent exposure to stressful situations and strains can increase the probability for negative long-term health conditions [Lar+15] and can increase the probability of post-traumatic stress disorder [Wal+16]. Moreover, physiological stress is connected to psychological stress [OKTW16] and can amplify the risk of negative long term health effects. The identification of such strains or events during deployment is challenging as real-time health data is difficult to acquire.

Not only negative influences on long-term health conditions but also negative influences on short-term health conditions have to be considered. A collapse during deployment influences the operational safety of each member. The identification of potential threats that lead to short-term health effects is essential to increase operational safety for each team member as well as the entire group.
In case deployed workers use protective textiles such as CBRN suits, workers are not allowed to operate more than 30 minutes using such textiles. This period of time is in most cases not sufficient to complete a task. In order to extend that working period the deployment of smart textiles in combination with mobile monitoring and cooling possibilities offer a solution.
Currently, remote health monitoring systems for professionals are hard-wired systems using sensors connected to a base unit. They measure body temperature, the humidity in the suit and the heart-rate of the worker. An expert, the medical advisor, attaches the sensors to the deployed worker. Each sensor is currently taped to the appropriate area on the body of the worker. User comfort is an open issue.
In most cases medical valid monitoring systems use data-loggers to store the measured data at the deployed worker. Real-time monitoring is not possible with such systems as data-loggers can only be accessed after a mission.
In case no remote-health monitoring system is used, a medical advisor relies on his or her experience and measurements after deployment to estimate the condition of the worker. The commander, who is typically the decision maker during deployment, decides when a worker has to stop a task. Consulting the doctor is inevitable for a commander. To the best of our knowledge, a comprehensive system that combines real-time monitoring, feedback channels among the included stakeholders as well as context/condition dependent cooling is not available for heavy duty operations.
The political situation, climate information and current weather conditions are not displayed in current remote health monitoring applications. Such factors can explain unusual value measurements and offer a context to estimate the medical condition. In the environmental context some measurements might be normal and do not require an immediate action of the medical advisor or the commander.
The physiological fingerprint must be considered, as it is unique for every participant. Quantities such as resting heart-rate, bloodtype, gender, allergies are all parameters that influence health estimation. Current applications such as the Blackghost[1] system do not provide such functionality.

[1] Blackghost from Equivital `http://www.equivital.co.uk/products/military`

A.2 Functional and Nonfunctional Requirements

In this paragraph the functional and nonfunctional requirements are described, the problem statement is provided and the chapter concludes with the contribution of the application.

FR 1 - Support of Dedicated Roles
The system must support different roles such as the mission participants, the medical advisor and a mission commander. The system must provide role specific views or interfaces.

FR 2 - Enable Real-time Monitoring
The system must allow real-time health monitoring of up to 8 participants in parallel as 8 was selected as typical group size.

FR 3 - Feedback Channel Among the Participants
A communication channel must be established among all three roles, the participant, the medical advisor and the commander. The system must provide a function to send a retreat advise from the medical advisor to the commander. Moreover, the commander must be able to send a retreat command to each participant. Each participant must be able to transmit an individual health status estimation. Each participant must be able to trigger an emergency help request as well as an assistance request to the mission commander.

FR 4 - Consideration of Physical Environmental Parameters
The system must consider physical parameters such as climate conditions, current weather or language constraints. It might have an influence on the decision making process of a medical advisor or a mission commander. The system must display such information for each mission.

FR 5 - Minimize Information at Deployed Worker
Information must be available to the deployed worker only in case it creates benefits. The system should make use of information filtering and aggregate information to avoid an unnecessary information overload. Information about the individual health condition at the deployed worker is not beneficial.

The following paragraphs describe the nonfunctional requirements of the system.

NFR 1 - Integration of Health Monitoring System into Textile
The monitoring system must be embedded into a comfortable textile design that deployed workers accept.

NFR 2 - Lean Textile User Interface Design
The system must define a lean and intuitive textile interface design for the deployed worker. It must provide triggers for emergency requests and status updates. Moreover, the textile must provide a display where commands are displayed such as a retreat message.

NFR 3 - Fault Tolerance when Applying Textile
The system must define a lean and intuitive textile connection interface design. Clear and distinct connectors must be designed that do not allow a wrong connection wiring.

NFR 4 - Washable Textile
The textile design must be washable. The connectors, wires and sensors must stand the washing procedure as the garment has direct contact to the skin of the deployed worker.

A.3 Contribution

We identified and addressed problems within the domain of remote health monitoring. Therefore, we created a research project that consists of software engineers, textile manufacturing experts, medical advisors, electrical engineers and technical practitioners. We brought together researchers from different domains to collaborate in this project all contributing with their domain specific knowledge.
We started our research with a first vertical prototype that showed the technical feasibility. Based on the system design of the first prototype, we extended the smart textile undergarment (Figure 2.16) which uses the mobile physiologic laboratory (mobPhysioLab^{TM}) and its core technology the HealthLab system. It is a modular, flexible, and intelligent bus system, which processes a multitude of physiological and environmental data at the same time. It offers the possibility to monitor military personnel during genuine missions and deployments in real-time and sends the recordings online to a base station. This system represents a major improvement to the first prototype and provides opportunities to optimize protective textiles, based on sound scientific research.
We extended the textile system to establish lean feedback channels for in-field professionals (Figure A.1b). The design combines textile interface design with smart

(a) **HealthLab:** the figure shows the **Health Data Collector**. We are using the HealthLab, which is a bus-based system that allows to extend the system with additional sensor satellites.

(b) **Textile Interface:** the **Emergency Button** consists of a stitched label that is attached with Velcro. A 3D printed button protection prevents accidental button pushes. For the prototype we used a Flic Button.

(c) **Textile Integration:** temperature sensors are integrated into the textile at the ankles and wrists. The HealthLab is located in a belly-bag.

Figure A.1: **Textile Components:** the figures illustrate the three parts the sensor garment consists of: the Healthlab, the outer textile interface design and the garment with the textile integration of the sensors.

technology. We deployed lean and simple devices to keep distraction of the professionals at a minimum. We used 3D printing technology to design a button protection to reduce the risk of false positives.

During the development we reduced the amount of information at the deployed worker. Deployed workers do not need to evaluate their health situation based on measured quantities. They know how they are feeling. Additional warnings or measurements can lead to increased stress and must be avoided. Therefore, medical advisors evaluate the situation and send only lean instructions to the deployed workers. An example of an instruction represents a message that the worker has to leave the danger zone in the next 5 minutes.

The smartwatch is used as output device only. We dropped touch interaction with the device as it is not applicable for the addressed scenarios. We keep information and interaction with the device at a minimum to avoid information overload and distraction. To allow real-time health monitoring we used a topic based broker architecture in combination with RESTful services. For real-time data we make use of the publish/subscribe protocol of MQTT. Historic information and user data is provided via RESTful services.

Appendix B

Health Data Visualization

During the implementation of the CHEST prototypes we figured out that little research about user interface design for medical advisors in professional work environments exists. User interfaces exist but evaluations and guidelines are missing. The same applies for mission commander user interfaces.

B.1 Problem Statement

Medical advisors are typically in charge for the health condition of deployed personnel in professional environments. In case a real-time remote health monitoring is applied, medical advisors profit from real-time health data of the deployed personnel. Typically, such data is shown on desktop or mobile applications such as the Blackghost system from equivital[1]. To the best of our knowledge the user interfaces lack an evaluation. They offer concurrent personnel monitoring but an evaluation of how such a user interface supports the medical advisor is missing. The same applies for mission commanders. To the best of our knowledge a system that supports medical advisors in combination with a mission commander is missing[2].
Medical advisors need to concurrently monitor deployed personnel. An overview that supports medical advisors during the decision making process and the corresponding design guidelines are missing. Evaluated widgets that aggregate important health values and widgets that indicate minimum and maximum values that do not distract medical advisors are to the best of our knowledge missing within the remote health monitoring research.

[1] `http://www.equivital.co.uk/`
[2] Information based on private conversation with Dr. Andreas Werner, German Air Force, Centre of Aerospace Medicine, Aviation Physiology

B.2 Functional and Nonfunctional Requirements

To propose an initial user interface design and the corresponding evaluation environment we defined the following functional and nonfunctional requirements.

FR 1 - Overview of Deployed Workers
The system must provide an overview of the deployed workers which allows the medical advisor and the commander to observe up to 8 workers in parallel.

FR 2 - Calculation of Group Stress-level The system must calculate a group stress-level based on the stress-level of each individual deployed worker.

FR 3 - Provide Graphs for Measured Health Values
The system must provide a graph for humidity, core body temperature, limb temperature and heart-rate values over time. It must add new values in real-time to the already measured ones.

FR 4 - Provision of a Communication Panel
The system must provide a communication panel that the medical advisor is able to advice the commander to retreat a deployed worker based on the assumptions made. The commander has to be able to send retreat messages to the deployed workers.

FR 5 - Provision of Position Data
The system must provide position data of each deployed worker and show it on a map.

FR 6 - Simulation Scripts for Evaluation
The system must provide a function to simulate health and position values. Therefore, the system must be able to read a previously defined script with events.

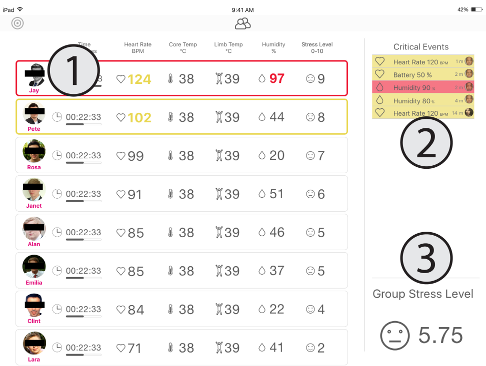
Additionally to the functional requirements, nonfunctional requirements are defined.

NFR 1 - Lean User Interface Design
The system must define a lean and intuitive user interface design that provides functions that are commonly used.

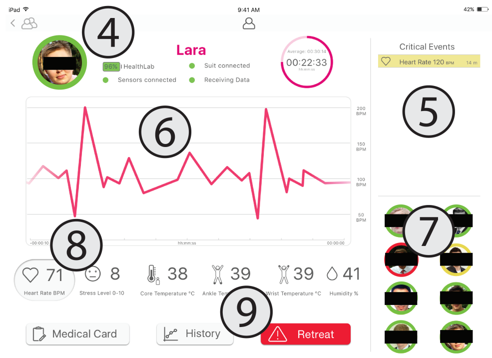
NFR 2 - Widgets the Support Decision Making
The system must define widgets that support the medical advisor as well as the commander in the decision making process.

B.3 Contribution

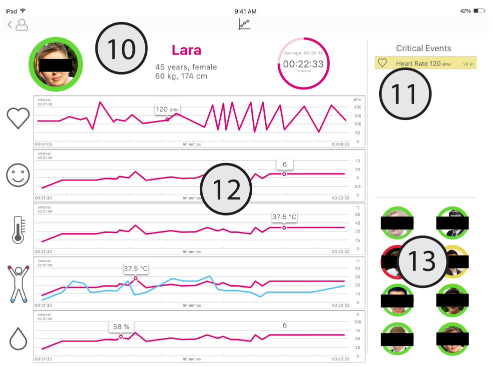
For the medical advisor and mission commander we developed a user interface. A mission commander handles the mission setup, add workers and assign a medical advisor to the mission. As soon as a mission starts the user interface (Figure B.1d)



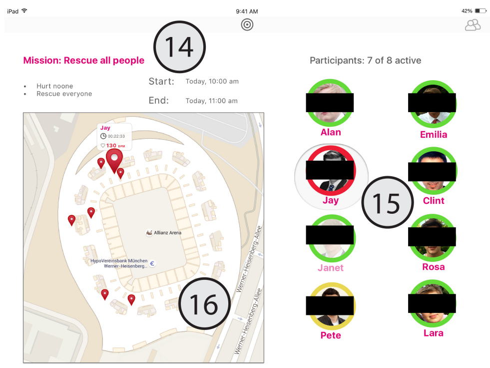
(a) **Overview:** (1) shows a list of all deployed worker ordered by stress-level, (2) the critical events list and (3) the aggregated group stress-level.



(b) **Detail View** (4) shows the technical parameters panel (5) the critical events, (6) a real-time graph, (7) avatar-based deployed worker overview, (8) sensor selector and (9) the communication panel.



(c) **Historic View:** (10) shows the technical parameters panel, (11) the critical events, (12) the historical data graphs and (13) the avatar-based deployed worker overview.

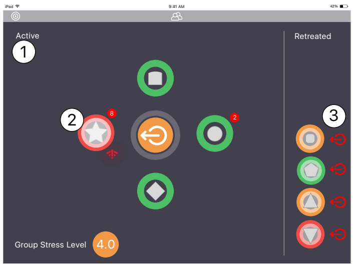


(d) **Commander View:** (14) shows the mission details, (15) the avatar-based deployed worker overview and (16) the map with locations of each deployed worker.

