IoT/CPS Opportunity Report

“Towards Enhanced EU-US ICT Pre-competitive Collaboration”

Draft Version for Public Dissemination

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Christian Sonntag, Sebastian Engell
Process Dynamics and Operations Group (DYN)
Dept. of Biochemical and Chemical Engineering (BCI)
TU Dortmund University, Germany

ICT Policy, Research and Innovation for a Smart Society

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www.picasso-project.eu
The aim of the 30-months PICASSO project is (1) to reinforce EU-US collaboration in ICT research and innovation focusing on the pre-competitive research in key enabling technologies related to societal challenges - 5G Networks, Big Data, Internet of Things and Cyber Physical Systems, and (2) to support the EU-US ICT policy dialogue by contributions related to e.g. privacy, security, internet governance, interoperability, ethics.

PICASSO is oriented to industrial needs, provides a forum for ICT communities and involves 24 EU and US prominent specialists in the three technology-oriented ICT Expert Groups and an ICT Policy Expert Group, working closely together to identify policy gaps in the technology domains and to take measures to stimulate the policy dialogue in these areas. A synergy between experts in ICT policies and in ICT technologies is a unique feature of PICASSO.

A number of analyses will be accomplished, as well as related publications, that will for a major part be made public and contribute to the project’s outreach. Dedicated communication and dissemination material will be prepared that should support the operational work and widespread dissemination though different channels (website, social media, publications ...). The outreach campaign will also include 30+ events, success stories, factsheets, info sessions, and webinars.
# List of Acronyms

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<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>AIOTI</td>
<td>Alliance of IoT Innovation</td>
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<tr>
<td>CPS</td>
<td>Cyber-physical System</td>
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<td>CPSoS</td>
<td>Cyber-physical System of Systems</td>
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<td>CPS-VO</td>
<td>CPS Virtual Organization</td>
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<td>CPU</td>
<td>Central Processing Unit</td>
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<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
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<td>DHS</td>
<td>Department of Homeland Security</td>
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<td>EC</td>
<td>European Commission</td>
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<td>EG</td>
<td>Expert Group</td>
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<td>EU</td>
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<td>FoF</td>
<td>Factories of the Future</td>
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<td>FP7</td>
<td>Framework Programme 7</td>
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<td>FY</td>
<td>Financial Year</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>H2020</td>
<td>Horizon 2020</td>
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<td>HMI</td>
<td>Human Machine Interface</td>
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<td>IA</td>
<td>Industry Association</td>
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<td>ICT</td>
<td>Information and Communication Technology</td>
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<td>IERC</td>
<td>IoT European Research Cluster</td>
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<td>IIC</td>
<td>Industrial Internet Consortium</td>
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<td>Industrial Internet of Things</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<td>ITS</td>
<td>Intelligent Traffic System</td>
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<td>JU</td>
<td>Joint Undertaking</td>
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<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>NIT</td>
<td>Networking and Information Technology</td>
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<td>NITRD</td>
<td>Networking and Information Technology Research and Development</td>
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<td>NSF</td>
<td>National Science Foundation</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>M2M</td>
<td>Machine-to-Machine</td>
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<td>M&amp;S</td>
<td>Modeling and Simulation</td>
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<td>OCF</td>
<td>Open Connectivity Foundation</td>
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<td>PCAST</td>
<td>President's Council of Advisors on Science and Technology</td>
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<td>PPP</td>
<td>Public-private Partnership</td>
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<td>Public Working Group</td>
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<td>TRL</td>
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<td>V2I</td>
<td>Vehicle-to-infrastructure</td>
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1. Introduction and Overview

Over the last years, different definitions of the Internet of Things (IoT) have been created that describe the IoT as both a technological system and a concept. For example, in (1), the IoT is defined as “a new era of ubiquitous connectivity and intelligence, where a set of components, products, services and platforms connects, virtualizes, and integrates everything in a communication network for digital processing.” While the IERC definition (see http://www.internet-of-things-research.eu/about_iot.htm) states that the IoT is “a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual “things” have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network.”.

Within PICASSO, we focus less on the connectivity aspect of the IoT and more on the opportunities that the provision of streams of real-time data from a large number of IoT-connected devices with sensing capabilities provides for monitoring, optimization, management, and intelligent service provision in modern large-scale technical systems. In such technical systems, which are often called cyber-physical systems (CPS), real-time computing elements and physical systems interact tightly. Cyber-physical systems are ubiquitous, as computing devices and software are enabling and enhancing the performance of all except the simplest technical systems. The most challenging class of cyber-physical systems are cyber-physical systems of systems (CPSoS, see e.g. www.cpsos.eu) which are characterized by being spatially distributed, having distributed control, supervision, and management with partial autonomy of the subsystems, are dynamically reconfigured on different time scales, can show emerging behaviors, and involve human interactions (e.g. with operators or managers). Examples of cyber-physical systems of systems are the electrical grid, railway systems, the public transport system of a city, smart buildings, and production processes with many cooperating elements as e.g. robots, machines, warehouses, or large processing plants with many process units.

CPS and CPSoS are already equipped with a large number of sensing devices. The IoT will make the access to the information provided by these sensors a lot simpler and more flexible, and the connectivity provided by the Internet of Things will become an enabling technology for cyber-physical systems of systems in which the loop from a myriad of sensors to the way the systems are operated and also to the demands of the users is closed (2). This will enable improved monitoring, management and hence new levels of energy and resource efficiency, product and service quality, and safe and reliable operation. Thus, according to the PICASSO definition the IoT can be seen as an enabling technology for CPS or CPSoS, while other, more encompassing definitions include also applications outside the domain of CPS and CPSoS, such as IoT-connected home entertainment systems or geolocation-enabled tracking infrastructures for consumer items.

The merging of IoT and large-scale CPS into closed-loop, real-time IoT-driven cyber-physical systems is seen as an important future challenge in both the EU and the US. In the EU, this challenge is recognized by several institutions, such as the ARTEMIS Industry Association who e.g. believe that the “Internet of Things, and consequently the Things of the Internet, and Cyber-Physical Systems are complementary directions which together will help to shape a society where humans and machines increasingly interact to provide services and solutions for the benefit of society that are inconceivable with the present state-of-the-art technology” (3), and the European Alliance of IoT Innovation (AIOTI) who see this as a macro-challenge, stating “Getting billions of objects duly connected and managing these to create a reliable monitoring/actuating substrate only partially caters for the challenges ahead. These challenges cannot be complete without considering how to handle the huge amount of data produced and how to transform it into useful and actionable knowledge.” (4). On the US side, for example the Industrial Internet Consortium (IIC) promotes that “Companies need to close the loop across associated processes.” (5), the US branch of Samsung sees the CPS draft framework by NIST as an important prerequisite for the future of IoT (6), and the NSF is currently funding several research projects that cover the idea of using the IoT as an enabler for CPS.
The enormous potential of these novel technologies has been recognized by both the EU and the US. The social and economic challenges are common across the world, and there are opportunities for the EU and the US to work together on these global challenges for mutual benefit, not only in allowing solutions from EU and US providers to be sold within each other’s economic areas but also on a world-wide scale (7). In addition to economic benefits, there will be benefits to society and to end-users. Joint research and innovation will lead to a faster development of better solutions and will enable societal challenges to be addressed more efficiently.

