> Living in a networked world

Integrated research agenda Cyber-Physical Systems (agendaCPS)

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> CONTENTS

SUMMARY

In conjunction with microsystems technology, the sustained rapid advances in information technology and the resulting exponential increase in processing power and data capture, data transmission and data storage capacity are enabling ever more powerful peripheral, communication and control systems which are being networked more and more closely with each other. The combination of comprehensive IT systems and the Internet is leading to a continuous increase in the number, power and complexity of applications. Software-intensive systems and devices are becoming everyday commodities. By connecting them to each other in a variety of different ways and incorporating data and services from global networks, they are being transformed into integrated, comprehensive solutions that are increasingly pervading and connecting every area of our lives. Open, networked systems are emerging that use sensors to capture data about what is going on in the physical world, interpret these data and make them available to network-based services, whilst also using actuators to directly affect processes in the physical world and control the behaviour of devices, objects and services. These systems are known as Cyber-Physical Systems (CPS). They are giving rise to system landscapes and socio-technical systems with applications that are not just innovative but genuinely revolutionary.

In the future, Cyber-Physical Systems will make hitherto almost unimaginable contributions to quality of life, safety, security and efficiency, as well as to security of supply in the fields of energy, water and healthcare. They will thus help to solve some of the key challenges our society is facing. For example, modern smart health systems use sensors to record data about patients' health, connect patients, doctors and therapists with each other and provide them with access to patient data, and enable remote diagnosis and healthcare in the patient's own home. Smart Cyber-Physical Systems coordinate traffic flows, provide people with support in critical situations and cut energy consumption both in the transport system and through smart power grid management. These wide-ranging capabilities are driving rapid economic and social changes. We are witnessing a constant stream of innovations that need to be appropriately channelled. Cyber-Physical Systems require cross-domain cooperation in order to enable interactive value creation in economic ecosystems.

Targeted political, economic, technological and methodological efforts will be required to fully exploit this area of innovation. It will be necessary to resolve a variety of questions and challenges in order to enable the design and deployment of Cyber-Physical Systems and applications that meet people's needs.

Germany is a global market leader in the precursor technologies for Cyber-Physical Systems – embedded systems, integrated safety and security solutions and complex system solutions engineering. Given the huge drive for innovation in the field of Cyber-Physical Systems, Germany will only be able to maintain and develop this position if it secures its leadership in CPS innovation and extends its market leadership in embedded systems so that it can take full advantage of the potential offered by the trend towards Cyber-Physical Systems. One of the formal goals of the agendaCPS project and the integrated Cyber-Physical Systems research agenda presented in this study is to draw up a catalogue of measures that addresses the need for Germany not just to participate in the evolution of CPS and the concomitant economic and social changes but to play a major part in shaping the revolution by competing with other industries and technology centres around the world.

The rapid technological transformation induced by Cyber-Physical Systems is creating new business opportunities and is bringing about disruptive changes in the markets and business models of several key industries. It is therefore necessary to act swiftly in order to seize the moment.

Consequently, this study analyses and describes the capabilities, potential and challenges associated with

Cyber-Physical Systems, including the economic and social benefits and added value that they can bring and the technological, research, business and policy challenges that will need to be met to make Germany more innovative and competitive in this area. Its key contributions include analysing the challenges and unanswered questions with regard to the safety, security, risks and acceptance of CPS technology and its applications, as well as identifying the measures needed to meet these challenges.

There are many different challenges affecting both society and industry:

– **Society:** it is hoped that Cyber-Physical Systems will help solve some of the challenges facing our society such as the provision of care for the elderly and enabling people to lead independent and safe lives as they get older. There are a number of unresolved issues in this area with regard to data and privacy protection and human-machine interaction. These are accompanied by questions whose answers will influence the extent to which CPS are accepted, for example with regard to individual freedom, governance and fairness in systems with distributed control, as well as the self-organisation and self-management of infrastructure and utility systems.
– **Industry:** the potential of CPS is closely connected to the shift away from products and towards integrated, interactive services and solutions. The excess value that will be created in economic ecosystems will require a variety of new architectures and business models, together with open standards and platforms to ensure system interoperability.
– **Science and research:** a number of new technologies and integrated models and architectures are emerging, particularly human models and integrated models of human-machine interaction and cooperation. This requires interdisciplinary engineering and the relevant competencies for deploying and operating these technologies in order to ensure that they are properly controlled and that non-functional requirements are also met.

Based on the outcomes of these considerations, as well as the preliminary work of the National Roadmap Embedded Systems and our assessment of the current status of research and technology, the Agenda concludes with a detailed SWOT analysis that enables the priority action areas to be identified.

The study's conclusions point towards the strategic measures and themes that can give Germany an innovative edge in the field of Cyber-Physical Systems. These can provide significant leverage and are essential in order to ensure sustainable innovativeness across the whole of the economy and to address the challenges facing our society.