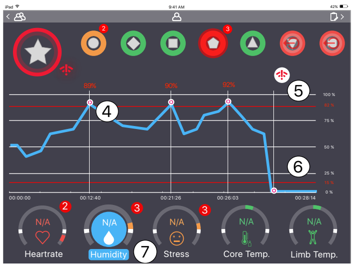
Figure B.1: **CHEST User Interfaces:** the figure shows the first implementation of the medical advisor user interfaces in Figure B.1a and Figure B.1b and the first commander user interface in Figure B.1d. The interfaces have been implemented for an iPad. All avatars have been anonymized for this illustration, random names and random pictures have been assigned to each avatar.

provides an overview of each deployed worker in combination with a map view. In addition to that we implemented a user interface for the medical advisor. It provides a mission overview (Figure B.1a) as well as a detailed view (Figure B.1b). To the best

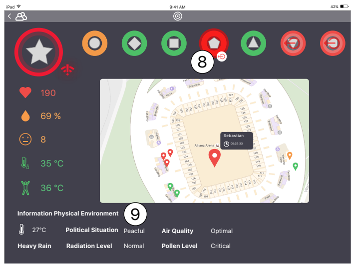
of our knowledge such a system in combination with role-based user interfaces is new and contributes to research of remote health monitoring systems for professionals.
We evaluated the medical advisor (Figure B.1) user interface and based on our results we proposed an improved UI design (Figure B.2.). We conducted a controlled lab experiment with predefined scenarios. We gathered quantitative results on how fast users of such a user interface react to critical events or critical health conditions. We gathered qualitative results on the user interface design. We improved the overview as two lists for active and retreated workers are now available. Moreover, we dropped the avatars and used geometric shapes as our results showed that visually appealing avatars might distract users of the medical advisor interface. We merged the historical (Figure B.1c) and detailed view (Figure B.1b) as shown in Figure B.2b. We added the thresholds minimum and maximum values directly to the real-time graph. The x-axis of the corresponding real-time graphs cover the mission time from start until the current mission time. The additional historical data view is obsolete. The selector widgets for each sensor summarize the current status as well as show unread notifications. A notification appears in case a threshold was exceeded. The notification counter on the right upper corner of the widget increases. As soon as the medical advisor has clicked on the widget and has seen the exceeded thresholds, the notification count decreases. We added environmental information to the commander view (Figure B.2c) and aligned the design to the new design guidelines. We chose a darker background to increase the contrast.



(a) **Overview:** (1) shows the list separator for active and retreated deployed workers, (2) shows the drag and drop retreat widget with colored stress level indicators, (3) shows the retreated deployed workers.



(b) **Detail View** (4) shows the real-time graph with indicated minimum (6) and maximum (4) values, (5) indicates a connection problem and (7) show the sensor widgets with a notification indicator, minimum, current and maximum value.



(c) **Commander View:** (8) shows the deployed worker overview, the map and current values as well as in (9) the environmental information.

Figure B.2: **Redesigned User Interface:** we decreased the navigational effort to retreat deployed workers and simplified the deployed worker overview in Figure B.2a. We merged the detail and historical view to one single view as shown in Figure B.2b. The commander application displays environmental information as shown in Figure B.2c. We do not use avatars as the results of our evaluation showed that avatars are connected with emotions and might result in a preference of choice to help.

Appendix C

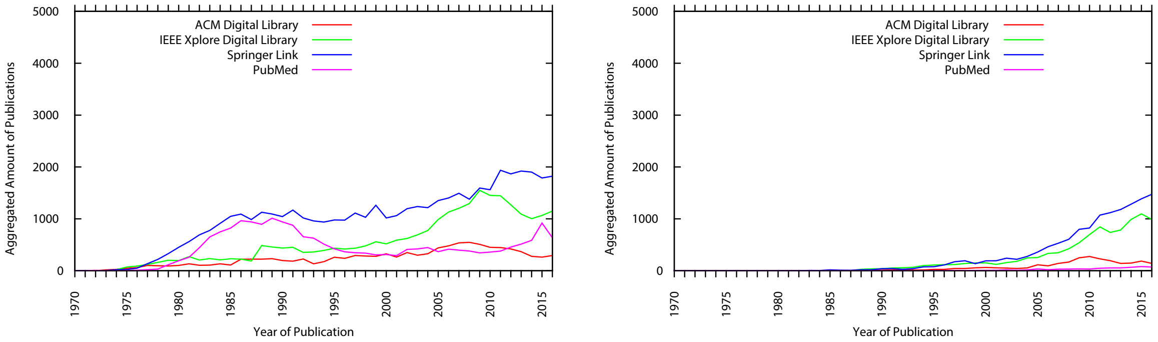
Literature Review

The literature review summarizes key technology enabler such as embedded systems and wireless sensor networks. It summarizes technological improvements and shows the results of the conducted literature review that covers publications from 2006 until 2014. Each analyzed publication is listed in a table with the corresponding summary, the reference, keywords, focus and a domain assignment.
For the publication amount analyses we selected the following online libraries to collect our data: ACM Digital Library (ACM Guide to Computing Literature), the IEEE Xplore Digital Library, Springer Link and PubMed. Those online libraries are the primary sources of publications for this dissertation.

C.1 Embedded Systems

Figure C.1a shows the aggregated amount of publications by year for the term 'Microprocessor'. The term was first mentioned in the mid 70s and gained great attention in research from then on. Within Springer Link database most publications have been found that mention the term microprocessor. PubMed showed an increasing number of publications during the 80s until 1990 and decreased in the following years. Since 2010 the number of publications increased within the PubMed library. At IEEE Xplore Digital Library the number of publications that contain this term started to grow, followed by a decline in 2010. Within the ACM Digital Library the lowest amount of publications was found. A decline of publications can be noticed since 2008.
The term 'Microcontroller' was used increasingly in the beginning of the 90s (Figure C.1b). The term 'Microcontroller' was first mentioned in the 80s, but gained attention in research almost 20 years later. The term 'Embedded System' was first mentioned in the beginning of the 80s, becoming popular in the 90s (Figure C.2). The development of microprocessors and microcontrollers contributed to the development of 'Embedded Systems'. Since 2010 the term 'Embedded System' seems to receive a slow down concerning publication rates within the IEEE Xplore Digital Library. For PubMed the publication amount is still increasing, for ACM Digital Library and Springer Link

the amount of publications per year is still very high but is not growing anymore as in the end of the 90s.



(a) Microprocessor

(b) Microcontroller

Figure C.1: **Microprocessor and Microcontroller:** total amount of publications containing the two terms aggregated by year. Data acquisition in May 2017.

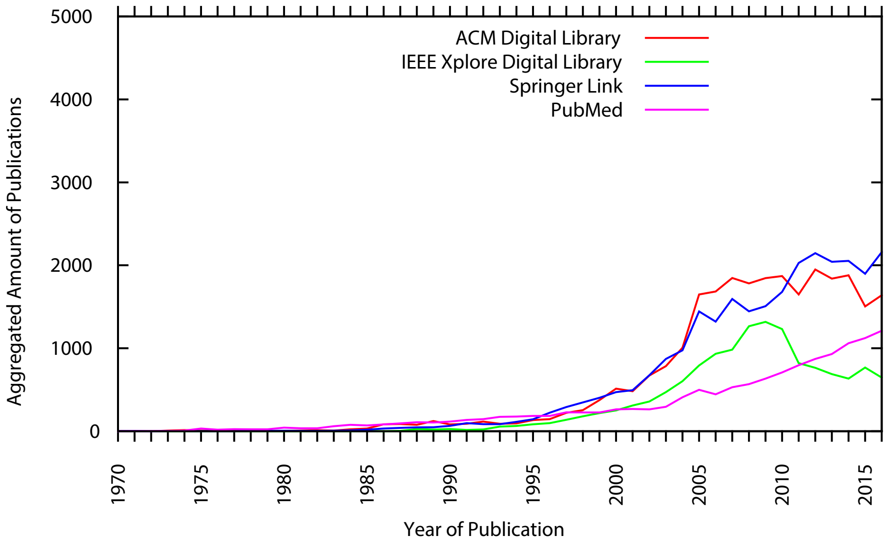


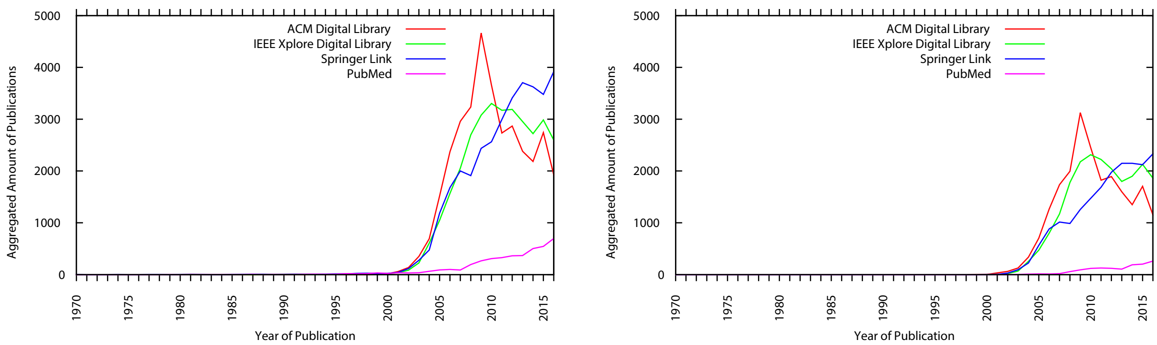
Figure C.2: **Embedded System:** total amount of publications containing the term aggregated by year. Data acquisition in January 2017.

Typical challenges in this field of research are security concerns, predictability of the systems and robustness. Additionally, the factor of almost being invisible to the user seems to be an important challenge in such systems.
Covered domains are mostly the automotive sector, consumer electronics, health, industrial control, networking and office automation. Typical examples are engine

control systems as well as airbag control systems, fax machines, hubs, routers and switches.

C.2 Wireless Sensor Networks

The term 'Sensor Network' started to appear in literature in the beginning of the 80s (Figure C.3a) but at first did not receive much attention in research. This has changed since the year 2000, where the publication rates increased exponentially. The term Wireless Sensor Network was first mentioned in literature in the end of the 90s and started to gain great interest in the beginning of 2003 (Figure C.3b). The standard IEEE 802.15.4 was released in 2003 and the first radio modules using that standard were available for consumer market in 2005 (e.g. Xbee radios from Maxstream). This might explain the growing publication rate since 2005. Looking at IEEE Digital Library and ACM Digital Library a declining publication rate can be observed since 2010.



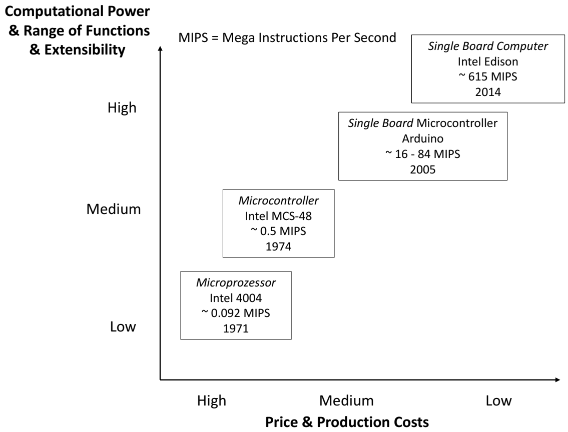
(a) Sensor Network

(b) Wireless Sensor Network

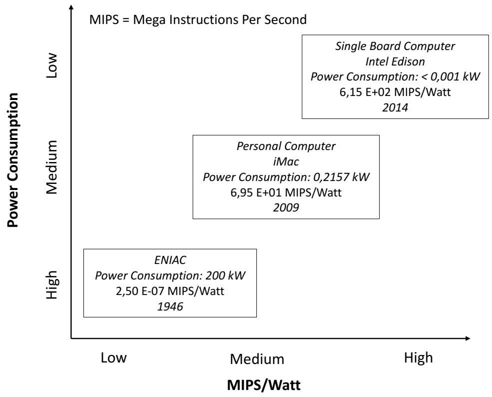
Figure C.3: **Sensor Network and Wireless Sensor Network:** total amount of publications containing the terms aggregated by year. Data acquisition in May 2017.

C.3 Technological Developments

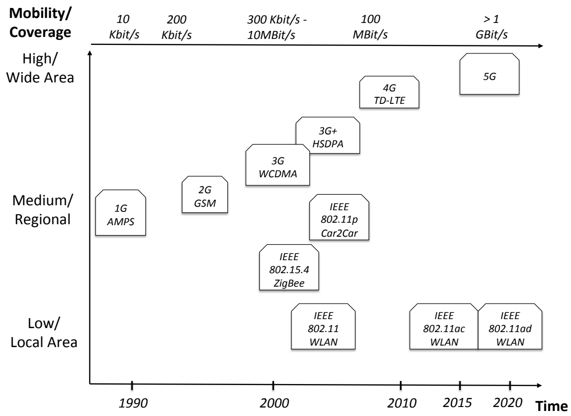
This section summarizes the technological improvements over the year. Figure C.4a illustrated the hardware development over time, Figure C.4b the development of the hardware concerning the power consumption and Figure C.4c describes the development of the protocols over time.