The objective of the PICASSO Expert Group on IoT/CPS is to identify the key societal challenges where these technologies will offer a large potential for improvements, to analyze technology strengths and technology gaps in the EU and in the US, and to make proposals for future EU-US on IoT-driven cyber-physical systems, in particular on how to handle the huge amounts of real-time data produced by IoT-connected sensors and how to transform it into useful knowledge and actions that will improve the performance, cost-efficiency, and safety of cyber-physical systems.

The objective of this report is to provide a draft selection of EU-US cooperation opportunities on IoT/CPS that were identified within the PICASSO project and that will be refined, validated, and extended during the remainder of the project. The report was compiled based on several sources. The most important inputs were derived from discussions with the PICASSO Expert Group on IoT/CPS (see http://www.picasso-project.eu/iotcps-expert-group/) that provided valuable insights into the R&I landscapes, needs, gaps, and opportunities on both sides of the pond. This input was enriched with background information from other sources that include e.g. the PICASSO reports (7), (8), and (9), technological and strategic documents and roadmaps that were published by relevant EU and US initiatives and institutions, and a database of R&I projects on the topics of IoT and CPS that are currently funded in the EU and the US.

The remainder of this report is structured as follows: Section 2 summarizes the current research and innovation priorities in the areas of CPS and IoT in the EU and the US and identifies major overlaps and gaps. Section 3 gives an overview of potential barriers to collaboration and of relevant US funding agencies, and provides a brief overview of potential collaboration mechanisms, some of which have already been successfully implemented. Section 4 proposes five R&I themes that were identified as most promising for EU-US collaboration in the areas of IoT and CPS, based on the analyses described in sections 2 and 3.
2. Research and Innovation Priorities in the EU and the US

This section summarizes the technological research and innovation priorities in the EU and the US in the sectors of the Internet of Things (IoT) and of cyber-physical systems (CPS) and summarizes the needs and drivers for important application sectors, including smart cities, smart energy, smart transportation, and smart production.

The section is based on several sources, both from within PICASSO and beyond. In addition to inputs by the PICASSO Expert Group on IoT/CPS, relevant documents and roadmaps by different strategic initiatives and institutions were analyzed (a graphical overview is given in Figure 1, more details are provided in the subsections below). Many of these documents were developed in year-long efforts by large networks of experts, and if a topic appears in several, or even all, of these documents, it is reasonable to assume that it is a high-priority topic. In addition, several PICASSO reports served as sources. The PICASSO report “Panorama of the ICT landscape in the EU and US” (7) provides a comprehensive overview of the current ICT landscape (including networks, initiatives, policies, and regulations) in the EU and US. Its focus lies on the application sectors of smart cities, smart energy, and smart transportation, but it also gives an overview of the IoT and CPS domains. The PICASSO report “Analysis of Industrial Drivers and Societal Needs” (8) provides an analysis of EU-US industrial drivers and societal needs and barriers for different application and technology domains, which were validated in a major effort via the interviewing and feedback collection from 150 experts from different industrial domains. This report has provided valuable pointers, and it was particularly useful for clarifying the impact that novel technological developments will have on application domains. The summary of the drivers and needs of application domains is partly based on this report.

To get a feel for the R&I funding priorities in the EU and US, and as an input for the PICASSO ICT toolkit CROSSROADS, a database of IoT and CPS R&I projects was created that covers the projects currently being funded by the most important funding programmes and agencies, including FP7, H2020, and EUREKA/ITEA on the EU side and the NSF, NIST, and the DoE on the US side. This database was used to identify focus areas that are currently getting funded in the EU and the US.\(^1\)

This section is structured as follows: Subsection 2.1 briefly summarizes the major societal cross-domain challenges in the EU and the US that drive the introduction of novel IoT/CPS technologies. Subsection 2.2 describes technological developments in the EU and the US that are important enabling technologies for the IoT-driven CPS, but that are not the focus of the R&I priorities that are relevant for PICASSO. Subsection 2.3 provides a (prioritized) list of R&I priorities for cyber-physical systems that are in the focus of EU and US research and development efforts, and subsection 2.4 does the same for the Internet of Things. Subsection 2.5 summarizes the major needs and drivers in important application sectors, and section 2.6 closes this part of the report with an analysis and comparison of EU and US research and innovation priorities, based on the previous sections.

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\(^1\) The database does not cover all R&I funding in the EU and the US, which amounts to several hundred projects overall (including more than 300 funded by the NSF on CPS topics alone). To reduce the number of projects to be analyzed, only the projects with the largest financial funding were considered, and only those projects were included that are relevant to the focus of this report, IoT-driven CPS. Overall, the database consists of 68 projects on CPS topics and 55 projects on IoT topics.
Figure 1: Documents and roadmaps by these strategic initiatives and institutions were used to create the R&I priority survey.

2.1. Cross-domain Drivers and Needs

This section briefly summarizes the major overarching societal challenges that are currently seen as the major drivers for the development and deployment of novel IoT/CPS-based technologies in the EU and the US. It is based on the PICASSO reports (7) and (8) and on discussions with the EG (Expert Group) members.

Combatting global climate change, the reduction of greenhouse gas emissions, and the provision of clean, renewable energy is seen as a major societal driver in the EU and the US. In this area, there is major demand by customers and governments, and companies see a large opportunity and are seeking to satisfy needs with both products and services.

Globalization and increased urbanization are seen as a key challenge for the future. The predicted growth of the world population, which is estimated to reach 9 billion by 2050, the move towards cities and megadistricts, and the expected deepening of international integration and globalization will create large challenges to provide energy supply, logistics, health care, security, food, and water. Smart ICT will be crucial for providing interconnectivity, information, and optimization of services to solve these challenges.

Increases in connectivity and autonomy in all domains, and the advent of smart and connected devices will drive technology and will provide numerous opportunities for the development of smart ICT solutions for the solution of societal challenges, such as the decarbonization of cities, the grid, production, and transport, or the introduction of renewable energy sources.

Vulnerability, trust, privacy, (cyber-)security, and safety are crucial drivers that are gaining relevance in all practical domains, particularly in the US.

The Industrial Internet of Things is seen as a major driver for the next generation of industrial systems and infrastructures.

2.2. Enabling Technologies

Future IoT-driven cyber-physical systems will be based on advances in a number of enabling technologies, many of which are currently in the focus of research and innovation programmes and efforts in the EU and US.
This section briefly summarizes those enabling technologies that are of the highest importance to IoT-driven CPS. It is based on the roadmaps and strategic documents that are described in subsequent sections, on the PICASSO reports (7) and (8), and on discussions with the EG (Expert Group) members.

The advancement of information technology and high-performance computing is a major focus in both the EU and the US. In this area, major topics include the development of cloud, edge, and fog computing technologies, ubiquitous mobile computing, distributed and heterogeneous systems, novel technologies for data and signal processing, and more generally advances in software engineering and algorithms.