The key conclusions in terms of the strategic action areas are as follows:

– It is necessary to implement a change of strategy and to rethink all levels of the value creation process, with a shift towards open, interactive markets and living spaces and the associated processes, as well as infrastructure and utility systems with integrated, interactive and networked services. This will require research to focus on specific priorities including enhanced human-machine interaction, requirements engineering, the development of requirements and domain models and innovative architectures, as well as interdisciplinary systems engineering and integrated quality assurance at all levels of the requirements and systems engineering process.
– It will be paramount to adopt an interdisciplinary approach to research, development and system design. Moreover, it will be necessary to integrate technology impact assessments, acceptance research and interactive system design into this process.

- New economic ecosystems are emerging. These will require the appropriate competitive strategies and excess-value architectures in order to foster innovation, diversity, safety, security and trust.
- It will be necessary to develop and implement models and standards for guaranteeing the quality of Cyber-Physical Systems.
- It will be necessary to ensure sustainable development of technological and operational competencies in the education and training systems and to make sure that the necessary conditions are created for industry.

Software becomes a dominant role in the control, design and use of data and services and in connecting the physical and virtual worlds. The ability to control large-scale, networked software systems with long service lives will therefore be of fundamental importance.

A variety of concrete operational recommendations aimed at policymakers and the scientific and business communities can be found in the "acatech POSITION PAPER" that was publicly launched at the 6th National IT Summit held in Munich in December 2011.

1 INTRODUCTION

The Integrated Research Agenda Cyber-Physical Systems project (hereafter abbreviated to agendaCPS) was initiated by acatech, Germany's National Academy of Science and Engineering. The project is funded by the Federal Ministry of Education and Research (BMBF) and has been carried out with extensive support from fortiss, an associated institute of the Technische Universität München.

1.1 GOALS AND STRUCTURE OF THE REPORT

Agenda Cyber-Physical Systems aims to provide a comprehensive and systematic overview of the technology trends and innovation potential associated with Cyber-Physical Systems (CPS) and draw conclusions concerning the priority areas for research and action. A number of significant fields of application are used to illustrate the economic and social importance of this topic. The goal of agendaCPS is to strengthen and develop Germany's position in the area of Cyber-Physical Systems.

Cyber-Physical Systems connect the physical world with the world of information technology. They evolve from complex interactions

- of embedded systems, application systems and infrastructures, for example controls on board vehicles, smart intersections, traffic management systems, communication networks and their connections to the Internet
- based on the networking and integration of the above
- and involving human-technology interaction in application processes.

As such, Cyber-Physical Systems are not self-contained entities, as can be seen, for example, in networked mobility *services*[1] or integrated patient telecare provided by several different service providers such as doctors, physiotherapists and pharmacies. Instead, they are open *socio-technical systems* that arise from extensive networking of the physical, social and virtual worlds and the smart use of information and communication technology. The tremendously fast development of the basic technologies and the wide range of aspects that they incorporate make Cyber-Physical Systems a complex topic to investigate – their areas of application and potential benefits are constantly developing and changing at a rapid pace. The main goal of agendaCPS is to illustrate the inherent change of the technologies and their applications. Cyber-Physical Systems open up extensive opportunities by enabling the functional connection of the physical and the software-based, virtual worlds. In the future, this will not only transform individual industries but will, in the long term, bring about a transformation of society as a whole as a result of "smart" *human-machine cooperation*.

In order to meet the overarching goals described above, the agenda aims:

- to provide a comprehensive overview of the phenomenon and knowledge field of Cyber-Physical Systems,
- to describe some of the key areas of application for Cyber-Physical Systems and their potential benefits,
- to describe the principal capabilities and features of Cyber-Physical Systems and the associated technological and social challenges,
- to describe the economic potential of Cyber-Physical Systems,
- to identify and classify the key research areas and establish where innovation initiatives are required,
- to provide recommendations for decision-makers from sciences, economy, politics and society,
- to raise awareness regarding the opportunities and challenges, both among the relevant experts and among the public as a whole and
- to contribute to the academic debate on Cyber-Physical Systems.

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[1] Any terms or parts of terms written in italics are explained in the glossary.

In particular, the analysis of the issues presented in the agenda is intended to serve as the basis for comprehensive recommendations.

1.1.1 STRUCTURE OF THE REPORT

In accordance with the goals of the agenda, Chapter 2 uses a handful of selected future scenarios to look at the technology and application trends of Cyber-Physical Systems. The scenarios provide a basis for describing the nature of Cyber-Physical Systems, their capabilities and the innovation potential and potential benefits associated with them. The areas of application and application scenarios that have been selected are:

- *smart mobility* concepts featuring extensive coordination, comfort and *safety services*,
- telemedicine and comprehensive patient care, including the use of medical *application platforms* and support from online *communities*,
- *smart grids*, i.e. the distributed and semi-autonomous control of electricity generation, storage, consumption and grid equipment in electricity grids and
- smart and flexibly networked manufacturing.