(a) Hardware development over time. Exemplary selection of hardware components over time.



(b) Hardware development over time concerning power consumption measured in MIPS/Watt.



(c) Change of bitrate and transmission range over time of wireless communication protocols and standards.

Figure C.4: **Hardware, power consumption and protocol developments over time:** the figures show that hardware price and its computational power, its range of functions and its extensibility increased over time. Additionally, hardware becomes lighter, smaller and consumes less energy. For the available protocols the bandwidth increased over time.

C.4 Domain Distribution

During the literature review 12 different domains have been identified. 48% of the overall publications are domain independent dealing with general topics applicable to CPSs. Publications that describe cyber-physical systems, such as position papers have been assigned to this category. The top five research domains are Energy, Mobility/Automotive, Aerospace, Health/Medical and Buildings (Figure C.5). We analyzed the keyword distribution we assigned to each publication. Models and

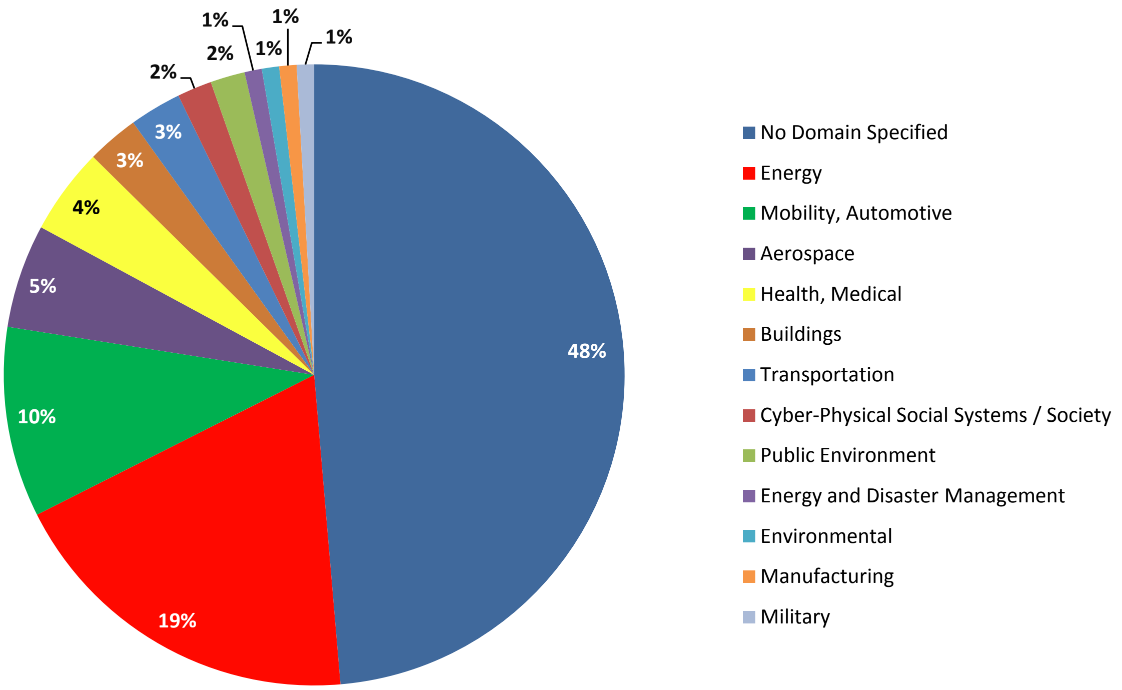


Figure C.5: **Domain Distribution:** pie chart showing the distribution of the publications from the literature review according to their assigned domains.

modeling of cyber-physical systems is the most prominent keyword assignment. 10.12 % of the publications have been assigned to the keyword position paper. 9.72 % of the publications have been assigned with the keyword simulation. In case we sum the publication amounts for the keywords 'Position Paper', 'Definition', 'Overview' and 'White Paper' the amount of keywords would reach 42. The results show that most of the publications deal with generic topics, about what a cyber-physical system is.
The research within CPSs is highly interdisciplinary. In literature a common definition of what a CPS is, is missing and, therefore, publications often define the term covering parts of its characteristics. Some publications originate from research of embedded systems or WSNs but the topic was transferred to the CPSs context focusing on model and design challenges. Publications often address a domain specific problem and apply it to the domain of CPS.

The tables in the appendix show the results of the literature research offering 111 publications and their short summary, focus and a domain categorization (Table C.2 - Table C.10). The next section will sum up the key aspects of CPSs proposing a definition of what a CPS actually is.

Table C.1: **Keyword Distribution:** the table lists the amount of assigned keywords (#) and the percentage of assignment. Some publications have been assigned to multiple keywords.

Keyword	#	%	Keyword	#	%
Model/Modeling	32	12.96	Challenges	3	1.21
Position Paper	25	10.12	Mechanism/Method	3	1.21
Simulation	24	9.72	Vision	3	1.21
Framework	23	9.31	Analysis	2	0.81
Survey	18	7.29	Platform	2	0.81
Approach	17	6.88	Protocol	2	0.81
Evaluation/Experiment	17	6.88	Collaboration	1	0.4
Architecture/Design	14	5.67	Communication	1	0.4
Case-Study/Use-Case	13	5.26	Microcontroller	1	0.4
Definition	11	4.45	Middleware	1	0.4
Algorithm	8	3.24	Real-time	1	0.4
Overview	5	2.02	Semantics	1	0.4
Formal	4	1.62	Software	1	0.4
Prototype	4	1.62	Stochastic Framework	1	0.4
System	4	1.62	White Paper	1	0.4
Theory	4	1.62			

C.5 Conclusion

In the previous sections enabling technologies for cyber-physical systems have been defined. Publication rates for enabling technologies such as microprocessors and microcontrollers have been examined. Those technology enabled research concerning embedded systems. With the invention of radio modules such as Xbee in combination with new wireless communication standards such as IEEE 802.15.4 wireless sensor network research was enforced. Technological improvements concerning calculation power, efficiency, size and bandwidth allow us to build cyber-physical systems. In addition to those results we conducted a literature survey covering publications that contain the keyword 'cyber-physical system'. We examined 111 publications from 2006 until 2014. We summarized, categorized and assigned them to domains and presented an overview of cyber-physical systems research.

Current cyber-physical system research is heterogeneous. It deals with the definition of the term, future challenges and visionary scenarios. It covers research in system architecture and design, system modeling as well as simulation aspects. Generally, research in this area is in an early stage. Yet, most of the publications are position papers defining the term CPS, offering challenges and visionary scenarios.
The following section presents the summary of the conducted literature research.

C.6 Publication Summary

Summary	Ref.	Keywords	Focus	Domain	pp.
Describes a type of CPS called programmable matter. It consists of small parts (catoms) that are able to form matter/shapes. Also referred to as claytronics.	[CGM06]	Position Paper	Vision, Vision of Programmable Matter, Physical Environment Rendering	X	3
Summarizes the research of CPS and major challenges such as adaption of transmission power, medium access control and communication protocols. The authors address topics such as how to reduce payload, filtering of information and perform on node feedback calculation.	[Tab06]	Position Paper	Resource Management	X	3

Table C.2: Survey 2006

Summary	**Ref.**	**Keywords**	**Focus**	**Domain**	**pp.**
In this paper the authors address timing problems focusing on an applicable middleware and operating systems for CPS. They claim a need to search for domain specific scheduling mechanisms.	[Gil07]	Position Paper	Timing Problems, Scheduling	Health, Medical	2
Authors claim that CPS are deployed in critical environments and have to face real-time characteristics. They include third party low-cost components. The authors propose a Simplex model to limit fault propagation due to unreliable components. They want to use a reference model such as Simplex to decompose the complex system being able to meet safety requirements.	[Cre+07]	Model, Real-Time	Fault Tolerance	Mobility, Automotive	10
The paper focuses on the composition of CPS claiming the need for the three major disciplines: control-, system- and software engineering to synergize.	[Szt07]	Position Paper	Design Challenges	X	2
Focusing on the power grid and the composition of components that may result in interference in the frequency domain. Introducing a real-time model created with RT-PROMELA and checked by RT-SPIN.	[SMLC07]	Model	Verification, Power Grid	Power Management, Electricity	7

Table C.3: Survey 2007

Summary	Ref.	Keywords	Focus	Domain	pp.
The authors address security issues in mobile wireless cyber-physical systems (McCLS) introducing bandwidth saving signature mechanism based on certificates .	[Xu+08]	Model, Evaluation	Mobile Wireless CPS	Mobility, Automotive	6
Offering a definition of the term Cyber-Physical System that cover the global timing problem, global quantifiers of confidence and communication mechanisms at all system levels. The authors differentiate events and information. Events are raw facts, whereas information is already processed. Each event has a life span, a confidence quantifier, a digital signature, an authentication code, trustworthiness which is a quantifier how trustful a publisher is and dependability which defines how depended a subscriber is on this information. The authors deal with event handling and knowledge data management.	[TGP08]	Definition, Architecture	CPS Architecture, Definition	X	2

This paper offers research challenges for automotive CPS. Automotive CPS need to compete with already existing systems such as smart phones. The authors claim that the development of automotive CPS is too slow compared to upcoming technologies. Addressing the need for openness and flexibility to compete with technologies for the next decades (use of a car for several years). To show that need the authors have Implemented a GPS-based traffic monitoring application and claim the need for open platforms (HM-CPS).	[WBJ08]	Position Paper, Use-Case	Automotive CPS, Challenges	Mobility, Automotive	3
The authors focus on cross domain event handling. The paper provides a good overview of event handling approaches in CPS. The authors propose an interactive agent mode for CPS.	[Tal08]	Model, Survey	Event Handling in CPS, Challenges	X	15

The publication deals with the question of how embedded real-time systems can be transformed into CPS, as it is infeasible to redesign existing systems from the scratch. The authors identify key challenges such as time predictability, conflicts, correctness and fault tolerance. They offer a theoretical approach for the transformation from an embedded system to a CPS.	[Bon08]	Position Paper	Challenges, Research Directions	X	2
This publication focuses on problems and challenges of CPS frameworks to offer design, modeling and simulation of such heterogeneous, large scale systems.	[KM08]	Definition Paper	Requirements, Design, Modeling, Simulation	X	2
Introducing a model for Cyber-Physical Energy Systems (CPES) used in electric power grids. Focusing on flexibility, efficiency, sustainability, reliability and security. The authors claim that little automated feedback for balancing power in such grids exists and they the missing feedback channels to end-user.	[IXKM08]	Definition Paper	Requirements, Modeling	Power Management, Electricity	9

This paper focuses on topics and challenges in network quality of service management. A CPS is seen as a result of WSANs and WSNs. CPS should be application-orientated and should offer QoS mechanisms.	[XMDS08]	Definition of QoS in CPS	Requirements, QoS	X	6
The authors define a design methodology for resilient CPS following a top-down approach and define a software architecture and its implementations.	[Woo+08]	Design, Model	SafetyTolerance, Fault Tolerance	X	4
The paper presents a study of task scheduling mechanisms in CPS that are regulated by feedback control laws. The authors have developed an algorithm aiming on predictability and power consumption.	[ZSWM08]	Simulation, Evaluation	Scheduling, Theoretical Evaluation	X	10
The authors are addressing real-time data services for CPS using real-time databases as an information centric approach.	[KS08]	Use-Case, Approach	Requirements, Real-Time	X	6
Offering an overview of security in CPS aiming on security goals such as attacks, automatic control, robust network control systems and fault tolerance.	[CAS08]	Definition, Challenges, Survey	Security, Safety, Attacks, Fault Tolerance	X	6

The authors describe a Cyber-Physical System that is capable to build actual physical environments using moxels or pixels that can be raised and lowered. The CPS bridges the virtual and physical world, actually rendering a physical environment.	[KH08]	Use-Case, Simulation, Vision	Physical Environment Rendering	X	6
Focusing on real-time, self-stabilization and life-critical systems such as medical ventilator. The authors point out the need for adaptability of such systems. For example in case the patients need less help the ventilation system support decreases.	[Che08]	Formal Method	Life Critical Systems, Ventilation Systems	Health, Medical	4
The authors developed a prototype that creates a video-based communication (AnySense) between 3G networks and internet hosts. The main challenge to support video-based CPS is to bridge packet switched and circuit switched networks for mobile devices.	[Xin+08]	Prototype, Architecture	Video streaming in CPS, Mobile Networks	X	6

Table C.4: Survey 2008

Summary	Ref.	Keywords	Focus	Domain	pp.
The publication defines the term CPS and its theory focusing on control theory. It offers possible future potentials of CPS, mainly increasing its efficiency.	[Wol09]	Definition, Position Paper	Potential of CPS, Control Theory	X	2
The paper proposes an approach of how to cluster WSNs that they can be transformed to CPS. The goal is to save energy and increase network life-time. The authors address the hot spot problem as nodes near a base station consuming much more transmission power as nodes far away. They offer an algorithm to detect cluster heads and propose a cluster algorithm.	[CL09]	Approach, Protocol, Simulation	WSNs as CPS, Energy Consumption	X	6
The paper deals with wireless CPS that focus on network wide energy consumption control. They make use of radio sleep scheduling with the goal to meet real-time communication deadlines.	[Xue+09]	Approach, Simulation	Power Consumption, Energy Efficiency, Real-Time Applications	X	6