Another area that is currently in the focus of intense R&I efforts is communication and network technology, reflecting the enormous growth in connectivity. Here, the current focus is on topics such as reliability and security in communication systems, real-time-capable communication, open and scalable communication and networking architectures, machine-to-machine (M2M) communications, network management and discovery, and broadband wireless and 5G communications (see 5G section of this report).

The current trend towards "being always connected" and the need to connect and power many billions of IoT-enabled devices poses major challenges that go beyond traditional networking and communication technologies (4). These include the need for ubiquitous connectivity schemes that support the syntactic and semantic integration of heterogeneous IoT sub-systems, mechanisms to provide reliable electricity to power many billions of IoT devices, such as energy harvesting technologies to power autonomous edge devices, scalable registration and discovery of IoT devices/services, bandwidth provision and management for connecting tens of billions of devices, and M2M communication optimization.

The need for highly reliable real-time IoT applications is driving major R&I initiatives and efforts to develop and mature the Tactile Internet that will enable low-latency communications in combination with high availability, reliability, and security. Some important topics in this area, which is covered within PICASSO by the 5G Expert Group, are the detection of security threats and anomalies in wireless communications, the orchestration of resources for reliability and dependability, and the virtualization of IoT functions (4).

The ubiquitous access to information via the IoT will also require advances in pervasive sensing and sensor technologies. Here, major topics are making sensors less expensive and more affordable, in-memory computing power of sensing devices, increasing the speed of data exchange between sensors and the internet, and the virtualization of sensing.

Major advances are currently also made in the areas of data processing and data analytics, which are covered in PICASSO by the Big Data Expert Group.

2.3. Cyber-physical Systems (CPS)

2.3.1. Research and Innovation Priorities in the EU

This section summarizes the major research and innovation priorities in the EU in the areas of cyber-physical systems (CPS) and cyber-physical systems of systems (CPSoS). CPS are one of the key pillars of the European Digital Single Market Strategy and the Digitising European Industry initiative, the innovation programme Smart Anything Everywhere, and other major European initiatives, such as H2020, EUREKA/ITEA, the ECSEL Joint Undertaking, and the ARTEMIS Industry Association, the latter two funding large-scale lighthouse projects that are essential to creating CPS reference technology platforms and open interoperability standards, such as CRYSTAL, CESAR, and EMC2. In addition, a large number of smaller CPS-related R&I projects are funded in different EU programmes, where the EC strategy has been to combine these into clusters, e.g. on CPS and on Systems of Systems. The EU-level initiatives are complemented by national programmes, such as Industrie 4.0 in Germany that drives work on CPS in manufacturing, or the Austrian programme Produktion der Zukunft. In addition, CPS competence centres have been set up to engage with European SMEs, and several public-private
partnerships (PPPs) have been started that are related to CPS or enabling technologies, such as Factories of the Future (FoF), Cybersecurity, 5G, Future Internet, and Robotics.

The major research and innovation priorities in the EU were identified based on different sources. In addition to input by the members of the IoT/CPS Expert Group and PICASSO reports such as (8), relevant strategic documents and roadmaps were analyzed. These include the Strategic Research Agenda 2016 of the ARTEMIS IA (3), the European Roadmap for Industrial Process Automation that was developed by the EU project Process.IT (10), materials that were prepared during workshops of the EU project Road2CPS (11), and the brochure Proposal of a European Research and Innovation Agenda on Cyber-physical Systems of Systems, 2016-2025 that was published by the consortium of the EU project CPSoS (12). In addition, 46 R&I projects were analyzed that are funded by EU-level initiatives including FP7, H2020, EUREKA/ITEA, ECSEL-JU, and ARTEMIS IA, 37 of which were found to relate to the technological topics described in the following.

Overall, nine R&I priorities were identified, four of which are mentioned in all strategic documents that were analyzed while the fifth topic was mentioned in three of the four analyzed documents. Another three topics are mentioned in two documents while two more topics are seen as important in only a single document. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

### 2.3.1.1. High-priority Research and Innovation Topics

Four topics are pushed as R&I priorities in all four of the analyzed strategic documents:

1. **(Systems) engineering support for highly dynamic, continuously evolving CPS**: This topic covers all aspects that relate to the engineering for modern CPS and CPSoS. Subtopics include
   - Integrated, virtual engineering of CPSoS over their full life-cycle
   - More agile and shorter development cycles for CPS
   - Heterogeneous modeling of CPS, which covers modeling-related challenges such as model evolution and adaptation, model maintenance, data-based and grey-box modeling, open simulation platforms and formalisms, simulator interoperability and co-simulation, stochastic models, modeling of human behaviors, integration of safety and security aspects into models, and access to user-friendly modeling tools

   Overall, 13 R&I projects were identified that deal with systems engineering support for CPS, which is the largest number for any of the EU CPS R&I priorities.

2. **Trust, (cyber-)security, robustness, resilience, and dependability**: Subtopics include
   - Secure real-time and mixed-criticality systems
   - Resilience to physical attacks
   - Intrusion detection and prevention
   - Certification and component-based recertification of high-dependability applications
   - Trust in large distributed systems

   7 R&I projects were identified in this area, most of which deal with secure real-time and mixed-criticality systems.

3. **Seamless integration, interoperability, flexibility, reconfiguration**: Subtopics include
   - Semantic interoperability, which ensures that different physical artefacts and computing elements ‘understand’ each other, even if they are implemented in different languages, tools, or platforms

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Increasing openness and pushing open platforms (while retaining security and safety properties)

Auto-reconfiguration, adaptation of CPS elements, e.g. based on learned operational patterns from past examples / historical data

Opportunistic flexibility, i.e. taking advantage of the currently accessible opportunities to dynamically improve the quality of service

4 R&I projects were identified in this area.

4. **Autonomy and humans in the loop**: Subtopics include

- Socio-technical aspects of CPS
- Autonomous CPS subsystems and their interaction with human operators
- Analysis of user behavior, detection of needs and anomalies
- Visualization and decision support, novel usability and HMI concepts to enable human operators to digest and react to large amounts of data and information quickly and effectively

One R&I project was identified in this area.

In addition, the following topic was identified as a priority in 3 of the 4 analyzed documents:

5. **Situational awareness in large-scale CPS**: Subtopics include

- Real-time monitoring, exception handling, fault detection, and mitigation of faults and degradation
- Large-scale, real-time data analytics
- Learning, adaptive behavior, and self-diagnosis tools
- Predictive condition monitoring and maintenance

In this area, 3 R&I projects were identified.

### 2.3.1.2. Lower-priority Research and Innovation Topics

In addition to the five high-priority topics given above, other topics were identified as important, even though they were only identified in 2 of the strategic documents that were analyzed. These topics are:

6. **Distributed, reliable, and efficient management, control, and automation**: This topic was identified as a priority in 2 of the 4 analyzed documents. Subtopics include

- Self-organization and structure formation
- Emerging behavior, deriving e.g. from interactions of autonomous agents
- Cloud-based real-time control

In this area, 7 R&I projects were identified.