A systematic analysis of these scenarios enables the key features and new capabilities of Cyber-Physical Systems to be described. These are in turn analysed in terms of the following criteria: the increasing openness of the systems, smart, semi-autonomous networking, adaptation and new forms of *human-machine interaction*.

Based on this characterisation, Chapter 3 addresses the unanswered questions and challenges relating to the future design and implementation of Cyber-Physical Systems' capabilities and potential in the context of the above-mentioned scenarios, which are analysed in depth. The key issues are as follows:

- the need for *smart infrastructures*, application architectures and communication platforms,
- challenges connected with networked acting in uncertain environments, including the systems' control, *safety* and *security*, together with *privacy* protection,
- the design of *human-system cooperation* and the challenges associated with enabling intuitively controllable, safe and secure interactions between human beings and systems and
- factors affecting the acceptance of Cyber-Physical Systems and what this means for the way they are developed.

Cyber-Physical Systems that are networked via the Internet are ubiquitous in nature. This will lead to far-reaching changes in both the public and private domains. Consequently, Chapter 4 of the agenda investigates the impact of the technology, focusing on the design of human-technology interactions. This aspect is especially important, since systems and *services* can only realise their benefits and gain acceptance if they are geared towards their users' and customers' needs and are found to be controllable and trustworthy in use. Both of these criteria are indispensable for the safe and independent use of Cyber-Physical Systems.

The results of the analysis of Cyber-Physical Systems undertaken in Chapters 2 to 4 form the basis for the identification of the key research questions and development goals. Chapter 5 identifies the relevant technologies, *engineering* concepts, research requirements and challenges relating to the design and implementation of Cyber-Physical Systems' capabilities. This allows a preliminary assessment to be made of the extent to which it will be possible to meet the research goals required for the development of the necessary key technologies.

In view of the dynamic and evolutionary nature of Cyber-Physical Systems and their applications, new interdisciplinary development methods and techniques will be required that engage users and customers in order to ensure that the systems are adapted and integrated to meet the needs of different situations. This will require systems engineering concepts to be expanded to include operation, maintenance, continued development and even strategic marketing that are all carried out in partnership between different companies. These new concepts will be implemented through co-operative networks of companies that constitute economic *ecosystems*. Based on this approach, Chapter 6 analyses the technological, methodological and economic challenges facing enterprises and their *business models*.

Chapter 7 presents a summary of the agenda's findings with regard to the potential and challenges associated with Cyber-Physical Systems and the relevant research requirements. Based on these findings and an assessment of Germany's position compared with other countries around the world, a SWOT analysis is performed with a view to finding ways of overcoming the challenges in question. Finally, the conclusions highlight the research, integrated training, policy and economy aspects where action is required.

The evolutionary development of Cyber-Physical Systems is the result of the interplay between technological advances, the resulting social and economic potentials and the possible use in economic and social processes. In order to gain an understanding of Cyber-Physical Systems, it is therefore necessary to adopt an integrated approach and to ensure *participatory development*. This interdisciplinary approach and cooperation between all the relevant actors through open innovation systems and ecosystems is indispensable if the full potential of this technology is to be unlocked. It is our hope that agendaCPS will contribute to furthering this understanding.

1.2 CYBER-PHYSICAL SYSTEMS – TRENDS AND CHARACTERISATION

Ever since it first appeared on the scene, information and communication technology (ICT) has been characterised by a continuous succession of rapid technological advances. The most striking examples are the progressive miniaturisation of integrated circuits and the continuous rapid increases in processing power and network bandwidth. In recent years, this rapid progress has led to a situation where all the performance and bandwidth we need is more or less readily available, meaning that information technology can now be used in every area of our lives. Affordable microcomputers and improved mobile network coverage have extended the reach and interconnectivity of software from beyond the traditional mainframes and home PCs to mobile end devices such as notebooks, tablets and smartphones. IT is everywhere – the vision of *ubiquitous computing* has become reality. Previously closed and proprietary embedded systems and devices and IT-based information and management systems are now becoming increasingly open and connected to other systems. This trend is leading to the emergence of open, networked, flexible and interactive systems that seamlessly connect the physical world with the virtual world of information technology. As a result of their multiple interconnections and the incorporation of data and *services* from global networks, software-intensive systems and devices are increasingly being transformed into integrated global services and solutions that are used in every area of our lives.

1.2.1 THE POTENTIAL OF CONVERGING CPS TRENDS

Cyber-Physical Systems are the product of the ongoing development and integrated utilisation of two main innovation fields: systems containing embedded software and global data networks like the Internet, featuring distributed and interactive application systems. These are enabled by a powerful infrastructure comprising *sensors, actuators* and communication networks that are employed by companies acting and cooperating at a global level.