This paper focuses on the battery-life extension using smart energy consumption methods namely a dynamic battery discharge model. The authors describe that when a battery is discharged under a pulsed discharge current, the diffusion process increases the electrolyte concentration at the electrodes during the idle time. This triggers the recovery effect that makes the battery regaining portions of its capacity.	[ZSW09]	Model, Evaluation	Battery Discharge in CPS, Battery Life-Time	X	6
The authors introduce a theoretical passivity-based framework for resilient CPS. The framework is able to function under a cyber-attack such as a Denial-of-Service targeting the CPS controller.	[KKS09]	Framework, Theoretical	Resilient, Security	X	8
The authors focus on user-centric CPS that deal with uncertainty and surprise being able to estimate such uncertainties with run-time monitoring.	[BBB09]	Approach, Theoretical	Stochastic Approach	X	6

The authors introduce a vision of the Cyber-Physical Internet (CPI). The paper summarizes and defines important terminologies such as CPS, IoT, Embedded Systems, Satellite Networks and WSNs. Large scale CPS are referred as Internet of CPS adding the additional Cyber-Physical Layer above the Application Layer.	[KA09]	Survey, Vision	Internet of CPS, Integration, Real-Time	X	6
Defines an adversary model focusing on attacker groups such as cyber criminals, disgruntled employees, terrorists, activists, organized criminal groups and nation states. The authors discuss new security problems, consequences of attacks, attack detection and attack-resilient algorithms.	[Car+09]	Position Paper, Survey	Security Challenges	X	7

Focus on Cyber-Physical Energy Systems (CPES) on an extremely large scale. The authors claim the need to bring together communication engineers, security engineers, control system engineers and engineers familiar with physical processes. They show and test possible attack scenarios in CPES such as attacks at SCADA networks, they discuss challenges in CPES security, offering a roadmap for security within CPESs.	[Mor+09]	Position Paper, Vision, Survey, Simulation	Energy Systems, Security, Testbed	Energy	6
Implemented a model for a service-orientated architecture in CPS. The model does not only describe the service itself, but it considers the physical entity profile, the context and the services. The services have constraints, context, preconditions (such as the physical entity has to be at a certain location), effects, context effects and service provision constraints.	[Hua+09]	Model	Context, Service orientated architecture	Disaster Management	8

Proposing a Diagnosis Quality Driven Adaptive Health Monitoring (DQAHM) System for CPS, considering resource constraints, resource requirement, diagnosis quality and criticality of each component. The described use case focuses on robots tracking objects (Mobile Object Tracking).	[Zha+09]	Model, Evaluation	Decision Making, Resource Management	X	10
In this paper the authors address the temporal and spatial properties of events, defining a novel CPS architecture, and developing a layered spatio-temporal event model for CPS.	[TVG09]	Model, Architecture	Event Handling in CPS, Temporal and Spatial	X	7
Initial work for real-time hybrid structural testing in CPS. The authors aim to create a highly configurable architecture for integrating computers and physical components that support real-time operations in distributed hybrid testing.	[Tid+09]	Approach, Case-Study, Evaluation	CPS Structural Testing	X	8
The authors use an existing simulation framework and extend it with Matlab to simulate Cyber-Physical Water Distribution Systems.	[LSM09]	Case-Study, Simulation	Integrated Simulation	Public Environment	6

The authors focus on the development of a formal approach to design methods for embedded controllers achieving prognosis and learning capabilities.	[BB09]	Formal Approach	Hilbertean formal methods, Semantics	X	10

Table C.5: Survey 2009

Summary	Ref.	Keywords	Focus	Domain	pp.
The authors combine computational network resources (cyber environment) and cooling systems (thermal physical network) with the aim to save energy in data centers. As high computation results in higher temperatures, cooling systems should be considering such information resources as system input to control the thermal network.	[PSKW12]	Approach, Simulation	Energy Cost Reduction, Energy Management	Energy	10
Introduction of an automatic abstraction model for CPS based on a petri-net approach that focuses on temperature monitoring in nuclear power plants.	[TJMZ10]	Model, Case-Study	Fault Tolerance	Energy	10
The authors examine Cyber-Physical Energy Systems (CPES) with the aim to categorize different building types and to improve energy efficiency in a 150 000 sq feet office building. The paper describes the power consumption at the University of California at San Diego (UCSD) campus for mixed-used buildings.	[KA10]	Case-Study, Analysis	Energy Consumption, Energy Saving, Zero Net Energy Building	Energy	6

This paper summarizes and tries to define the term CPS. It offers a good overview of current research topics, challenges and visions.	[RLSS10]	Position Paper, Survey	Challenges, Research Direction	Energy and Disaster Management	6
The paper provides a short summary of the research field of CPS, offering challenges and examples of CPS.	[Poo10]	Position Paper, Survey	Challenges, Research Direction	X	4
Discussing current technological trends in Medical Cyber-Physical Systems (MCPS), covering reliance on software, network connectivity and continuous patient monitoring. Robotic surgeries need real-time processing capabilities and haptic feedback. The authors claim that devices are more and more connected to each other. Automated system monitoring can help to improve safety due to human error.	[LS10]	Position Paper, Survey	Challenges, Opportunities, Research Direction	Health, Medical	6

Offering possible attacks in Cyber-Physical Systems (CPS) by abstracting the general process of a CPS. Generally, it consists out of systems that monitor physical processes, networking systems, computing and actuation systems. The authors propose a context-aware security framework addressing actuation security, feedback security, communication security, computing security and sensing security.	[Wan+10]	Analysis, Survey, Framework	Security, Attacks, Framework	X	6
Addressing trustworthiness in CPS focusing on an example of intrusion objects (e.g. enemy soldier). It illustrates the intrusion detection in a military harsh environment (Battle-Network) that improves existing approaches.	[Tan+10]	Case-Study, Evaluation	Case-Study, Trustworthiness	Military	6
The authors use a base-station approach such as in Wireless Sensor Networks using motes aggregating data in areas that are affected by congestion. They focus on congestion control in CPS and focus on the influences of spatio/temporal data.	[AAG10]	Protocol, Model, Simulation, Evaluation	Congestion Control	X	10

The authors focus on gridable vehicles that can be used as energy sources, to balance energy loads, as power storage and as small power plants in Cyber-Physical Energy grids. Additionally, the authors have conducted an evaluation and comparison of randomly charging/discharging grid vehicles, load levelling optimization that follows a smart grid model. They propose to charge the vehicle grid if renewable energy sources are available and they discharge it during peak hours.	[SV10]	Model, Approach, Evaluation	Gridable Vehicles, Smart Grid, Energy Leveling	Energy	10
The authors describe the need for end-user feedback and information sharing capabilities in power grids, such as price information and energy availability, energy locations and customers choice of service. The paper proposes a cyber-physical dynamic model including mathematical models.	[IXKM10]	Modeling CPS	How to Model CPS in CPES	Energy	15

The authors propose a mixed-criticality property for energy systems and have developed an overload-resilience metric called ductility. They target on real-time or critical tasks that can still be processed in situations of energy overloads by taking resources from tasks with lower criticality. The algorithm was applied within a radar surveillance application.	[LDNRM10]	Approach, Algorithm, Evaluation	Load Balancing, Task Allocation, Resource Management	Aerospace	10
The paper describes a semantic model (Semantic Link Model) to support decentralized intelligent applications focusing on semantic networking.	[Zhu10]	Model, Semantics, White Paper	Cyber Physical Society, Semantic, Relations	Cyber-Physical Social Systems / Society	8
The authors describe the term CPS and its different characteristics using a case study in the domain of health. The paper provides a short survey of other CPS. Moreover, they propose an early staged framework for specification and analyzing CPS.	[WMH10]	Framework, Position Paper, Survey, Case-Study	CPS Design, Simulation, Verification	Health, Medical	8

Focusing on real-time CPS detecting unauthorized instructions using timing constraints of application code. Introducing three new software methodologies that analyse timing constraints.	[ZBMM10]	Software, Simulation, Approach	Security, Intrusion Detection, Deeply Embedded Systems	X	10

Table C.6: Survey 2010

Summary	Ref.	Keywords	Focus	Domain	pp.
The authors provide a survey on Cyber-Physical Energy Systems, describing main areas of research, presenting related work and offer a proposal of how to model smart grids.	[MQMN11]	Survey, Position Paper, Approach	Smart Grids, Energy Systems	Energy	7
Offers a CPS definition and defines the term dependability in CPS. The authors explain dependability in CPS using a case-study of a hydropower production field.	[MS11]	Definition, Model	Dependability, Availability, Correctness, Security, Self Testing	Energy	5
Offering a detailed literature review and cover features of CPS. The authors summarizing current research processes, possible domains and research challenges.	[SWYS11]	Survey, Position Paper	CPS in general, Features, Challenges, Research Fields	X	6
The publication describes a new architecture and algorithm for CPS that focuses on communication and control co-desing. The main goal is to guarantee system stability in case messages violate their timing constraints.	[GSC11]	Algorithm, Use-Case, Simulation, Evaluation	Flex-Ray, Bus-System, Communication Delays	X	6

Discussing current state of the art QoS mechanisms, challenges and propose a new web of things based QoS framework. QoS comprises computation, network and hardware. The framework modularizes a CPS where the kernel of the CPS is handling all the QoS.	[DPST11]	Mechanism, Case-Study	Quality of Service	Energy	6
The authors describe Cyber-Physical Social Systems that integrate the cyber and physical space as well as human knowledge, mental capabilities and sociocultural elements. Additionally, they propose a framework for self-synchronization that integrates self-organizing and self-adapting command and control processes.	[Liu+11]	Definition, Framework	Cyber-Physical Social Systems, Self-Organisation	Cyber-Physical Social Systems, Society	5
Proposing a framework and monitoring procedures to detect and identify network malfunction caused by adversary. Offering limitations of static and dynamic attack detection and an evaluation of it.	[PDB11]	Model, Framework, Design, Evaluation	Power Networks, Detection and Identification of Attacks	Energy	7
Giving an overview about CPS in Smart Grids. Offering market trends and technological trends and finally discussing emerging directions.	[Kar11]	Position Paper	Smart Grids, Market,Technology Trends	Energy	4

Introducing a system called Cyber-Physical Cloud where multiple Wireless Sensor Networks are connected to each other providing multiple data recourses for a variety of applications. Focusing on real-time query schedule offering long life-times of motes keeping energy consumption at a minimum.	[Phu+11]	Model, Framework, Evaluation	QoS and Energy Consumption, Virtualization, Cloud	X	10
Presenting energy consumption interaction automata to model energy consumption constraints in CPS. As a result, an analysis of interaction behavior and energy consumption can be performed.	[JZX11]	Formal Model	Energy Consumption Constraints, Energy Analysis	X	4
Offers an overview and definition of CPS concerning energy sustainability and efficiency. Additionally names CPS examples and CPS architectures such as Body Sensor Networks and Data Center.	[GMVB11]	Position Paper, Survey	Energy Sustainability in CPS, Research Directions, Resource Management	Energy	18
Developed a prototype for public transportation where data is acquired by public masses to enhance planning with public transportation. Deploying the CPS in the cyber physical socio space where user interaction is a key factor.	[LTL11]	Prototype System, Evaluation	Public Transport Information Exchange ,Extendability, API	Transportation	6

The authors designed a hybrid theoretical framework for robust and resilient control design applying it to a power generator system.	[ZB11]	Theoretical Framework	Robustness and Resilient Control Design for CPS	Energy	6
Addressing the security problem due to unknown controller software within the CPS. They make the use of sandboxing (simplex architecture) as a common technique to reduce security risks from an untrusted CPS controller.	[BMMC11]	Model, Design	Sandboxing, Software, Security	X	10
Using statistical model checking to face uncertainties like unreliable sensor reading and addressing the verification problem in CPS. As CPS model they use a fuel control system modeled with Stateflow/Simulink.	[CZ11]	Model, Simulation	Statistical Models, Simulation used for Embedded Systems	X	12

Table C.7: Survey 2011

Summary	Ref.	Keywords	Focus	Domain	pp.
The authors offer a detailed survey about CPS from a historical point of view and from a technological perspective. They offer research challenges such as security, QoS, design and development within the domain of energy systems, transportation and health-care and medical systems.	[KK12]	Survey, Position Paper	On Historical Review, Technologies, Challenges, Overview	X	20
Focusing on communication addressing the challenge of uncertain destinations in CPS. The authors developed a framework tested within an 4-bus power grid.	[LLP12]	Framework, Communication, Evaluation	Multicast Routing, Framework to Test Communication	Energy	11
The authors describe a component-based software engineering approach where the actual program logic is separated from hardware configuration logic. Adapted the Kevoree model from Android and Java and ported it to microcontroller to reconfigure nodes with reconfiguration scripts directly uploaded.	[Fou+12]	Framework, Case-Study, Microcontroller	Arduino, Reconfigurability, Flexibility	Buildings	10
Dealing with Cyber-Physical Security in Smart Grids, showing system requirements and possible attacks in Cyber-Physical Systems.	[Mo+12]	Position Paper	Cyber-Physical Security	Energy	15