7. **Validation, verification, and computation of key properties of CPS**: This topic was identified as a priority in 2 of the 4 analyzed documents. 1 R&I project was identified in this area.

In addition, two topics were identified that are mentioned in only a single strategic document. These topics are:

8. **CPS reference designs and architecture principles**: Subtopics include
Extending the use of digital platforms to build stronger eco-systems with new business models

Integration of functions across application contexts

1 R&I project was identified in this area.

9. **Open R&I environments, test beds:** In this area, no R&I projects were identified.

### 2.3.2. Research and Innovation Priorities in the US

This section summarizes the major research and innovation priorities in the US in the areas of cyber-physical systems (CPS) and cyber-physical systems of systems (CPSoS). In the US, the CPS Senior Steering Group (SSG) of the Networking and Information Technology Research and Development (NITRD) Program is responsible for coordinating programmes, budgets, and policy recommendations for CPS research and development, and CPS-related work is mainly being driven by the NSF Cyber-Physical Systems programme that has funded over 350 projects that focus on fundamental CPS research, which has for example led to the creation of a thriving CPS Virtual Organization (CPS-VO). Other federal agencies have independent research efforts. For example, DARPA is funding a range of large CPS-related projects, agencies such as DoT, DoE, and DHS are implementing mission-specific pograms for e.g. transportation, energy, and CPS security, and NIST has established the Cyber-Physical Systems and Smart Grid Program Office that coordinates its CPS efforts, such as the establishment of a Public Working Group (CPS PWG), the development of a CPS Framework in partnership with industry, academic and government experts, and the establishment of a CPS test bed program.

The US definition of CPS is somewhat different to the one generally used in the EU. While EU definitions clearly separate between embedded systems and cyber-physical systems, in the US, CPS are often seen as an extension of embedded systems, as e.g. illustrated by the CPS definitions in (13) and (14). Like in the EU, the US has realized that the benefits of the development and deployment of novel NIT (Networking and Information Technology, which is the US equivalent of the European term ICT) technologies such as CPS in the coming years and decades is enormous (14), and that IoT advancements will be a crucial enabler for CPS in a large variety of application domains (15). Current national priorities include health, energy, manufacturing, education, and privacy (13).

The major research and innovation priorities in the US were identified based on inputs by the members of the IoT/CPS Expert Group, PICASSO reports, and an analysis of relevant strategic documents, roadmaps, and funded projects. These strategic documents that were analyzed include the report *Designing a Digital Future* by the President's Council of Advisors on Science and Technology (PCAST) (13), a *CPS Vision Statement* that was published by NITRD (14), the NIST report *Strategic R&D Opportunities for 21st Century CPS* (16), the Action Plan that was developed by the EU project *CPS Summit* (15), a White House memorandum on *Multi-Agency Science and Technology Priorities for the FY 2017 Budget* (17), and a workshop report on a bilateral US-German workshop on IoT/CPS that was held in 2016 in Washington DC (18).

In addition, 23 R&I projects were analyzed, most of which are funded by NSF. The projects were selected from the overall list of NSF-funded CPS projects, and only the largest (in terms of funding) projects were chosen that are relevant to IoT-driven large-scale CPS. 19 of these projects were found to relate to the technological topics described in the following.

Overall, ten R&I priorities were identified, seven of which are mentioned in at least three of the strategic documents that were analyzed. Another three topics are mentioned in only one or two roadmaps. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

#### 2.3.2.1. High-priority Research and Innovation Topics

Seven topics are pushed as R&I priorities in at least three of the analyzed strategic documents:
1. **Privacy and cyber-security R&D**: This topic is seen in several documents as having the highest priority overall. Subtopics include
   - Resilience to cyber-attacks
   - Defending cyber-infrastructure, such as civil and governmental communications networks, electrical power generation and distribution systems, financial systems, logistics, fuels, water, and emergency services
   - Realizing the benefits of collective personal information without compromising the privacy of individuals
   - Trust in technical systems

   In this area, 2 R&I projects were identified.

2. **Situational awareness, diagnostics, prognostics**: The major objectives of this topic are to identify, predict, learn from, and prevent or recover from faults in complex systems. Subtopics include
   - Large-scale data management and analysis
   - Machine learning
   - Real-time monitoring, fault detection and mitigation
   - Ensuring access to and retention of critical community research data collections

   In this area, 5 R&I projects were identified.

3. **Validation of novel technologies via prototypes and test beds**: this area, 2 R&I projects were identified.

4. **Effective and reliable system integration and interoperability**: Subtopics include
   - Semantic interoperability between elements constructed in different formalisms, tools, engineering domains, and sectors
   - Abstractions, modularity and composability to enable a reliable and verifiable assembly of individual CPS elements

   In this area, 1 R&I project was identified.

5. **Autonomy and human-computer interaction**: Subtopics include
   a. Socio-technical aspects of CPS, i.e. leveraging the interaction between people and technology, and between complex infrastructures and human behavior
   b. Models and approaches for autonomous CPS systems, and of humans interacting with them
   c. Social computing to develop novel approaches to enable social collaboration and problem-solving in a networked, online environment

   1 R&I project was identified in this area.

6. **Model-based systems science and engineering methodologies**: Subtopics include
   - Systems engineering based architectures and standards to enable efficient design and development of reliability systems while ensuring interoperability and integration with legacy systems
   - Development of a mature systems science for high-confidence CPS
• Conceptualizations of the deep interdependencies among engineered systems and the natural world
• System-wide design
• Heterogeneous CPS models, which includes modeling-related challenges such as the integration of multi-physics models and models of software to enable co-design of physical engineered and computational elements, common terminologies, modeling languages, and rigorous semantics for describing interactions across heterogeneous systems, and stochastics and uncertainty in models

1 R&I project was identified in this area.

7. **Validation, verification, and certification:** Subtopics include
   • Rapid online (re-)verification and real-time health monitoring approaches
   • Time-critical and mixed-criticality architectures
   • Dealing with uncertainty, safety, and risk

   In this area, 2 R&I projects were identified.

**2.3.2.2. Lower-priority Research and Innovation Topics**

Three R&I topics were identified in two or fewer strategic documents:

8. **Educational technology, education and training for cross-disciplinary CPS:** This topic represents the challenge that science and engineering of CPS are cross-disciplinary in nature, requiring expertise in computer science, mathematics, statistics, engineering, and many other disciplines. Thus, new dynamic, multi-disciplinary education and training approaches and tools are needed to educate a skilled workforce for future CPS.

   In this area, no R&I projects were identified.

9. **Distributed control,** e.g. in the form of adaptive and predictive hierarchical hybrid control, is required to achieve tightly coordinated and synchronized actions and interactions in systems that are intrinsically asynchronous, distributed, and noisy.

   In this area, 4 R&I projects were identified.

10. **Open reference architectures** are needed to create universal definitions for representing ultra-large heterogeneous systems.

   In this area, 1 R&I project was identified.