The following technologies and trends act as the key drivers:

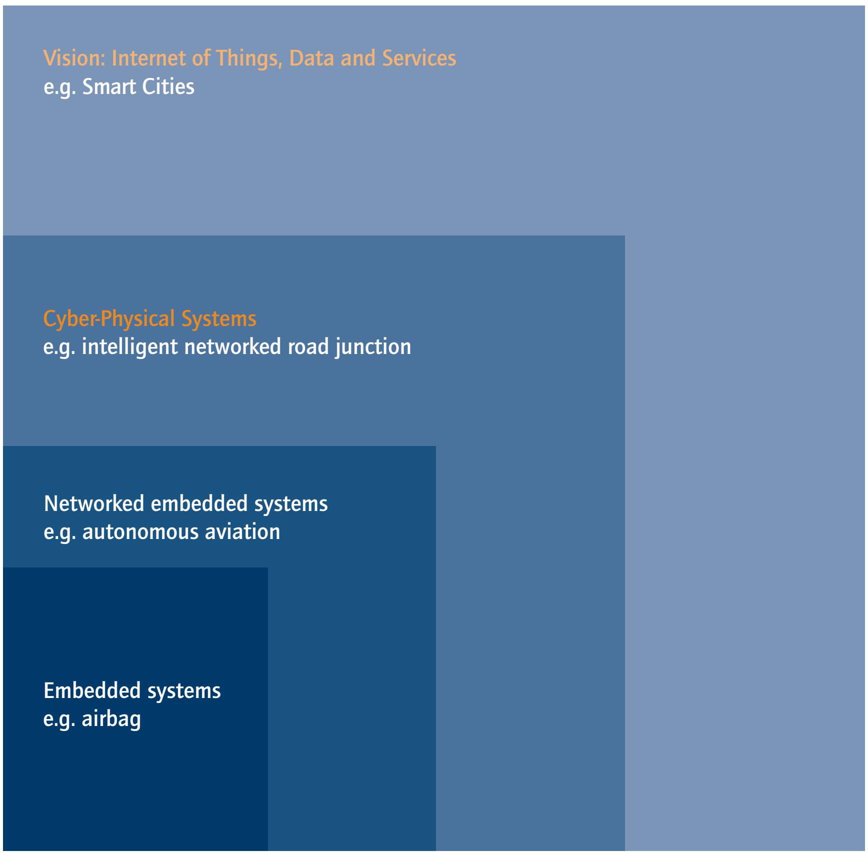
1. The use of powerful *smart embedded systems*, mobile *services* and *ubiquitous computing*:
   One of the basic key components of Cyber-Physical Systems involves powerful embedded systems that already operate in a cooperative and networked manner today, albeit as closed systems. Localised but increasingly mobile *sensor*, regulation and control *services* already exist, mainly in the automotive and aviation industries but also in manufacturing. The increasingly open networking, interaction, cooperation and use of mobility *services* and other online *services* is leading to a variety of novel alternatives and potential uses in several different fields of application and areas of our lives.

2. The use of the Internet as a *business web*, i.e. as a platform for economic cooperation, in two mutually complementary manners:
   a) The use of smart, networked components fitted with *sensors* – as in *RFID* technology, for example – is particularly widespread in commerce and logistics but also occurs in other fields of application such as remote equipment maintenance. Increasingly, the status and environmental monitoring functions and "memory" of digital components are also being used for networked control, coordination and optimisation e.g. of goods flows, maintenance procedures or fleet management. Moreover, the status of and interactions between objects and *services* can increasingly be followed and interactively influenced by customers online.
   b) Traditional IT and administrative tasks are increasingly being farmed out to the *cloud*, i.e. to globally distributed external service providers. This means that they are no longer dependent on local data centres. The same also applies to functions in the areas of distributed coordination, operations and billing. The *business web* makes it possible to represent the capabilities and *services* provided by Cyber-Physical Systems on the Internet and enable their use as online *services*. It forms the basis of integrated Web-based *business models*.

3. The use of the *semantic Web* and *Web 2.0* processes and the interactive design of integrated *services*:
   a) The opportunities provided by user-controlled interactions and the resulting creation of knowledge and communication networks and online *social communities* is generating huge volumes of data and information that can be used to specifically target potential customers. Moreover, requirements and demand for new *services*, integrated solutions and facilities are now arising, particularly in connection with self-organising expert, application and interest groups as well as *business-to-business* applications and corporate partnerships. It is possible to provide these *services* thanks to the way that Cyber-Physical Systems connect the virtual, physical and social worlds.
   b) Developer *communities* can contribute to these innovations. These *communities* tend to focus on specific development platforms and usually involve *open-source* initiatives to develop software using open-source codes. They may be self-organising or be overseen by a company or consortium. Other self-organising *communities* focus on specific fields of application, i.e. they are driven by a particular problem that has been encountered by users and customers or comprise a social network of experts in a specific field.