Focuses on autonomous driving vehicles. Summarizing the results of 2007 DARPA Urban Challenge from the last 5 years in autonomous driving vehicles seen as Cyber-Physical Systems. Offering a survey on challenges, results and techniques within CPS research.	[BR12]	Position Paper, Survey	Summary, Autonomous Driving, Challenges	Mobility, Automotive	10
Explaining the three aspects sustainability, safety and security in CPS and their key aspects resulting in a formal framework for CPS representation, demonstrating them in several domains.	[BVMG12]	Survey, Formal Framework	Safety, Security, Sustainability	X	17
Claiming the need for a more holistic system design in CPS in automotive domain, focusing on Electronic Control Units communication over CAN or Flexray, offering a design flow.	[Gos+12]	Position Paper, System Design	Challenges, Automotive CPS	Mobility, Automotive	9
The authors focus on the design phase of the system life-cycle, proposing a passivity-based approach to decouple system stability from cyber timing. It is a passivity-based approach to decouple system stability from timing uncertainties.	[Szt+12]	Approach, Simulation, Evaluation	System Integration in CPS, Unmanned Vehicles	Aerospace	16

Service-orientated architecture for Transportation CPS focusing on Computation, Communication, Control and Service. Introducing a layer architecture that consists of perception- , communicating-, computation-, control-, and service-layer.	[YDWX12]	Architecture, Model	T-CPS, Intelligent Transportation System	Transportation	5
Authors want to improve reliability in CPS implementing a data-centric monitoring system (ARIS) using data-analysing techniques and an operator in-the-loop to detect abnormal behaviors.	[WK12]	Framework	Case-Study, Framework, Reliability, Monitoring System	Buildings	6
Dealing with challenges associated with communication, altitude and orbit determination, control and payload management. Providing an overview of cyber and physical elements in space specific CPS.	[KCA12]	Challenges, Position Paper	Communication, Payload Management	Aerospace	8
Offering a risk assessment process and methodologies for impact evaluation. Illustrating security concerns resulting in research efforts and possible weaknesses.	[SHG12]	Challenges, Overview	Security, Cyber Security, Power Grids	Energy	15
Monitor patients remotely, pre-processing of events (heart-beats) with an additional classification scheme, delivering classified data saving time and storage.	[DCM12]	Architecture	Architecture Design Framework, Events, Test, M-CPS	Health, Medical	5

The authors examine cascading network failures in CPS where a node failure in network A results in node failure in network B. B causes node failure in A again resulting in an avalanche of failures. Proposing an interlink-allocation model to overcome random attacks.	[YQZC12]	System Model, Simulation	Cascading Network Failures, Random Network Attacks	X	13
Offering a formulated algorithm for mixed critical systems such as vehicles. The algorithm improves QoC still guaranteeing schedulability.	[SGMC12]	Algorithm	Real-Time Constraints and Quality of Control	X	8

Table C.8: Survey 2012

Summary	Ref.	Keywords	Focus	Domain	pp.
Cooperation project with the aim to develop a reliable, safe and secure run-time platform for CPS. Describing the requirements, current status and upcoming results.	[Lim+13]	Architecture, Platform	Run-Time Platform	X	7
The authors discuss a diagnostic and prognostic framework applying it to two use-cases, a regenerative braking system and an electric power generation and storage system.	[SKP13]	Framework, Simulation	Diagnostic, Prognostic, Failures	Mobility, Automotive	5
The authors describe their modeling framework for CPS with the focus on detectability and identificability of an attack. Authors discover that some attacks are undetectable.	[PDB13]	Mathematical Framework	Attack Detection and Identification, Graph Theory	X	14
In this paper an unmanned air vehicle (UAV) is modeled with the framework Ptolemy II. After the design they simulate the system.	[Kan+13]	Design, Simulation, Framework	Modeling, Simulation, Prolemy II Framework	Aerospace	4

Implemented CPSim that is capable to integrate several simulators designed for CPS subsystems. Focusing on synchronization issues offering a design and simulation framework for CPS keeping synchronization times at a minimum.	[CS13]	Framework, Simulation	Simulation for Large Scale CPS	Transportation	8
Survey of recent research of Cyber-Physical Energy Systems also mentioning other research areas and applications. Offering an overview and summarizing recent publications.	[KM13]	Survey, Position Paper	Power Grids, Classification, Design Approaches, Other Areas	Energy	5
The authors combine two powerful frameworks for modeling and verification, namely Averest and KeYmaera to offer interactive verification.	[LBS13]	Framework, Simulation	Verification, Interactive Verification	X	8
Focusing on the collaboration in CPS especially between control and embedded software engineers. Offering different types of interface contracts both domains can use. Additionally, the work offers an overview of simulation frameworks and concepts of both engineering domains.	[DLTT13]	Framework, Collaboration, Overview	Interface Contracts, Collaboration, Timing and functionality	X	10

Author focuses on cell phone based CPS addressing the need for proper validation, verification and modeling techniques. Offering an overview on difficulties and giving an insight towards cell phone based CPS applications.	[Pod13]	Position Paper, Overview	Cell Phone based CPS	X	5
Offering a reusable and reliable human interactive hardware in the loop simulation framework for fully distributed operating environments.	[KKKC13]	Simulation, Framework	Hardware in the Loop Simulation, Case-Study	Aerospace	5
Implemented a simulation framework for CPS called HybridSim, testing it in a case-study of smart buildings concerning packet loss and sampling rate.	[WB13]	Simulation, Framework	Simulation, Modeling, Simulation, Toolchain	Buildings	8
Introducing definitions of the term CPS and System of Systems. Offers potential risk factors in CPS and how to measure such risks. Additionally, offers risk minimization strategies.	[Axe13]	Overview, Position Paper, Model	Security, Risk Management, Risk Factors	X	6
Design of resilient controllers in CPS facing DoS attacks. The authors are proposing a methodology to design the intrusion detection system configuration policy at the cyber-layer and the controller for the physical layer system.	[Yua+13]	Approach Simulation	DoS Attacks, Malicious Jamming, Security	Energy	6

Offering a vulnerability analysis for CPS. Using an attack tree being able to calculate the threat vector of an attack path.	[Xie+13]	Approach	Risk Assessment, Security	X	4
The authors offer a modeling and specification approach for CPS systems applying the lessons learned from a practical design of biodigester. They suggest the 3D Approach based on the 4-Variable Model.	[Ord+13]	Approach, Modeling	Requirements of CPS, 4 Variable Model	Environmental	8

Table C.9: Survey 2013

Summary	Ref.	Keywords	Focus	Domain	pp.
The authors address the problem of buffer overshoots during runtime verification, designing an extra controller. The controller is tested in a case study of engine air/fuel control system.	[MKBF14]	Approach, Case-Study, Experiment	Time Predictability, Runtime Verification, Control Theory	Mobility, Automotive	12
Describing a Vehicular CPS architecture consisting of traffic control center, road side units, relay nodes and mobile devices. Proposing the two services: Interactive Navigation Service and Pedestrian Protection Service.	[JL14]	Design, Architecture	Vehicular CPS, Smart Road Services	Mobility, Automotive	6
The authors are introducing a stochastic analytical framework to study epidemic routing using network coding (ERNC) in Vehicular CPS. Additionally, simulations are performed offering detailed performance analysis.	[Zen+14]	Stochastic Framework, Simulations	Vehicular CPS, Routing	Mobility, Automotive	12
Offering distributed and centralized scheduling algorithms for wireless communication (MAC-Layer) in CPS. Simulation and evaluation of the algorithms is offered.	[LHDZ14]	Model, Algorithms	Traffic Scheduling, Hybrid Systems	Energy	11

Focusing on self -configuring honeypots in CPS Networks using network analysis tools. Aim is to observe and attract network intruder activities. The algorithm was tested within a small campus grid.	[VM14b]	Algorithm, Simulation	HoneyPots, Network analysis, Autoconfiguration	Manufacturing	11
Overview of the terms Cyber-Physical Cloud, Cloud of Sensors and Internet of Things. Demonstrating their special characteristics, differences and similarities.	[SPR14]	Survey, Overview	CPS, CP-Cloud, Cloud of Sensors, IoT	X	9
The author offers a middleware using state of the art and state of practise verification and validation techniques. Conducted expert interviews, developed a framework for unit and integration testing for CPS applications.	[Zhe14]	Middleware	Verification, Validation, Debug, Middleware	X	3
Introduce a generic functional Cyber Intelligent Enterprise Architecture including a physical layer, a middleware layer and an application layer. Describing its components in detail.	[Rep+14]	Framework	Cyber Intelligent Enterprise	X	6
Developed a CPS architecture model of an aircraft fuel management system using binary decision diagram and continuous-time Markov Chain to analyse the reliability of the CPS.	[SHWZ14]	Model	Markov-Model, Phased-Mission System, Reliability of CPS	Aerospace	5

Offering an approach to secure hierarchical multi-agent systems using cryptography and steganography to create secure CPS. Keys are generated and distributed due to an outside entity and stenographically integrated in images.	[VM14a]	Model, Algorithm, System	Security, Encryption	X	4
Introducing a method to compute a language based guarantee. The guarantee characterises the deadline hit and miss patterns of jobs in a task.	[DKGT14]	Method	Language Based Guarantee, Deadline, Timing	X	6
Offering a traffic morphing algorithm to hide CPS specific traffic within internet communication, to reduce traffic analysis attacks, showing moderate overhead still meeting real-time constraints.	[LDZ14]	Algorithm	Security, CPS Communication Morphing, Evaluation	X	7
Using a functional modelling compiler used in the design phase to evaluate how different automotive components can be used to meet non- and functional requirements for future automotive CPS.	[CFR14]	Model, Simulation	Compiler, Automation, Simulation	Mobility, Automotive	2
Implemented a SystemC-based virtual platform framework,testing it with an automotive fuel injection control system. Aiming on stress-, robustness- and mutation-testing.	[BKM14]	Platform, Experiment	Model based Design, Physical Environment	Mobility, Automotive	8

Table C.10: Survey 2014

Bibliography

[AAG10] H. Ahmadi, T. F. Abdelzaher, and I. Gupta. "Congestion control for spatio-temporal data in cyber-physical systems." In: *International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. 2010, pp. 89–98 (cit. on p. 110).

[Aar04] E. H. L. Aarts. "Ambient Intelligence: A Multimedia Perspective." In: *IEEE MultiMedia* 11.1 (2004), pp. 12–19 (cit. on p. 5).

[Ain10] B. Ainapure. *Object Oriented Modeling And Design*. Technical Publications, 2010 (cit. on p. 13).

[ASFB17] L. Alperowitz, C. Scheuermann, N. von Frankenberg, and B. Bruegge. "From Storyboards to Code: Visual Product Backlogs in Agile Project Courses." In: *5. Workshop für Software Engineering im Unterricht der Hochschulen*. Hanover, 2017 (cit. on p. 19).

[AV10] I. Akyildiz and M. Vuran. *Wireless Sensor Networks*. Advanced Texts in Communications and Networking. Wiley, 2010 (cit. on p. 4).

[AW09] E. Aarts and R. Wichert. "Ambient intelligence." In: *Technology Guide: Principles – Applications – Trends*. Ed. by H.-J. Bullinger. Springer Berlin Heidelberg, 2009, pp. 244–249 (cit. on p. 5).

[Axe13] C. Axelrod. "Managing the risks of cyber-physical systems." In: *Systems, Applications and Technology Conference (LISAT)*. 2013, pp. 1–6 (cit. on p. 124).

[BB09] M. Bujorianu and H. Barringer. "An Integrated Specification Logic for Cyber-Physical Systems." In: *International Conference on Engineering of Complex Computer Systems*. IEEE. 2009, pp. 291–300 (cit. on p. 107).

[BBB09] M. Bujorianu, M. Bujorianu, and H. Barringer. "A unifying specification logic for cyber-physical systems." In: *Mediterranean Conference on Control and Automation*. 2009, pp. 1166–1171 (cit. on p. 103).

[BKM14] M. Becker, C. Kuznik, and W. Mueller. "Virtual Platforms for Model-Based Design of Dependable Cyber-Physical System Software." In: *Euromicro Conference on Digital System Design (DSD)*. 2014, pp. 246–253 (cit. on p. 128).

[BMMC11] S. Bak, K. Manamcheri, S. Mitra, and M. Caccamo. “Sandboxing controllers for cyber-physical systems.” In: *International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. 2011, pp. 3–12 (cit. on p. 117).

[Bon08] B. Bonakdarpour. “Challenges in transformation of existing real-time embedded systems to cyber-physical systems.” In: *ACM SIGBED Review* 5.1 (2008), p. 11 (cit. on p. 99).