**2.4. The Internet of Things (IoT)**

**2.4.1. Research and Innovation Priorities in the EU**

This section summarizes the major research and innovation priorities in the EU on the Internet of Things (IoT), from the viewpoint that the IoT will be an enabler for future large-scale CPS. Thus, topics that relate to enabling technologies (see above), such as communication technologies, are not covered in the following.

According to a recent European Commission study, the generating market value of the IoT in the EU is expected to exceed one trillion euros in 2020. Consequently, the IoT, like CPS, is a key pillar of the European Digital Single Market Strategy, the Digitising European Industry initiative, and the innovation programme Smart Anything Everywhere. The Alliance for the Internet of Things (AIOTI) was launched by the EC and key European
IoT players in 2015 to develop and support the dialogue and interaction among the various IoT actors in Europe and to facilitate the creation of a European IoT ecosystem, with IoT large-scale pilots being funded to promote IoT take up. The IoT ecosystem is built on the work of the IoT European Research Cluster (IERC), which brings together 40 EU-funded projects with the aim of defining a common vision, identifying common research challenges and coordinating and encouraging the convergence of ongoing work. In addition, there are other initiatives such as FIWARE or UniversAAL which are providing open architectures and specifications to allow developers, service providers, enterprises, and other organizations to develop IoT products, as well as 16 cross-sectoral Future Internet Accelerators that address different application sectors such as Smart Cities, E-Health, Transport, Energy and Environment, and Manufacturing and Logistics, and others. EU-level initiatives are complemented by national programmes such as Germany’s Industrie 4.0 platform, the UK’s IoT initiative, France’s ‘objets connectés’ and Spain’s smart city initiative.

The major IoT research and innovation priorities in the EU were identified based on different sources. In addition to input by the members of the IoT/CPS Expert Group and PICASSO reports, relevant strategic documents and roadmaps were analyzed. These include the book Digitising the Industry that was edited by senior representatives of the AIOTI alliance (4), the EU-China Joint White Paper on the Internet of Things by the EU-China IoT Advisory Group (19), and the roadmap by the EU project Process.IT (10). In addition, 32 R&I projects were analyzed that are funded by EU-level initiatives including FP7, H2020, EUREKA/ITEA, ECSEL-JU, and ARTEMIS IA. 14 of these projects were found to relate to the technological topics described in the following.

Overall, seven R&I priorities were identified, two of which are mentioned in more than one of the strategic documents that were analyzed. Another four topics are identified in only one of the strategic roadmaps, and one topic was identified based on funded projects alone. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

2.4.1.1. High-priority Research and Innovation Topics

Two topics are pushed as R&I priorities in at least two of the analyzed strategic documents:

1. **Automatic, semantic interoperability and integration of heterogeneous systems and platforms:** Subtopics include
   - Data semantics, semantic models, semantic integration
   - Automatic configuration

   In this area, 4 R&I projects were identified.

2. **Open architectures, platforms, and innovation ecosystems:** Subtopics include
   - Open IoT architectures and cross-domain infrastructures
   - Standarization and certification

   In this area, 2 R&I projects were identified.

2.4.1.2. Lower-priority Research and Innovation Topics

In addition to the two high-priority topics, four topics were identified that appear in one of the strategic documents.

3. **Closing the loop - creating a reliable monitoring/actuating IoT substrate:** This topic goes beyond pure connectivity and covers the challenges that arise when trying to transform the deluge of data provided by IoT-connected systems into knowledge and useful actions. This topic is seen as the most demanding IoT “macro-challenge” in (4). Subtopics include
2.4.2. Research and Innovation Priorities in the US

This section summarizes the major research and innovation priorities in the US on the Internet of Things (IoT). As in the previous section, the topics reflect the viewpoint that IoT will be an enabler for future large-scale CPS, and topics that relate to enabling technologies are not covered.

In the US, IoT developments are largely driven by companies instead of R&I programmes or federal agencies, with major players being Google, Cisco, Samsung, and others. The Department of Commerce (DoC), which estimates that digitization, of which the future of the IoT is a major part, has the potential to boost annual US GDP by up to $2.2 trillion by 2025 (20), is promoting growth of the digital economy and as part of the Digital Economy Agenda, and the National Telecommunications and Information Administration is initiating an inquiry to review the current technological and policy landscape for IoT and issue a “green paper” that will highlight potential benefits and challenges, and possible roles for the federal government in fostering the advancement of IoT technologies in partnership with the private sector. The uptake of IoT technologies is promoted via various industry-driven consortia and alliances that include the Industrial Internet Consortium (IIC), the Allseen Alliance (that is dedicated to providing an open environment for the Internet of Things), and the Open Connectivity Foundation (OCF) that was founded by major companies (Intel, Microsoft, Samsung, Qualcomm, GE Digital, and Cisco Systems) to work towards a single standard for IoT.

The major IoT research and innovation priorities in the US were identified based on different sources. In addition to input by the members of the IoT/CPS Expert Group and PICASSO reports, relevant strategic documents were analyzed. Due to the current lack of involvement of federal and governmental agencies and programmes in IoT, comprehensive roadmaps are difficult to find in this sector. However, several white papers are available by the IIC (5) (21) (22) and by the company Samsung (6) that were analyzed, plus a few more general strategic documents that were published by governmental agencies such as the DoC (20), the White House (17), and the US Senate (23). In addition, 23 R&I projects were analyzed that are mostly funded by the NSF. 12 of these projects were found to relate to the technological topics described in the following.

Overall, five R&I priorities were identified, three of which are mentioned in at least three of the strategic documents that were analyzed. Another two topics are identified in two or fewer of the strategic documents. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

2.4.2.1. High-priority Research and Innovation Topics

Three priorities are identified in three or more of the strategic documents that were analyzed:

• Real-time data processing and analytics, i.e. novel methods and tools to transformation data into useful and actionable knowledge

• Distributed/decentralized reasoning, low-latency cognitive (feedback) loops

• Humans in the loop and self-management of IoT systems

In this area, 1 R&I project was identified.

4. **Large-scale test beds and pilots**, such as the ones provided by the initiatives FIWARE and FIRE. 5 R&I projects were identified in this area

5. **End-to-end IoT security, trust, dependability, and privacy**, for which 1 R&I project was identified

6. **Fully autonomous IoT devices**, for which no R&I project was identified

One more topic was identified that was not mentioned in any strategic documents:

7. **Smart machine-to-machine (M2M) networks**, for which 1 R&I project was identified
1. **Open architectures, platforms, interoperability:** This topic is seen as highly important, e.g. the DoC sees IoT openness as a grand policy challenge and states that “a free and open global Internet, with minimal barriers to the flow of data and services across borders, is the lynchpin of the digital economy’s success”. Subtopics include
   - Semantic technologies, semantic models, semantic integration
   - Novel IoT architectures and cross-domain infrastructures
   - Innovation ecosystems

   In this area, 7 R&I projects were identified.

2. **(Cyber-)security, privacy, resilience to faults/attacks, trust:** Subtopics include
   - Risk assessment and management
   - Fault and outage detection
   - Trust and security online
   - Robustification and additional security capabilities of legacy systems in industrial environments
   - Consumer protection

   In this area, 5 R&I projects were identified.