The interaction between these trends – and in particular the evolutionary development of open interactions with users and customers and the applications that this enables, as described in (1) and (2) above – harbours huge potential for innovation and value creation going forward. This will result in dynamic and disruptive changes to markets,

Figure 1.1: The evolution of embedded systems towards the Internet of Things, Data and Services



industry *models* and *business models*. Figure 1.1 illustrates this trend from the viewpoint of the embedded systems expert community.

Two things are occurring as far as the technology itself is concerned. Networked and increasingly smart *RFID* and *sensor* technology continues to be developed and is now generally referred to as the *Internet of Things* [BMW09, UHM11b]. This has implications for commerce and logistics. Meanwhile, in the realm of the *Internet of Services*, the range services and technologies in the fields of e-commerce, online *services* and media management continues to expand; see also the Theseus research programme [BMW10b].

1.2.2 INITIAL CHARACTERISATION OF CYBER-PHYSICAL SYSTEMS

The term Cyber-Physical Systems refers to embedded systems, i.e. devices, buildings, vehicles and medical equipment, as well as logistics, coordination and management processes and Internet *services* that

- use *sensors* to directly capture physical data and *actuators* to affect physical processes,
- interpret and store data which they then use as the basis for active or reactive interactions with the physical and digital worlds,
- are connected to each other via digital networks that may be wireless or wired and local or global,
- use data and *services* that are available globally,
- possess a range of *multimodal human-machine interfaces*, offering a variety of differentiated and dedicated options for both communication and control, for example using voice and gesture commands.

Cyber-Physical Systems enable a variety of novel functions, services and features that far exceed the current capabilities of embedded systems with controlled behaviour. Powerful Cyber-Physical Systems are able to directly register the situation of their current distributed application and environment, interactively influence it in conjunction with their users and make targeted changes to their own behaviour in accordance with the current situation. The systems thus provide their *services* to the relevant users and *stakeholders*

- largely independently of their location,
- but nevertheless in a context-aware manner,
- in accordance with the requirements of the current application situation
- semi-autonomously,
- in a semi-automated manner,
- multifunctionally and
- in a distributed and networked manner.

Examples include situation-based management of integrated transport solutions or online healthcare *service* coordination. A particularly significant feature of Cyber-Physical Systems is the fact that they are directly integrated into the physical world ("real world awareness").

One of the key contributions of this study consists in analysing these features and the novel capabilities of Cyber-Physical Systems as well as their different potential applications and innovations.

1.3 THE IMPORTANCE AND POTENTIAL OF CYBER-PHYSICAL SYSTEMS FOR GERMAN ECONOMY

As a result of advances in information and communication technology (*ICT*) and the way it is networked, previously separate industries are becoming connected to each other and *ICT* is becoming an integrated part of products and *services*. There are very few industries that do not now use *ICT* to improve their internal processes. Manufacturers are increasingly using embedded information technology and integrated *services* to add value to their products. The opportunities provided by networked data acquisition and interactive support for customer and user processes hold huge potential for innovation and new *business models*. More and more, information and smart information processing are becoming the key enablers of a business's competitive success. This involves putting the data and information generated by Cyber-Physical Systems to good use. It is also especially important to understand how current and future customer needs can be better met through the use of smart, networked technology. The rapid pace of these developments has huge implications for the future prospects of industries where Germany is currently a world leader.

The **automotive industry** illustrates the potential and significance of Cyber-Physical Systems perhaps better than any other. The vast majority of innovations that lead to greater safety, comfort and efficiency are now coming about thanks to Cyber-Physical Systems. Vehicles are being connected with each other, with objects in their environment and increasingly also with external information systems and mobile end devices belonging to drivers and other actors. The German automotive industry invests approximately 20 billion euros in R&D, or more than a third of all industrial R&D investment in Germany. It also employs around 715,000 people [Sta11]. It is therefore crucial to German industry as a whole that the automotive sector should play a leading role in the research, development and deployment of Cyber-Physical Systems. The link with the trend towards electric mobility[2] provides Germany with a particularly good opportunity to become established as a leading supplier of Cyber-Physical Systems. For example, route management for battery-powered cars or the integration of electric vehicles into the energy infrastructure[3] would simply not be possible without Cyber-Physical Systems. Time is running out, since the race is already well underway in the automotive industry to network vehicles[4] and provide drivers with wide-ranging support in a variety of different driving and communication situations.

Medical technology is one of the largest growth industries around the world. R&D investment in this sector accounts for some eight percent of turnover, approximately double the average for industry as a whole [BW08]. The German medical technology industry estimates that its turnover will increase by around eight percent a year between now and 2020.

In addition to remote monitoring of vital signs, implanted devices and integrated patient care, networked sensors and innovative devices also enable better diagnosis and treatment options. Furthermore, they provide a variety of opportunities to optimise healthcare delivery processes, for example emergency service responses or enhanced individual patient care in hospitals. Many of the innovations in this area are only possible thanks to the fact that devices which were formerly used in isolation are now able to communicate with each other and because data and information can now be linked up according to the requirements of each specific situation. Demographic change is going to lead to increased demand for ways of supporting older people so that they can live independently in their own homes. *AAL* solutions (*Ambient Assisted Living*, see also Chapter 2.3) can only be delivered through Cyber-Physical Systems.