[BR12] C. Berger and B. Rumpe. “Autonomous Driving - 5 Years after the Urban Challenge: The Anticipatory Vehicle as a Cyber-Physical System.” In: *GI-Jahrestagung*. 2012, pp. 789–798 (cit. on pp. 12, 119).

[BVMG12] A. Banerjee, K. Venkatasubramanian, T. Mukherjee, and S. Gupta. “Ensuring Safety, Security, and Sustainability of Mission-Critical Cyber-Physical Systems.” In: *Proceedings of the IEEE* 100.1 (2012), pp. 283–299 (cit. on p. 119).

[CAJ09] D. J. Cook, J. C. Augusto, and V. R. Jakkula. “Ambient intelligence: Technologies, applications, and opportunities.” In: *Pervasive and Mobile Computing* 5.4 (2009), pp. 277–298 (cit. on p. 5).

[Cal03] E. H. Callaway. *Wireless Sensor Networks: Architectures and Protocols*. Internet and Communications. Taylor & Francis, 2003 (cit. on p. 4).

[Car+09] A. Cardenas, S. Amin, B. Sinopoli, A. Giani, A. Perrig, and S. Sastry. “Challenges for securing cyber physical systems.” In: *Workshop on future directions in cyber-physical systems security*. 2009 (cit. on p. 104).

[CAS08] A. Cardenas, S. Amin, and S. Sastry. “Secure Control: Towards Survivable Cyber-Physical Systems.” In: *International Conference on Distributed Computing Systems Workshops (ICDCS)*. 2008, pp. 495–500 (cit. on p. 100).

[CFR14] A. Canedo, M. A. A. Faruque, and J. H. Richter. “Multi-disciplinary integrated design automation tool for automotive cyber-physical systems.” In: *Design, Automation & Test in Europe Conference & Exhibition*. 2014, pp. 1–2 (cit. on p. 128).

[CGM06] J. Campbell, S. Goldstein, and T. Mowry. “Cyber-physical systems.” In: *National Science Foundation Workshop on Cyber-Physical Systems*. 2006 (cit. on pp. 11, 95).

[Che08] A. Cheng. “Cyber-Physical Medical and Medication Systems.” In: *International Conference on Distributed Computing Systems Workshops (ICDCS)*. 2008, pp. 529–532 (cit. on pp. 12, 101).

[CL09] J. Cao and H. Li. “Energy-Efficient Structuralized Clustering for Sensor-Based Cyber Physical Systems.” In: *Symposia and Workshops on Ubiquitous, Autonomic and Trusted Computing*. 2009, pp. 234–239 (cit. on p. 102).

[Com+16] B. Combemale, R. France, J. Jézéquel, B. Rumpe, J. Steel, and D. Vojtisek. *Engineering Modeling Languages: Turning Domain Knowledge into Tools*. Chapman & Hall/CRC Innovations in Software Engineering and Software Development Series. CRC Press, 2016 (cit. on p. 13).

[Cre+07] T. L. Crenshaw, E. Gunter, C. L. Robinson, L. Sha, and P. Kumar. "The simplex reference model: Limiting fault-propagation due to unreliable components in cyber-physical system architectures." In: *International Symposium on Real-Time Systems*. IEEE. 2007, pp. 400–412 (cit. on p. 96).

[CS13] C.-T. Chu and C.-S. Shih. "CPSSim: Simulation framework for large-scale Cyber-Physical Systems." In: *International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)*. IEEE. 2013, pp. 44–51 (cit. on p. 123).

[CZ11] E. M. Clarke and P. Zuliani. "Statistical model checking for cyber-physical systems." In: *Automated Technology for Verification and Analysis*. Springer, 2011, pp. 1–12 (cit. on p. 117).

[DCM12] S. Don, E. Choi, and D. Min. "Event driven adaptive awareness system for Medical Cyber Physical Systems." In: *International Conference on Awareness Science and Technology (iCAST)*. 2012, pp. 238–242 (cit. on p. 120).

[DKGT14] N. Dhruva, P. Kumar, G. Giannopoulou, and L. Thiele. "Computing a language-based guarantee for timing properties of cyber-physical systems." In: *Design, Automation and Test in Europe Conference and Exhibition*. 2014, pp. 1–6 (cit. on p. 128).

[DLTT13] P. Derler, E. A. Lee, S. Tripakis, and M. Tòrngren. "Cyber-physical System Design Contracts." In: *International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. 2013, pp. 109–118 (cit. on p. 123).

[DP10] W. Dargie and C. Poellabauer. *Fundamentals of Wireless Sensor Networks: Theory and Practice*. Wireless Communications and Mobile Computing. Wiley, 2010 (cit. on pp. 3, 4).

[DPST11] T. Dillon, V. Potdar, J. Singh, and A. Talevski. "Cyber-physical systems: Providing Quality of Service (QoS) in a heterogeneous systems-of-systems environment." In: *International Conference on Digital Ecosystems and Technologies Conference (DEST)*. IEEE. 2011 (cit. on p. 115).

[Fou+12] F. Fouquet, B. Morin, F. Fleurey, O. Barais, N. Plouzeau, and J.-M. Jezequel. "A dynamic component model for cyber physical systems." In: *Symposium on Component Based Software Engineering*. ACM. 2012, pp. 135–144 (cit. on p. 118).

[Gil07] C. Gill. “Cyber-Physical System Software for HCMDSS.” In: *Joint Workshop on High Confidence Medical Devices, Software, and Systems and Medical Device Plug-and-Play Interoperability*. IEEE. 2007, pp. 176–177 (cit. on p. 96).

[Gli+15] K. Glitz, U Seibel, U Rohde, W Gorges, A Witzki, C Piekarski, and D Leyk. “Reducing heat stress under thermal insulation in protective clothing: microclimate cooling by a ’physiological’ method.” In: *Ergonomics* 58.8 (2015), pp. 1461–1469 (cit. on p. 75).

[GMVB11] S. K. Gupta, T. Mukherjee, G. Varsamopoulos, and A. Banerjee. “Research directions in energy-sustainable cyber-physical systems.” In: *Sustainable Computing: Informatics and Systems* 1.1 (2011), pp. 57–74 (cit. on p. 116).

[Gos+12] D. Goswami, R. Schneider, A. Masrur, M. Lukasiewycz, S. Chakraborty, H. Voit, and A. Annaswamy. “Challenges in automotive cyber-physical systems design.” In: *International Conference on Embedded Computer Systems (SAMOS)*. IEEE. 2012, pp. 346–354 (cit. on p. 119).

[GSC11] D. Goswami, R. Schneider, and S. Chakraborty. “Co-design of cyber-physical systems via controllers with flexible delay constraints.” In: *Asia and South Pacific Design Automation Conference*. IEEE. 2011, pp. 225–230 (cit. on p. 114).

[GSDL15] T. Guo, B. Shang, B. Duan, and X. Luo. “Design and testing of a liquid cooled garment for hot environments.” In: *Journal of thermal biology* 49 (2015), pp. 47–54 (cit. on p. 75).

[Hea02] S. Heath. *Embedded Systems Design*. Elsevier Science, 2002 (cit. on p. 2).

[HPO16] M. Hermann, T. Pentek, and B. Otto. “Design Principles for Industrie 4.0 Scenarios.” In: *Hawaii International Conference on System Sciences (HICSS)*. 2016, pp. 3928–3937 (cit. on pp. 5, 6).

[Hua+09] J. Huang, F. Bastani, I.-L. Yen, J. Dong, W. Zhang, F.-J. Wang, and H.-J. Hsu. “Extending service model to build an effective service composition framework for cyber-physical systems.” In: *International Conference on Service-Oriented Computing and Applications (SOCA)*. IEEE. 2009, pp. 1–8 (cit. on p. 105).

[IXKM08] M. D. Ilic, L. Xie, U. A. Khan, and J. M. Moura. “Modeling future cyber-physical energy systems.” In: *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*. IEEE. 2008, pp. 1–9 (cit. on pp. 12, 99).

[IXKM10] M. D. Ilic, L. Xie, U. A. Khan, and J. M. F. Moura. “Modeling of Future Cyber Physical Energy Systems for Distributed Sensing and Control.” In: *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 40.4 (2010), pp. 825–838 (cit. on p. 111).

[Jaa+09] M. G. Jaatun, E. Albrechtsen, M. B. Line, I. A. Tøndel, and O. H. Longva. "A framework for incident response management in the petroleum industry." In: *International Journal of Critical Infrastructure Protection* 2.1 (2009), pp. 26–37 (cit. on p. 31).

[JL14] J. Jeong and E. Lee. "VCPS: Vehicular Cyber-physical Systems for Smart Road Services." In: *International Conference on Advanced Information Networking and Applications Workshops (WAINA)*. 2014, pp. 133–138 (cit. on pp. 12, 126).

[JZX11] Y. Jia, Z. Zhang, and S. Xie. "Modeling and verification of interactive behavior for cyber-physical systems." In: *International Conference on Software Engineering and Service Science (ICSESS)*. IEEE. 2011, pp. 552–555 (cit. on p. 116).

[KA09] A. Koubâa and B. Andersson. "A vision of cyber-physical internet." In: *Satellite Workshop to ECRTS Proc. of the Workshop of Real-Time Networks (RTN)*. 2009 (cit. on p. 104).

[KA10] J. Kleissl and Y. Agarwal. "Cyber-physical energy systems: Focus on smart buildings." In: *Design Automation Conference*. 2010, pp. 749–754 (cit. on pp. 12, 108).

[Kan+13] A. Kanduri, A.-M. Rahmani, P. Liljeberg, K. Wan, K. L. Man, and J. Plosila. "A multicore approach to model-based analysis and design of Cyber-Physical Systems." In: *International SoC Design Conference (ISOCC)*. 2013, pp. 278–281 (cit. on p. 122).

[Kar11] S. Karnouskos. "Cyber-Physical Systems in the SmartGrid." In: *International Conference on Industrial Informatics (INDIN)*. IEEE. 2011, pp. 20–23 (cit. on p. 115).

[KCA12] A. Klesh, J. Cutler, and E. Atkins. "Cyber-Physical Challenges for Space Systems." In: *Third International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. 2012, pp. 45–52 (cit. on p. 120).

[KH08] V. Krunic and R. Han. "Towards Cyber-Physical Holodeck Systems Via Physically Rendered Environments (PRE's)." In: *International Conference on Distributed Computing Systems Workshops (ICDCS)*. 2008, pp. 507–512 (cit. on pp. 11, 101).

[Kim+07] S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser, and M. Turon. "Health monitoring of civil infrastructures using wireless sensor networks." In: *International Symposium on Information Processing in Sensor Networks (IPSN)*. IEEE. 2007, pp. 254–263 (cit. on p. 4).

[KK12] K.-D. Kim and P. Kumar. “Cyber-Physical Systems: A Perspective at the Centennial.” In: *Proceedings of the IEEE* 100.Special Centennial Issue (2012), pp. 1287–1308 (cit. on p. 118).

[KKKC13] M.-J. Kim, S. Kang, W.-T. Kim, and I. geol Chun. “Human-interactive hardware-in-the-loop simulation framework for cyber-physical systems.” In: *Second International Conference on Informatics and Applications (ICIA)*. 2013, pp. 198–202 (cit. on p. 124).

[KKP99] J. M. Kahn, R. H. Katz, and K. S. J. Pister. “Next Century Challenges: Mobile Networking for ’Smart Dust’.” In: *International Conference on Mobile Computing and Networking*. MobiCom ’99. ACM/IEEE. New York, NY, USA: ACM, 1999, pp. 271–278 (cit. on p. 3).

[KKS09] N. Kottenstette, G. Karsai, and J. Sztipanovits. “A passivity-based framework for resilient cyber physical systems.” In: *International Symposium on Resilient Control Systems (ISRCS)*. 2009, pp. 43–50 (cit. on p. 103).

[KM08] J. E. Kim and D. Mosse. “Generic framework for design, modeling and simulation of cyber physical systems.” In: *ACM SIGBED Review* 5.1 (2008), p. 1 (cit. on p. 99).

[KM13] S. Khaitan and J. McCalley. “Cyber physical system approach for design of power grids: A survey.” In: *Power and Energy Society General Meeting (PES)*. IEEE. 2013, pp. 1–5 (cit. on pp. 12, 123).

[KS08] K.-D. Kang and S. Son. “Real-Time Data Services for Cyber Physical Systems.” In: *International Conference on Distributed Computing Systems Workshops (ICDCS)*. 2008, pp. 483–488 (cit. on p. 100).

[Lar+15] B. Larsen, R. Snow, G. Vincent, J. Tran, A. Wolkow, and B. Aisbett. “Multiple days of heat exposure on firefighters’ work performance and physiology.” In: *PloS one* 10.9 (2015), e0136413 (cit. on p. 75).

[LBS13] X. Li, K. Bauer, and K. Schneider. “Interactive verification of cyber-physical systems: Interfacing Averest and KeYmaera.” In: *Federated Conference on Computer Science and Information Systems (FedCSIS)*. 2013, pp. 1405–1412 (cit. on p. 123).