3. **Closing the loop: IoT as an enabler for future CPS:** This topic is very similar to topic 3 in the IoT-EU list above and covers the challenges that arise when trying to transform the deluge of data provided by IoT-connected systems into knowledge and useful actions. Subtopics include
   - Tools and platforms for real-time data analytics and transmission
   - Site-wide integration and convergence of control systems with information technology (IT) and operational technology (OT) systems
   - IIoT edge devices / smart assets
   - IoT-enabled predictive maintenance and remote monitoring

   In this area, no R&I projects were identified.

2.4.2.2. **Lower-priority Research and Innovation Topics**

Another two topics are identified in two or less of the strategic documents:

4. **Human-centered IoT systems,** which acknowledges the fact that human capital remains critical to decision support. No R&I projects were identified in this area

5. **Promotion of skill-building initiatives,** such as the National Initiative for Cyber Education (NICE). No R&I projects were identified in this area

2.5. **Application Sectors: Drivers and Needs**

This section briefly summarizes the major drivers and needs in the application sectors of smart production (which includes smart manufacturing and processing, but not other types of production such as smart farming), smart cities, smart energy, and smart transport. This section is partly based on the PICASSO report (8) that provides a comprehensive survey of three of the four sectors as well as feedback by industrial interview contacts, and on inputs by the IoT/CPS Expert Group. In addition, the strategic documents and roadmaps that were used to create the survey in section 2.4 were analyzed for application-relevant information.
While each vertical industry and application sector has unique needs (see e.g. (21)), research and innovation actors in both the EU and the US are aware that there are many cross-cutting R&I challenges in IoT and CPS, the solutions to which will benefit multiple sectors. As an example of this, the NITRD (14) states in its CPS vision statement that “attempts to establish extensible architectures for unmanned aerial vehicles or self-driving cars in the transportation sector will directly benefit the designers of networked industrial control systems in manufacturing”. On the EU side, the research agenda proposed by the CPSoS project (12) is an example of this fact, since only four of the R&I priorities they propose target specific application sectors while seven priorities are cross-cutting. Consequently, we have also found in interviews with companies and research institutes (8) that there is a general interest in all of the PICASSO application sectors. As examples, topics such as increased connectivity, increased autonomy, and the need for assurance and cyber-security are seen as being relevant for all application domains.

2.5.1. Smart Production

Making progress on advanced manufacturing and smart production systems is seen as essential in both the EU and the US. Current key drivers in this area are the German initiative Industrie 4.0 in the EU and the Industrial Internet of Things (IIoT) in the US.

Production systems are currently evolving into global, highly integrated cyber-physical systems of systems that go beyond pure production and that cover all parts of the value chain. This evolution is driven by quickly changing customer requirements that are more aware of environmental impact, ask for a high degree of product customization and configurability, and require efficient, yet sustainable production. Major drivers in the production sector are the trend towards zero-waste and environmentally neutral processes and plants, efficient resource usage, site-wide optimal operation, high availability and safety, increases in complexity and flexibility with reduced time to market, and the need for a highly skilled work force for the design and operation of modern production systems.

Novel ICT technologies, in particular CPS technologies and the (industrial) IoT, are seen as vital to preserve the competitiveness on both sides of the Atlantic (12), (14). The major needs in the smart production sector are:

- **Interoperability and standardization**: Production systems consist of thousands of (often proprietary) hardware and cyber components by a large number of manufacturers that have to be integrated with each other and with legacy systems. Interoperability is a key prerequisite for novel ICT technologies that will require global real-time access to all devices at the field and automation levels. Thus, challenges such as plug-and-play reconfiguration, zero-configuration integration of automation systems, real-time analytics and optimization, monitoring and diagnostics, and others depend on the interoperability of technical systems. There is a need for companies to move away from proprietary solutions towards open interfaces and platforms. The production of Industrie 4.0 compatible automation products is seen as an opportunity for harmonization within the industry, and the expectation is that the cloud and the IIoT will be used to connect smart components. Another need that is currently arising is that of complete value chain integration of production systems.

- **Exploiting the IoT - Real-time analytics, situational awareness, predictive maintenance, data-based operation/optimization**: The availability of IoT-connected, financially viable sensors, software and devices will enable manufacturers to generate compelling business value. There is thus an opportunity for automation systems and optimization of processes based on much greater collection of data. Monitoring is also seen as a key driver for the industry. There are many new ideas being promoted such as the “augmented operator” where information is provided to wearables, smart phones, and other smart devices. This is being used to provide information for optimization, asset management, and predictive maintenance to operators as they walk around the factory. A success story by Intel provides a good case for the enormous business value that can be added based on data and real-time analytics (22): In one of its factories, Intel installed sensors on CPU assembly modules that are
employed in the final steps of CPU manufacturing. Using analytics software, Intel was able to reduce the number of machine failures, detect defects on the assembly line, and boost assembly line uptime and productivity. This led to a time and inspection effort reduction by a staggering 90 percent.

- **Cyber-security** is quickly becoming the key issue in smart production with the advent of ubiquitous connectivity in industrial environments.

- **Integrated management and control structures, system-wide management**: With increasing complexity and integration in large production systems, decentralized and system-wide control and management of production complexes will become a major need, with a key area being management to improve energy efficiency. More generally, increases of automation in production systems have additional advantages, such as the reduction of human exposure to dangerous areas through remote operation, and the reduction of personnel requirements (e.g. night shift operators) for the 24/7 operation in production complexes that are never switched off, such as chemical plants.

- **Integrated engineering approaches for cyber-physical systems** is a key need to enable engineers to deal with the challenges that arise from the complexity, quick evolution, and required flexibility of modern production systems. In addition, supply and value chain integration is an important topic in the smart production sector.

The feedback that we have obtained so far indicates that it is (at least potentially) possible for the EU and US to work together in all technological areas of smart production. However, in the production sector there are conflicting strategic and commercial interests between both sides that will be significant barriers, with a major challenge being to find partners who are willing to collaborate.

### 2.5.2. Smart Cities

The Smart Cities industry is estimated to be valued at more than $400 billion globally by 2020. In contrast to other sectors, the scope that is covered under the smart city keyword is often not clearly defined, and the area of smart cities consequently may cover a very wide scope that goes beyond interactions with citizens and use of their data to also include control and management of energy, waste, buildings, utilities, and infrastructure, as well as social interactions with government, education, and e-health. In some definitions, smart energy and smart transportation are also seen as part of smart cities. These sectors are described later below.

Major drivers in this sector are reductions in greenhouse gas emissions (decarbonization), the need for clean air and water, the need for increased security and safety, efficient use of space, infrastructure, and other resources, globalization, the trend towards migration to cities, increases in autonomous functionality and connectivity, and advances in artificial intelligence.

The major needs in the smart cities sector that will benefit from the development and deployment of novel IoT and CPS technologies are:

- **Interoperability and integration** (of data and infrastructures) is seen as a major challenge. Due to the increase in connectivity, concepts such as integrated smart transportation systems are receiving widespread attention.