Our supply of fossil fuels is dwindling and climate protection is becoming an increasingly important issue. Efficiency, usage optimisation and individual demand coverage in the generation, distribution, storage and consumption of energy are therefore key issues. This is true for the **energy industry**, for policymakers and for **consumers**, whether they be businesses, public buildings or private homes in towns and cities or rural communities. There are a number of challenges in this context – in addition to the fluctuating supply of renewable electricity and the decentralisation of energy production and distribution via *smart grids*, it is also necessary to meet a whole host of different requirements that arise as a result of consumer behaviour. Cyber-Physical Systems will play a key role in grid management, coordinating and optimising consumption and energy production planning.

The potential and challenges associated with Cyber-Physical Systems are particularly apparent in the **machinery and plant manufacturing**[5] and **automation engineering industries.**[6] Quality, optimisation and efficiency gains are enabled by sensor-based networking of smart machines and products both with each other and with global production planning, energy management and warehousing systems that may be shared between several different companies. In particular, these benefits occur as a result of the ability

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2 See e.g. [BDD+11].

3 Without the ability to optimise charging times or coordinate the available energy supply and the times when people charge their vehicles, peak demand would quickly hit critical levels even before electric vehicles came into widespread use. In other words, it is necessary for the charging of electric vehicle batteries to be controllable either by individual users or by a service provider; for further details, see [GMF09, Sch10b].

4 See for example [car11].

5 At the end of 2010, some 913,000 people were employed by Germany's machinery and plant manufacturing industry. German businesses are market leaders in several different branches of this industry. See [VDM11].

6 See also "Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution" [KLW11].

to adapt production flexibly to customers' processes and to control globally distributed logistics processes accordingly.

Cyber-Physical Systems are capable of standardised self-description and of *self-organisation* using standard mechanisms. This enables factories and manufacturing systems – even spread across several different companies – to adapt and optimise their manufacturing and logistics processes in line with individual customer requirements. Self-organisation through goal-oriented negotiation of work-pieces, equipment and material flow systems results in these processes becoming significantly more flexible – whilst today they are based on a central planning approach, in the future they will be characterised by a decentralised optimisation approach.

Mobile communications are a key basic technology for Cyber-Physical Systems, since many applications depend on the networking and integration of mobile devices via a reliable and high-performance mobile communications infrastructure. The number of mobile Internet users in Germany as a proportion of the total population is set to rise from 21 percent to more than 40 percent by 2014.[7] There is also significant potential for growth in the fields of **positioning and navigation**. The global market for end devices with integrated GPS receivers is expected to double in size between 2009 and 2014[8]. New programs providing greater precision and simpler market access, such as the Galileo satellite system, will allow this technology to become even more widespread and enable new applications, particularly in networked systems. Furthermore, mobile communications data and geo-information can be used for a variety of applications such as route optimisation and congestion avoidance by deriving information about congestion from the current movement profiles of networked vehicles and road users.

Germany offers a unique set of conditions for developing Cyber-Physical Systems applications even before the actual infrastructure is operational, as demonstrated, for example, by the German Galileo test environment GATE [GHW10].

In the **logistics** and the goods transport sectors, it has become standard practice to use technology that is networked with the manufacturing environment in order to identify, locate and establish the status of goods. The use of Cyber-Physical Systems in logistics promises new applications thanks to smart, active objects and large-scale open infrastructure networks. These include functions such as end-to-end position tracking and *real-time* status queries that provide new opportunities with regard to the coordination, planning and control of goods transport. At the same time, this area serves as a good example of the networking and coordination challenges that will have to be met by Cyber-Physical Systems.[9]

In the field of **smart buildings and homes**, Cyber-Physical Systems enable the upkeep and maintenance of buildings, facilities, residential areas and business parks to be integrated into people's domestic and working lives. Support is provided through integrated *security* strategies and measures to increase *energy efficiency*, for example through smart management of decentralised energy generation systems such as *solar* PV.[10] Moreover, there are a number of additional applications for industrial buildings and manufacturing facilities, e.g. with regard to the interactions between building and machinery control systems. However, this will require cooperation between systems that have traditionally operated independently of each other. The smart buildings sector forecast that its sales would grow by five percent in 2011. The key growth drivers are investments in measurement, control and regulation technology and in the associated building management systems. These investments

7 See [GS10]. The introduction and deployment of the Long-Term Evolution (LTE) mobile communications standard and the associated networks will be essential in order to enable permanent networking of end devices.

8 See "Global Navigation Satellite Positioning Solutions: Markets and Applications for GPS" [ABI09].

9 For further details, see e.g. the Collaborative Research Center on "modelling of large-scale logistics networks" [SFBa].