[LDNRM10] K. Lakshmanan, D. De Niz, R. Rajkumar, and G. Moreno. “Resource Allocation in Distributed Mixed-Criticality Cyber-Physical Systems.” In: *International Conference on Distributed Computing Systems (ICDCS)*. IEEE. 2010, pp. 169–178 (cit. on p. 112).

[LDZ14] Y. Li, R. Dai, and J. Zhang. “Morphing communications of Cyber-Physical Systems towards moving-target defense.” In: *International Conference on Communications (ICC)*. IEEE. 2014, pp. 592–598 (cit. on p. 128).

[Lee08] E. A Lee. “Cyber Physical Systems: Design Challenges.” In: *International Symposium on Object Oriented Real-Time Distributed Computing (ISORC).* IEEE. 2008, pp. 363–369 (cit. on pp. 11, 12).

[LHDZ14] H. Li, Z. Han, A. Dimitrovski, and Z. Zhang. “Data Traffic Scheduling for Cyber Physical Systems With Application in Voltage Control of Distributed Generations: A Hybrid System Framework.” In: *Systems Journal, IEEE* 8.2 (2014), pp. 542–552 (cit. on p. 126).

[Lim+13] S.-S. Lim, E.-J. Im, N. Dutt, K. W. Lee, I. Shin, C.-G. Lee, and I. Lee. “A Reliable, Safe, and Secure Run-Time Platform for Cyber Physical Systems.” In: *International Conference on Service-Oriented Computing and Applications (SOCA).* IEEE. 2013, pp. 268–274 (cit. on p. 122).

[Liu+11] Z. Liu, D.-S. Yang, D. Wen, W.-M. Zhang, and W. Mao. “Cyber-Physical-Social Systems for Command and Control.” In: *Intelligent Systems, IEEE* 26.4 (2011), pp. 92–96 (cit. on pp. 12, 13, 115).

[LKV01] R. R. Lummus, D. W. Krumwiede, and R. J. Vokurka. “The relationship of logistics to supply chain management: developing a common industry definition.” In: *Industrial Management & Data Systems* 101.8 (2001), pp. 426–432 (cit. on p. 26).

[LLP12] H. Li, L. Lai, and H. Poor. “Multicast Routing for Decentralized Control of Cyber Physical Systems with an Application in Smart Grid.” In: *IEEE Journal on Selected Areas in Communications* 30.6 (2012), pp. 1097–1107 (cit. on p. 118).

[LMU99] C. of Logistics Management (U.S.) *What It’s All About–purpose, Objectives, Programs, Policies.* The Council, 1999 (cit. on p. 26).

[LS10] I. Lee and O. Sokolsky. “Medical Cyber Physical Systems.” In: *Design Automation Conference (DAC).* ACM/IEEE. 2010, pp. 743–748 (cit. on pp. 12, 109).

[LSM09] J. Lin, S. Sedigh, and A. Miller. “Towards Integrated Simulation of Cyber-Physical Systems: A Case Study on Intelligent Water Distribution.” In: *International Conference on Dependable, Autonomic and Secure Computing.* IEEE. 2009, pp. 690–695 (cit. on p. 106).

[LTL11] J.-S. Lau, C.-K. Tham, and T. Luo. “Participatory Cyber Physical System in Public Transport Application.” In: *International Conference on Utility and Cloud Computing (UCC).* IEEE. 2011, pp. 355–360 (cit. on p. 116).

[LY02] K. Lyytinen and Y. Yoo. “Ubiquitous computing.” In: *Communications of the ACM* 45.12 (2002), pp. 63–96 (cit. on p. 5).

[Mar10] P. Marwedel. *Embedded System Design: Embedded Systems Foundations of Cyber-Physical Systems*. Embedded Systems. Springer, 2010 (cit. on pp. 2, 11).

[MC14] R. Mitchell and I. Chen. “A Survey of Intrusion Detection Techniques for Cyber-physical Systems.” In: *ACM Comput. Surv.* 46.4 (2014), 55:1–55:29 (cit. on p. 12).

[MKBF14] R. Medhat, D. Kumar, B. Bonakdarpour, and S. Fischmeister. “Sacrificing a little space can significantly improve monitoring of time-sensitive cyber-physical systems.” In: *International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. 2014, pp. 115–126 (cit. on p. 126).

[Mo+12] Y. Mo, T.-H. Kim, K. Brancik, D. Dickinson, H. Lee, A. Perrig, and B. Sinopoli. “Cyber-Physical Security of a Smart Grid Infrastructure.” In: *Proceedings of the IEEE* 100.1 (2012), pp. 195–209 (cit. on p. 118).

[Moh14] A. V. Moholkar. “Security for Cyber-Physical Systems.” In: 1.6 (2014), pp. 257–262 (cit. on p. 11).

[Mor+09] T. Morris, A. Srivastava, B. Reaves, K. Pavurapu, S. Abdelwahed, R. Vaughn, W. McGrew, and Y. Dandass. “Engineering future cyber-physical energy systems: Challenges, research needs, and roadmap.” In: *North American Power Symposium (NAPS)*. 2009, pp. 1–6 (cit. on pp. 12, 105).

[MPPT12] N. Mitton, S. Papavassiliou, A. Puliafito, and K. S. Trivedi. “Combining Cloud and sensors in a smart city environment.” In: *EURASIP Journal on Wireless Communications and Networking* 2012.1 (2012), p. 247 (cit. on p. 6).

[MQMN11] C. Macana, N. Quijano, and E. Mojica-Nava. “A survey on Cyber Physical Energy Systems and their applications on smart grids.” In: *PES Conference on Innovative Smart Grid Technologies (ISGT Latin America)*. IEEE. 2011, pp. 1–7 (cit. on pp. 12, 114).

[MS11] L. Miclea and T. Sanislav. “About dependability in cyber-physical systems.” In: *East-West Design Test Symposium (EWDTS)*. 2011, pp. 17–21 (cit. on p. 114).

[Nap+11] M. Naphade, G. Banavar, C. Harrison, J. Paraszczak, and R. Morris. “Smarter cities and their innovation challenges.” In: *Computer* 44.6 (2011), pp. 32–39 (cit. on p. 6).

[Noe12] T. Noergaard. *Embedded Systems Architecture: A Comprehensive Guide for Engineers and Programmers*. Embedded technology series. Elsevier Science, 2012 (cit. on p. 2).

[Nor+10] E. Normand, J. L. Wert, H. Quinn, T. D. Fairbanks, S. Michalak, G. Grider, P. Iwanchuk, J. Morrison, S. Wender, and S. Johnson. "First Record of Single-Event Upset on Ground, Cray-1 Computer at Los Alamos in 1976." In: *IEEE Transactions on Nuclear Science* 57.6 (2010), pp. 3114–3120 (cit. on p. 1).

[OKTW16] H. Otani, M. Kaya, A. Tamaki, and P. Watson. "Separate and combined effects of exposure to heat stress and mental fatigue on endurance exercise capacity in the heat." In: *European Journal of Applied Physiology* (2016), pp. 1–11 (cit. on p. 75).

[Ord+13] L. Ordinez, O. Alimenti, E. Rinland, M. Gomez, and J. Marchetti. "Modeling and Specifying Requirements for Cyber-Physical Systems." In: *Latin America Transactions, IEEE (Revista IEEE America Latina)* 11.1 (2013), pp. 625–632 (cit. on p. 125).

[PDB11] F. Pasqualetti, F. Dorfler, and F. Bullo. "Cyber-physical attacks in power networks: Models, fundamental limitations and monitor design." In: *Conference on Decision and Control and European Control Conference (CDC-ECC)*. IEEE. 2011, pp. 2195–2201 (cit. on p. 115).

[PDB13] F. Pasqualetti, F. Dorfler, and F. Bullo. "Attack Detection and Identification in Cyber-Physical Systems." In: *IEEE Transactions on Automatic Control* 58.11 (2013), pp. 2715–2729 (cit. on p. 122).

[Pet16] S. M. Peters. "MIBO – A Framework for the Integration of Multimodal Intuitive Controls in Smart Buildings." Dissertation. München: Technische Universität München, 2016 (cit. on pp. 14, 16).

[Phu+11] L. T. T. Phuong, N. T. Hieu, J. Wang, S. Lee, and Y.-K. Lee. "Energy Efficiency Based on Quality of Data for Cyber Physical Systems." In: *International Conference on on Cyber, Physical and Social Computing Internet of Things (iThings/CPSCom)*. 2011, pp. 232–241 (cit. on p. 116).

[Pod13] R. Podorozhny. "Design and verification of cellphone-based cyber-physical systems: A position paper." In: *International Conference Conference on Collaborative Computing: Networking, Applications and Worksharing (Collaboratecom)*. 2013, pp. 603–607 (cit. on p. 124).

[Poo10] R. Poovendran. "Cyber-Physical Systems: Close Encounters Between Two Parallel Worlds [Point of View]." In: *Proceedings of the IEEE* 98.8 (2010), pp. 1363–1366 (cit. on p. 109).

[PSKW12] L. Parolini, B. Sinopoli, B. Krogh, and Z. Wang. "A Cyber-Physical Systems Approach to Data Center Modeling and Control for Energy Efficiency." In: *Proceedings of the IEEE* 100.1 (2012), pp. 254–268 (cit. on pp. 12, 108).

[Rep+14] D. Repta, A. Stanescu, M. Moisescu, I. Sacala, and M. Benea. "A cyber-physical systems approach to develop a generic enterprise architecture." In: *International ICE Conference on Engineering, Technology and Innovation (ICE)*. 2014, pp. 1–6 (cit. on p. 127).

[RKFN13] P. A. P. Ruiz, B. Kamsu-Foguem, and D. Noyes. "Knowledge reuse integrating the collaboration from experts in industrial maintenance management." In: *Knowledge-Based Systems* 50 (2013), pp. 171–186 (cit. on p. 31).

[RLSS10] R. R. Rajkumar, I. Lee, L. Sha, and J. Stankovic. "Cyber-physical Systems: The Next Computing Revolution." In: *Design Automation Conference (DAC)*. ACM, 2010, pp. 731–736 (cit. on pp. 2, 11, 12, 109).

[Sat01] M. Satyanarayanan. "Pervasive computing: Vision and challenges." In: *IEEE Personal Communications* 8.4 (2001), pp. 10–17 (cit. on p. 5).

[SBFV15] C. Scheuermann, B. Bruegge, J. Folmer, and S. Verclas. "Incident Localization and Assistance System: A Case Study of a Cyber-Physical Human System." In: *International Conference on Communications: ICCC International Workshop on Internet of Things*. IEEE. 2015 (cit. on p. 40).

[SGMC12] R. Schneider, D. Goswami, A. Masrur, and S. Chakraborty. "QoC-oriented efficient schedule synthesis for mixed-criticality cyber-physical systems." In: *Forum on Specification and Design Languages (FDL)*. 2012, pp. 60–67 (cit. on p. 121).

[Sha14] S. Shackelford. *Managing Cyber Attacks in International Law, Business, and Relations: In Search of Cyber Peace*. Cambridge University Press, 2014 (cit. on p. 11).

[SHBV17] C. Scheuermann, F. Heinz, B. Bruegge, and S. Verclas. "Real-Time Support During a Logistic Process Using Smart Gloves." In: *Smart Systech 2017 - Accepted for Publication*. Munich, 2017 (cit. on p. 40).

[SHG12] S. Sridhar, A. Hahn, and M. Govindarasu. "Cyber-Physical System Security for the Electric Power Grid." In: *Proceedings of the IEEE* 100.1 (2012), pp. 210–224 (cit. on p. 120).

[SHWZ14] X. Sun, N. Huang, B. Wang, and J. Zhou. "Reliability of cyber physical systems assessment of the aircraft fuel management system." In: *Annual International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)*. IEEE. 2014, pp. 424–428 (cit. on p. 127).

[Sim+04] G. Simon, M. Maróti, Á. Lédeczi, G. Balogh, B. Kusy, A. Nádas, G. Pap, J. Sallai, and K. Frampton. "Sensor network-based countersniper system." In: *International Conference on Embedded Networked Sensor Systems*. ACM. 2004, pp. 1–12 (cit. on p. 4).

[SK10] D. Shin and S. Korea. “A Realization of Pervasive Computing: Ubiquitous City.” In: (2010) (cit. on p. 6).

[SKP13] C. Sankavaram, A. Kodali, and K. Pattipati. “An integrated health management process for automotive cyber-physical systems.” In: *International Conference on Computing, Networking and Communications (ICNC)*. 2013, pp. 82–86 (cit. on p. 122).

[SLF11] K. Su, J. Li, and H. Fu. “Smart City and the Applications.” In: (2011), pp. 1028–1031 (cit. on p. 6).

[SMBV16] C. Scheuermann, F. Meissgeier, B. Bruegge, and S. Verclas. “Mobile Augmented Reality Based Annotation System: A Cyber-Physical Human System.” In: *Augmented Reality, Virtual Reality, and Computer Graphics: Third International Conference, AVR 2016, Lecce, Italy, June 15-18, 2016. Proceedings, Part I*. Ed. by L. T. De Paolis and A. Mongelli. Cham: Springer International Publishing, 2016, pp. 267–280 (cit. on p. 40).