- **Cyber-security, safety, and privacy**: As in the other application sectors, cyber-security is seen as a major challenge for smart city platforms and applications. In addition, guaranteeing privacy is essential due to the strong involvement of private citizens.

- **(Real-time) data analytics**: The spread of connectivity are expected to enable novel concepts and solutions for smart city applications such as smart lighting (“Internet of Lighting”), smart building management (“Internet of Buildings”), smart garbage collection, optimal use of water and energy, and monitoring for the safety and well-being of inhabitants.
• IoT platforms for smart city applications.

The feedback that we have obtained so far indicates that it is likely that there are collaboration opportunities on different topics, such as interoperability of data, infrastructures, cloud computing, and real-time data analytics. Collaboration on privacy and security topics may be difficult due to differences in regulations and strategic interests.

2.5.3. Smart Energy

The energy sectors in the EU the US have high demands for quality, repeatability and performance, and are mainly driven by green initiatives and the decarbonization of the grid, e.g. in Europe to reduce greenhouse gas emissions by 40% by 2030. The inclusion of renewables and decentralized production are major drivers, as is the improvement of grid stability.

ICT is already exploited in many areas within the energy supply sector and is used to provide availability of services, for management to reduce consumption and CO₂ emissions, to improve stability and safety, and to integrate renewables. The move to the IoT is seen as a key driver in both the EU and the US. For example, PG&E has created the new moniker Grid of Things to make the IoT more applicable to utilities, and in Europe the “Internet of Energy” term has been coined. Furthermore, CPS technologies are seen as important for the creation of a smart infrastructure for realizing a smart grid, enabling the optimization and management of resources and facilities and allowing consumers to control and manage their energy consumption.

The major needs in the smart energy sector that will benefit from the development and deployment of novel IoT and CPS technologies are:

• Cyber-security and safety: As in the other application sectors, cyber-security is seen as a major challenge for smart energy applications.

• Novel approaches for the engineering and dynamic management of smart grids with decentralized production / renewables: There is a major need for novel engineering and dynamic power management methodologies for applications ranging from single devices to complete grids, including using real-time data for optimal energy management.

• Interoperability and harmonization of standards: Currently, standards for interoperability are being driven by the EC and EFTA on the EU side and NIST and FERC on the US side. A challenge is the harmonization of interoperability standards developments.

• Exploiting the IoT and intelligent connectivity for smart grid applications.

The feedback that we have obtained so far indicates that there is significant pessimism with respect to collaboration opportunities due to differences in the grid topologies, standards, and technologies between the EU and the US, and due to differences in the requirements for Smart Grids (8). However, there may be opportunities for joint research in the areas of smart metering, energy efficiency and management, low-carbon economy, and renewable energy. The BILAT project (24) has found that there is interest from EU and US partners in advancing already existing collaborations around energy.

2.5.4. Smart Transportation

The sector of smart transportation covers several modes, i.e. road/automotive, rail, aerospace, and maritime. North America and Europe are expected to become the largest markets for ITS (Intelligent Traffic Systems). Within Europe, sustainability (via the promotion of e.g. electric mobility / decarbonization of transport) is a key driver, with a dramatic anticipated increase in both freight and passenger transport and associated emissions. Other drivers are to reduce casualties (for which autonomous mobility is pushed) and to reduce congestion via ITS. To achieve these goals, EU programmes of enormous size have been set up, such as the Trans-European...
Transport Networks (TEN-T) policy with an investment volume of € 400 billion. The drivers in the US are similar to the European ones, with the added driver of homeland security.

ICT is already being used in smart transportation to provide an optimized use of infrastructure to increase capacity and also to improve the safety of road transport, e.g. via traffic management systems that are relying on increased connectivity between cars and between cars and infrastructure. The consensus is that there is an urgent need to deploy novel ICT technologies, such as CPS technologies, to improve efficiency and safety in transportation, with a notable opportunity being increased autonomy which is expected to lead to fundamental changes to traffic operation.

The major needs in the smart transportation sector that will benefit from the development and deployment of novel IoT and CPS technologies are:

- **Interoperability**: There are several areas in which interoperability between heterogeneous transportation systems is essential. These include the uniform compatibility of electric vehicle charging stations with all electric vehicles from the EU and the US, standards and protocols for vehicle-to-vehicle (V2V) communication, integration and compatibility of vehicle-to-infrastructure (V2I) systems (including interoperable interfaces for roadside infrastructure), and harmonized information exchange between transportation systems from the maritime domain. There is also a need for future automation system architectures to be more open.

- **(Cyber-)security and safety**: As in the other application sectors, cyber-security is seen as a major challenge for smart transportation applications. Approaches to mixed criticality are another need here.

- **Intelligent traffic management, drive-by-wire vehicles, autonomy**: ICT is needed for the optimized use of transport infrastructure to increase capacity and to improve safety, using e.g. data collection and processing and new technologies for autonomous vehicles.

- **Systems engineering and supply chain integration**, including interoperability of tools, integration of engineering domains, integration of different disciplines across the supply chain, and integrated systems engineering approaches for future transportation infrastructures.

In addition, education and training of a high-skill work force was identified in several of the transportation domains as a major need for the future.

There is already considerable joint work going on between the EU and US, e.g. developing interoperability of charging stations. In addition, an implementation agreement was signed to boost cooperative activities in the field of research, technology and innovation for all modes of transport (24). Key areas include freight transport and logistics, sustainability, safe and seamless mobility, road traffic management, and human factors. Our analysis (8) showed that further EU-US collaboration might be possible on challenges such as traffic management, autonomous and electric cars, integration of vehicle and infrastructure systems, traffic management using ITS, data collection and processing, and model-based systems engineering.

**2.6. Analysis**

This section summarizes some major conclusions from the assessment of the drivers, needs, and research and innovation priorities in the EU and the US that was presented above.

1. **The intersection of the IoT and future CPS is an important area in both the EU and the US.**

   The CPS and IoT domains are vast, and the development of concrete and feasible collaboration opportunities is only possible by restricting our focus on subsets of these domains. Our analysis has revealed that restricting the scope of the PICASSO work on IoT/CPS to the intersection of the IoT and CPS is a good option, as it is of high relevance in both the EU and the US, and the IoT is seen as an important driver for the design and operation of
future CPS. In the EU, this challenge is recognized by several institutions, such as the ARTEMIS Industry Association who believe that the “Internet of Things, and consequently the Things of the Internet, and Cyber-Physical Systems are complementary directions which together will help to shape a society where humans and machines increasingly interact to provide services and solutions for the benefit of society that are inconceivable with the present state-of-the-art technology” (3), and the European Alliance of IoT Innovation (AIOTI) who see this as a macro-challenge, stating “Getting billions of objects duly connected and managing these to create a reliable monitoring/actuating substrate only partially caters for the challenges ahead. These challenges cannot be complete without considering how to handle the huge amount of data produced and how to transform it into useful and actionable knowledge.” (4). On the US side, for example the Industrial Internet Consortium (IIC) promotes the message that “Companies need to close the loop across associated processes.” (5), the US branch of Samsung sees the CPS draft framework by NIST as an important prerequisite for the future of IoT (6), and the NSF is currently funding several research projects that cover the idea of using the IoT as an enabler for CPS.