10 This area has huge potential, since buildings account for more than 40 percent of total energy consumption in Germany [BRO11].

have a much shorter payback period than investments in other energy measures. Moreover, the technology can generate efficiency gains by interacting with manufacturing systems and vehicles.

All of the above examples illustrate the enormous potential for innovation of Cyber-Physical Systems and how they are capable of transforming industry and our everyday lives. This was also demonstrated by the cutting-edge presentations about the latest ICT- and CPS-driven *services*, applications and *business models* at the Mobile World Congress 2012 [RGH12, Sch12, Ohl12, GL12, Kes12]. One feature shared by all the examples is the way that the value creation process is transferred to networks of several different companies, often from different industries, that cooperate with each other in a variety of different ways. Companies of different sizes from many different sectors and fields of application are increasingly collaborating both with each other and with service providers, software manufacturers and telecommunications providers. The effect is to bring together the competencies needed to produce innovations across all the areas of value creation associated with Cyber-Physical Systems. Supported by a close interaction with the systems' customers and users, this is resulting in product innovations that span several different industries, shifting the boundaries of existing markets and leading to rapid convergence of markets that were previously discrete.

1.4 METHODOLOGY AND PROCESS

Figure 1.2 provides an overview of the study design and the process that was followed. The core of the project focused on the modelling and analysis of future scenarios based on the established *requirements engineering* approach of analysing use cases and scenarios.

1.4.1 SCENARIO ANALYSIS AND STRUCTURED IDENTIFICATION OF CPS CAPABILITIES AND CORE TECHNOLOGIES

A number of use case scenarios were devised in order to determine the required features and capabilities of Cyber-Physical Systems and the challenges associated with their innovative design.

1.4.1.1 Analysis methods and structural design of the agenda

Based on the description of various scenarios and the actors, components, systems and *services* involved in them, all of which were assumed to behave optimally,

- the different applications' users and *stakeholders* were identified,
- their goals and the system's operation and architecture (interactions, roles and tasks) were analysed and
  - **a)** the benefits and value-added for the *stakeholders* and
  - **b)** the capabilities needed by the relevant (individual and networked) Cyber-Physical Systems and associated *services* were identified.

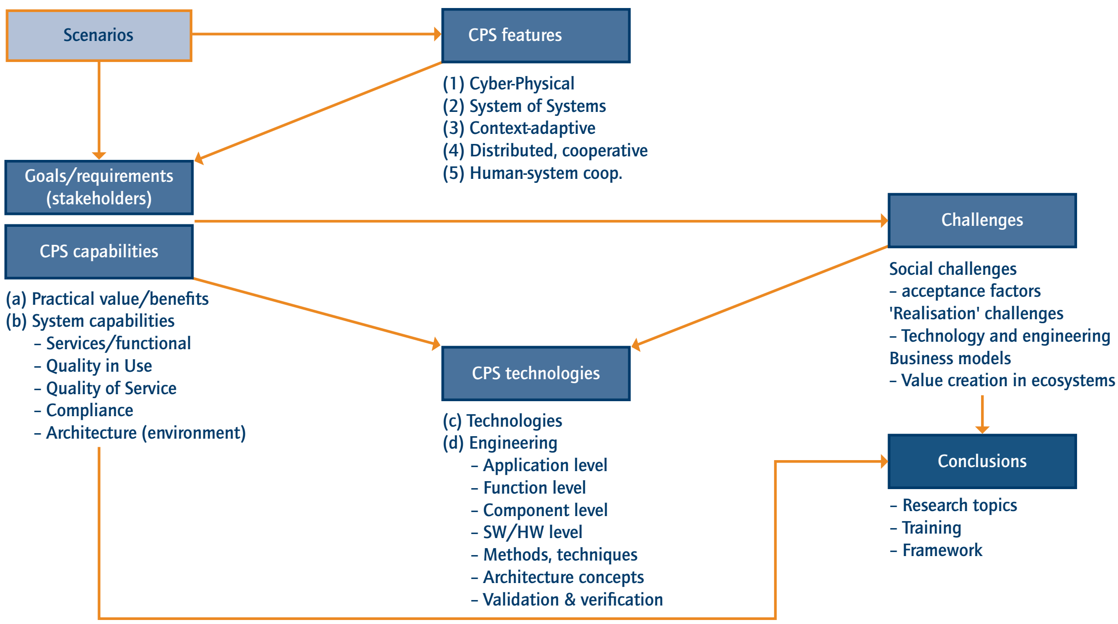
Following on from this analysis of their capabilities, the new evolutionary and revolutionary features of Cyber-Physical Systems were systematically described:

(1) merging of the physical and virtual worlds
(2) *a System of Systems* with dynamically shifting system boundaries
(3) context-adaptive systems with fully or semi-autonomous operation, active *real-time* control
(4) cooperative systems with distributed changing control
(5) extensive *human-system cooperation.*

These properties and capabilities entail a variety of opportunities and challenges with regard to the realisation and

Figure 1.2: Methodology and process employed in the agendaCPS project. CPS use scenarios [light blue] with different use goals and stakeholder requirements [blue] were used to identify characteristic Cyber-Physical Systems features [blue] and the required CPS capabilities [blue]. These were in turn used to identify the economic and social challenges [blue] and required technologies [blue]. All of the above provided the basis for establishing the action required with regard to integrated research and education [dark blue].