[SMLC07] Y. Sun, B. McMillin, X. F. Liu, and D. Cape. “Verifying noninterference in a cyber-physical system the advanced electric power grid.” In: *Seventh International Conference on Quality Software (QSIC)*. IEEE. 2007, pp. 363–369 (cit. on p. 96).

[SPR14] V. Sehgal, A. Patrick, and L. Rajpoot. “A comparative study of cyber physical cloud, cloud of sensors and internet of things: Their ideology, similarities and differences.” In: *International Advance Computing Conference (IACC)*. IEEE. 2014, pp. 708–716 (cit. on p. 127).

[SSBV16] C. Scheuermann, M. Strobel, B. Bruegge, and S. Verclas. “Increasing the Support to Humans in Factory Environments using a Smart Glove: An Evaluation.” In: *International Conferences on Ubiquitous Intelligence & Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People, and Smart World Congress*. Toulouse, France, 2016, pp. 847–854 (cit. on p. 40).

[Sta04] R. Stake. *Standards-Based and Responsive Evaluation*. SAGE Publications, 2004 (cit. on p. 7).

[SV10] A. Saber and G. Venayagamoorthy. “Efficient Utilization of Renewable Energy Sources by Gridable Vehicles in Cyber-Physical Energy Systems.” In: *IEEE Systems Journal* 4.3 (2010), pp. 285–294 (cit. on p. 111).

[SVB15] C. Scheuermann, S. Verclas, and B. Bruegge. “Agile Factory - An Example of an Industry 4.0 Manufacturing Process.” In: *International Conference on Cyber-Physical Systems, Networks, and Applications*. IEEE. 2015, pp. 43–47 (cit. on p. 40).

[SWYS11] J. Shi, J. Wan, H. Yan, and H. Suo. “A survey of Cyber-Physical Systems.” In: *International Conference on Wireless Communications and Signal Processing (WCSP)*. 2011, pp. 1–6 (cit. on p. 114).

[Szt+12] J. Sztipanovits, X. Koutsoukos, G. Karsai, N. Kottenstette, P. Antsaklis, V. Gupta, B. Goodwine, J. Baras, and S. Wang. “Toward a Science of Cyber-Physical System Integration.” In: *Proceedings of the IEEE* 100.1 (2012), pp. 29–44 (cit. on p. 119).

[Szt07] J. Sztipanovits. “Composition of Cyber-Physical Systems.” In: *Annual International Conference and Workshops on the Engineering of Computer-Based Systems (ECBS)*. IEEE. 2007, pp. 3–6 (cit. on p. 96).

[Tab06] P. Tabuada. “Cyber-physical systems: Position paper.” In: *NSF Workshop on Cyber-Physical Systems*. 2006 (cit. on p. 95).

[Tal08] C. Talcott. “Cyber-physical systems and events.” In: *Software-Intensive Systems and New Computing Paradigms*. Springer, 2008, pp. 101–115 (cit. on p. 98).

[Tan+10] L.-A. Tang, X. Yu, S. Kim, J. Han, C.-C. Hung, and W.-C. Peng. “Tru-Alarm: Trustworthiness Analysis of Sensor Networks in Cyber-Physical Systems.” In: *International Conference on Data Mining (ICDM)*. IEEE. 2010, pp. 1079–1084 (cit. on p. 110).

[TGP08] Y. Tan, S. Goddard, and L. C. Pérez. “A Prototype Architecture for Cyber-physical Systems.” In: *SIGBED Rev.* 5.1 (2008), 26:1–26:2 (cit. on p. 97).

[Tid+09] T. Tidwell, X. Gao, H.-M. Huang, C. Lu, S. Dyke, and C. Gill. “Towards Configurable Real-Time Hybrid Structural Testing: A Cyber-Physical System Approach.” In: *International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing (ISORC)*. IEEE. 2009, pp. 37–44 (cit. on p. 106).

[TJMZ10] R. A. Thacker, K. R. Jones, C. J. Myers, and H. Zheng. “Automatic Abstraction for Verification of Cyber-physical Systems.” In: *International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. ACM, 2010, pp. 12–21 (cit. on p. 108).

[TVG09] Y. Tan, M. C. Vuran, and S. Goddard. “Spatio-Temporal Event Model for Cyber-Physical Systems.” In: *International Conference on Distributed Computing Systems Workshops (ICDCS Workshops)*. IEEE. 2009, pp. 44–50 (cit. on p. 106).

[VLH04] L. Van Langenhove and C. Hertleer. “Smart clothing: a new life.” In: *International Journal of Clothing Science and Technology* 16.1/2 (2004), pp. 63–72 (cit. on p. 18).

[VM14a] L. Vegh and L. Miclea. “A new approach towards increased security in cyber-physical systems.” In: *International Conference on Systems, Signals and Image Processing (IWSSIP)*. 2014, pp. 175–178 (cit. on p. 128).

[VM14b] T. Vollmer and M. Manic. “Cyber-Physical System Security With Deceptive Virtual Hosts for Industrial Control Networks.” In: *IEEE Transactions on Industrial Informatics* 10.2 (2014), pp. 1337–1347 (cit. on p. 127).

[WA+06] G. Werner-Allen, K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees, and M. Welsh. “Deploying a wireless sensor network on an active volcano.” In: *IEEE Internet Computing* 10.2 (2006), pp. 18–25 (cit. on p. 3).

[Wal+16] A. Walker, A. McKune, S. Ferguson, D. B. Pyne, and B. Rattray. “Chronic occupational exposures can influence the rate of PTSD and depressive disorders in first responders and military personnel.” In: *Extreme Physiology & Medicine* 5.1 (2016), p. 8 (cit. on p. 75).

[Wan+10] E. Wang, Y. Ye, X. Xu, S. Yiu, L. Hui, and K. Chow. “Security Issues and Challenges for Cyber Physical System.” In: *International Conference on Cyber, Physical and Social Computing (CPSCom) and Green Computing and Communications (GreenCom)*. IEEE/ACM. 2010, pp. 733–738 (cit. on p. 110).

[WB13] B. Wang and J. Baras. “HybridSim: A Modeling and Co-simulation Toolchain for Cyber-physical Systems.” In: *International Symposium on Distributed Simulation and Real Time Applications (DS-RT)*. IEEE/ACM. 2013, pp. 33–40 (cit. on p. 124).

[WBJ08] D. Work, A. Bayen, and Q. Jacobson. “Automotive cyber physical systems in the context of human mobility.” In: *National Workshop on high-confidence automotive cyber-physical systems, Troy, MI*. 2008 (cit. on pp. 12, 98).

[Wei93] M. Weiser. “Some Computer Science Issues in Ubiquitous Computing.” In: (1993) (cit. on p. 5).

[WK12] L. Wu and G. Kaiser. “An Autonomic Reliability Improvement System for Cyber-Physical Systems.” In: *International Symposium on High-Assurance Systems Engineering (HASE)*. 2012, pp. 56–61 (cit. on p. 120).

[WMH10] K. Wan, K. Man, and D Hughes. “Specification, analyzing challenges and approaches for cyber-physical systems (CPS).” In: *Engineering Letters* 18.3 (2010), p. 308 (cit. on pp. 12, 112).

[Wol09] W. Wolf. “Cyber-physical Systems.” In: *Computer* 42.3 (2009), pp. 88–89 (cit. on p. 102).

[Woo+08] H. Woo, J. Yi, J. Browne, A. Mok, E. Atkins, and F. Xie. "Design and Development Methodology for Resilient Cyber-Physical Systems." In: *International Conference on Distributed Computing Systems (ICDCS)*. 2008, pp. 525–528 (cit. on p. 100).

[Xie+13] F. Xie, T. Lu, X. Guo, J. Liu, Y. Peng, and Y. Gao. "Security Analysis on Cyber-physical System Using Attack Tree." In: *International Conference on Intelligent Information Hiding and Multimedia Signal Processing*. 2013, pp. 429–432 (cit. on p. 125).

[Xin+08] G. Xing, W. Jia, Y. Du, P. Tso, M. Sha, and X. Liu. "Toward ubiquitous Video-based Cyber-Physical Systems." In: *International Conference on Systems, Man and Cybernetics (SMC)*. IEEE. 2008, pp. 48–53 (cit. on p. 101).

[XMDS08] F. Xia, L. Ma, J. Dong, and Y. Sun. "Network QoS management in cyber-physical systems." In: *International Conference on Embedded Software and Systems Symposia (ICESS)*. IEEE. 2008, pp. 302–307 (cit. on p. 100).

[Xu+04] N. Xu, S. Rangwala, K. K. Chintalapudi, D. Ganesan, A. Broad, R. Govindan, and D. Estrin. "A wireless sensor network for structural monitoring." In: *International Conference on Embedded Networked Sensor Systems*. ACM. 2004, pp. 13–24 (cit. on p. 3).

[Xu+08] Z. Xu, X. Liu, G. Zhang, W. He, G. Dai, and W. Shu. "A certificateless signature scheme for mobile wireless cyber-physical systems." In: *International Conference on Distributed Computing Systems (ICDCS)*. IEEE. 2008, pp. 489–494 (cit. on p. 97).

[Xue+09] C. Xue, G. Xing, Z. Yuan, Z. Shao, and E. Sha. "Joint Sleep Scheduling and Mode Assignment in Wireless Cyber-Physical Systems." In: *International Conference on Distributed Computing Systems Workshops (ICDCS)*. IEEE. 2009, pp. 1–6 (cit. on p. 102).

[YDWX12] L. Yongfu, S. Dihua, L. Weining, and Z. Xuebo. "A service-oriented architecture for the transportation Cyber-Physical Systems." In: *Control Conference (CCC), 2012 31st Chinese*. 2012, pp. 7674–7678 (cit. on p. 120).

[YQZC12] O. Yagan, D. Qian, J. Zhang, and D. Cochran. "Optimal Allocation of Interconnecting Links in Cyber-Physical Systems: Interdependence, Cascading Failures, and Robustness." In: *IEEE Transactions on Parallel and Distributed Systems* 23.9 (2012), pp. 1708–1720 (cit. on p. 121).

[Yua+13] Y. Yuan, Q. Zhu, F. Sun, Q. Wang, and T. Basar. "Resilient control of cyber-physical systems against Denial-of-Service attacks." In: *International Symposium on Resilient Control Systems (ISRCS)*. 2013, pp. 54–59 (cit. on p. 124).

[ZB11] Q. Zhu and T. Basar. “Robust and resilient control design for cyber-physical systems with an application to power systems.” In: *Conference on Decision and Control and European Control Conference (CDC-ECC)*. IEEE. 2011, pp. 4066–4071 (cit. on p. 117).

[ZBMM10] C. Zimmer, B. Bhat, F. Mueller, and S. Mohan. “Time-based Intrusion Detection in Cyber-physical Systems.” In: *International Conference on Cyber-Physical Systems (ICCPS)*. IEEE. ACM, 2010, pp. 109–118 (cit. on pp. 12, 113).

[Zen+14] D. Zeng, S. Guo, A. Barnawi, S. Yu, and I. Stojmenovic. “An Improved Stochastic Modeling of Opportunistic Routing in Vehicular CPS.” In: *IEEE Transactions on Computers* PP.99 (2014), pp. 1–1 (cit. on pp. 12, 126).

[ZG04] F. Zhao and L. Guibas. *Wireless Sensor Networks: An Information Processing Approach*. The Morgan Kaufmann series in networking. Morgan Kaufmann, 2004 (cit. on p. 3).

[Zha+09] Y. Zhang, I.-L. Yen, F. Bastani, A. Tai, and S. Chau. “Optimal Adaptive System Health Monitoring and Diagnosis for Resource Constrained Cyber-Physical Systems.” In: *International Symposium on Software Reliability Engineering (ISSRE)*. 2009, pp. 51–60 (cit. on pp. 12, 106).

[Zhe14] X. Zheng. “Physically informed assertions for cyber physical systems development and debugging.” In: *International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*. IEEE. 2014, pp. 181–183 (cit. on p. 127).

[Zhu10] H. Zhuge. “Socio-Natural Thought Semantic Link Network: A Method of Semantic Networking in the Cyber Physical Society.” In: *International Conference on Advanced Information Networking and Applications (AINA)*. IEEE. 2010, pp. 19–26 (cit. on p. 112).

[ZSW09] F. Zhang, Z. Shi, and W. Wolf. “A Dynamic Battery Model for Co-design in Cyber-Physical Systems.” In: *International Conference on Distributed Computing Systems Workshops (ICDCS)*. IEEE. 2009, pp. 51–56 (cit. on p. 103).

[ZSWM08] F. Zhang, K. Szwaykowska, W. Wolf, and V. Mooney. “Task Scheduling for Control Oriented Requirements for Cyber-Physical Systems.” In: *Real-Time Systems Symposium*. 2008, pp. 47–56 (cit. on p. 100).