OVERVIEW OF THE AGENDA'S ANALYSIS METHODS AND STRUCTURAL DESIGN



control of innovative CPS *services* and applications. There are several as yet unanswered questions concerning e.g. social acceptance, conflicting goals and the need to guarantee enhanced *safety, security, dependability* and *privacy* protection. Furthermore, it is necessary to identify any gaps in the designs and solutions, the relevant technologies and the key research topics and formulate the corresponding strategies to overcome and find solutions to these problems. In order to do this, we once again draw on the use case and scenario analysis and the structured description of the core CPS technologies and *engineering* capabilities.

The trends, system transformation and dynamic nature of the innovations associated with CPS mean that traditional system developers, industries and service providers are faced with major challenges to their businesses. The system transformation referred to above and the complexity of Cyber-Physical Systems' open networks make it necessary to develop the functions and roles performed by the companies involved in them. This will require new *business models* and new forms of organisation and cooperation. The architecture of these *value networks* and *application platforms* is also addressed, based on the analysis and modelling of the CPS scenarios and their underlying system architectures.

Chapter 7 draws on the results of the analysis to provide a summary of the key challenges posed by Cyber-Physical

Systems for research, development, industry and society. It also identifies the actions that are required, particularly in the field of training and development of the necessary *engineering* know-how.

1.4.1.2 Taxonomy of CPS capabilities

The analysis of typical use case scenarios identifies and classifies Cyber-Physical Systems' capabilities based on the following four criteria:

a) Benefits

This describes the benefits and value-added that a Cyber-Physical System provides for its user groups. In addition to customers and end users, these can also include companies, organisations and social groups that are affected in a more general sense. We describe the benefits, *services* and functions that Cyber-Physical Systems provide to these groups and the value-added that accrues from their use (value/*Quality in Use, value proposition*). Examples of the benefits include efficient healthcare, enhanced overall road traffic *safety* and protection and, more specifically, improved comfort and assistance for drivers and passengers in towns and cities.

b) System capabilities

This describes the capabilities (functions, services, features) that Cyber-Physical Systems possess or provide which are required in order to deliver the benefits of CPS applications as described in (a) or to meet the challenges and threats associated with the application (*data protection, data security, loss of control*) or its interaction with other systems and actors. As in (a), we consider the capabilities required for a total system comprising the relevant application situations, processes and goals to function correctly. These include generic capabilities, such as searching for the appropriate *services* on the Internet or personal data protection, and application-specific capabilities such as route optimisation, influencing traffic flow at junctions by synchronising traffic light phases based on current measurements and in accordance with a pre-defined strategy, secure communication between vehicles and the creation of a model of the surroundings including position location.

c) CPS technologies

These include existing and as yet undeveloped components, technologies and processes (for software, electronics and mechanics) that are needed to implement CPS applications in such a way that the system capabilities described under (b) can be controlled and the benefits referred to under (a) can be delivered. Examples of CPS technologies include *pattern recognition, smart sensors, real-time* control, IP protocols as frameworks for governing Internet communication and encryption technology. The technologies concern different system levels and architectures: total systems, *human-system-environment interaction* and interfaces, networking, subsystems, software and hardware, *security* technology and communications technology.

d) Engineering capabilities

These include the necessary *engineering* capabilities and skills (principles, processes, methods, techniques and *best practices* as well as integrated multidisciplinary tooling concepts) to enable the targeted development, design, implementation, operation, evolution and sustainably profitable deployment of Cyber-Physical Systems using the capabilities and features outlined under (a) and (b). Examples of these capabilities include methods for modelling, *requirements specification*, design engineering and end-to-end quality assurance (*validation* and *verification*), as well as the use of architecture principles and concepts for meeting non-functional requirements such as *usability, dependability, safety, security* and *privacy* protection.

1.4.2 VALIDATION OF THE RESULTS

Our work was supported and accompanied by expert workshops, interviews and a systematic analysis of current academic and applied research programmes, projects and initiatives. The results and key conclusions of the project were analysed and systematically consolidated in successive rounds of workshops with our partners from industry and the research community.

The results presented in this study are intended to serve as a basis for subsequent, more in-depth investigations of core CPS capabilities and technologies, their potential, the associated challenges and the (research) work that still needs to be done. Our aim is to lay the foundations for a full and open debate on the importance of Cyber-Physical Systems to our society.