2. There is a significant overlap between R&I priorities in CPS between the EU and the US.

When comparing the R&I priorities between the EU and the US in the CPS area (see Figure 2), it becomes apparent that EU and US actors have identified similar challenges and priorities.

![Figure 2: Comparison of CPS topics in the EU and the US.](image)

In particular, a comparison of the results shows that five R&I priorities are of high relevance in both the EU and the US:

- Model-based systems engineering
- Trust, (cyber-)security, robustness, resilience, and dependability
- Integration, interoperability, flexibility, and reconfiguration

The number of funded projects is shown in **green**.
• Autonomy and humans in the loop
• Situational awareness, diagnostics, and prognostics

In addition, the following common topics of lower priority were identified:
• Validation and verification
• Distributed, reliable, and efficient management, control, and automation
• Open environments, test beds
• CPS reference designs and architecture principles

An analysis of the funded R&I projects on these topics shows that:
• The important topics of autonomy and human interactions seem to be underfunded in both, the EU and the US. These topics should receive more funding, and there may be good opportunities for collaboration on these topics.
• Although management, control, and automation were not identified as high-priority topics in this analysis, the large number of projects that are funded in these areas indicate that this topic is seen as important. The topic has been added to the R&I theme on model-based engineering that is defined in section 4.1.

3. There is a significant overlap between R&I priorities in IoT between the EU and the US.

There is a significant overlap of the R&I priorities between the EU and the US in the area of IoT (when focusing on topics that are most relevant to using the IoT to enable future CPS), as shown in Figure 3.

A comparison of the results shows that four R&I priorities are of high relevance in both the EU and the US:
• Interoperability and integration
• Open architectures and platforms
• Closing the loop - IoT as an enabler for CPS
• (Cyber-)security, privacy, resilience to faults/attacks, trust

Figure 3: Comparison of IoT topics in the EU and the US.

The number of funded projects is shown in green.
An analysis of the funded R&I projects on IoT topics shows that

- The important topic of “closing the loop” seems to be severely underfunded in the IoT domain. This topic is essential for the future of IoT and CPS systems and should receive more funding, and there may be good opportunities for collaboration.

- In the EU, there is currently a strong push towards test beds and large-scale IoT pilots, which does not seem to be mirrored in the US. This topic has been added to the R&I theme “Integration, Interoperability, Flexibility, and Reconfiguration” that is described in section 4.3.

4. Several R&I priorities are of high relevance in both the CPS and the IoT domains.

Figure 4 shows a comparison of, and mapping between, the high-priority R&I priorities in the EU and the US. All of the high-priority IoT topics are linked to equivalent CPS topics, indicating that advancements of the state of the art in these topics will drive progress in both areas. Note that the topic of “closing the loop”, i.e. processing data from IoT devices to transform it into useful and actionable knowledge, or into useful actions, is a relatively recent topic in IoT. In contrast, this topic has been an important challenge in the CPS world for many years, and CPS researchers and practitioners have ample experience in this area. Over the decades, different R&I areas have sprung up that all aim to provide methods, theories, and tools to compute useful knowledge and to generate useful actions for technical CPS. These areas include model-based systems science and engineering, situational awareness, diagnosis, prognosis, monitoring, management, control, and automation, and validation and verification.

![Figure 4: Mappings between CPS and IoT topics in the EU and the US.](image)

Some additional conclusions can be drawn from our analysis:

- We have found that cyber-security and privacy are the dominant topics in the US, somewhat more so than in the EU (although they are seen as important in the EU as well). Some of our interview contacts indicated (8) that it may be challenging to collaborate on privacy-related topics due to differences in interests and policy between the EU and the US, and collaboration on cyber-security topics may be
difficult as well. However, technology-oriented research collaborations on related topics may be feasible, such as attack resilience and intrusion detection or secure real-time and mixed-criticality systems.

- Our findings are well aligned with those by other initiatives that work, or have worked, on the identification and promotion of R&I collaborations between the EU and the US, i.e. the EU project TAMS4CPS (25) that focuses on modeling and simulation (M&S) for CPS and the EU project CPS Summit (15). There are no contradictions between our results and the findings of these projects, and in particular the overlap with the findings of the CPS Summit project is significant (the limited scope of TAMS4CPS also restricts the breadth of their analysis). CPS Summit views the CPS foundational challenge as so great that a collaboration would prove to be beneficial for industry, academia, and governments, and it has identified the following technological challenges: the socio-technical character of CPS, systems theory and model-based systems engineering, cyber-security and dependability, interoperability, autonomy, technology platforms, data-driven approaches, verification and abstraction, dealing with uncertainty and risk, and humans in the loop.

5. All of the analyzed application sectors will profit from IoT/CPS advances and collaborations.

Our analysis has shown that institutions in both the EU and the US view CPS and IoT as pervasive technologies that will impact all application sectors and almost all aspects of life, and that there are many cross-cutting challenges and needs in the four domains of smart production, smart cities, smart energy, and smart transportation, as illustrated in Figure 5.

![Figure 5: Identified major needs in application sectors.](image)

While this does not necessarily mean that all of these challenges can be served adequately by generic, cross-cutting solutions and platforms (since there are application-specific differences in many of the needs and environments of the sectors), it does indicate that the development of cross-cutting new technologies will provide significant benefit to different application sectors.

6. Our analyses, discussions, and interviews have shown that there is significant potential for collaboration on IoT/CPS topics between the EU and the US.

There are many similarities in drivers, needs, challenges, priorities, and programmes being pursued in the EU and the US. It is also clear that there are a number of opportunities where joint R&I between the EU and US
would be beneficial, both on technological topics and on application topics, and our initial discussions with experts (8) and the members of the IoT/CPS Expert Group indicates that there is promising evidence for the willingness of collaboration between the EU and the US.

This view is reinforced by other EU projects that work on promoting EU-US collaboration, such as the CPS Summit, TAMS4CPS, and BILAT 4.0 projects. The latter project has e.g. found that ICT is the single most predominant area targeted for future EU-US cooperation, with promising topics including smart cities, the IoT, CPS, data management and open data, cognitive computing, automation, and cyber-security (24).
3. Barriers, Funding Agencies, and Mechanisms

Generally, most of the EU funding will be used to fund EU companies and research institutes, and US funding will focus on the support of US organizations and companies. Thus, EU-US collaboration will always be a complement, or even an exception, to local funding. This section gives a brief overview of US funding initiatives and agencies (where it is assumed that the EC is the only relevant agency for collaboration on the European side) and then summarizes barriers that may hamper EU-US collaboration. The section closes with a selection of possible collaboration mechanisms to inspire the development of concrete collaboration opportunities and mechanisms in PICASSO.

3.1. An Overview of US Funding Agencies

This section provides a brief overview of US agencies and their roles in R&I funding. This section is based on inputs by the Expert Group on IoT/CPS and the PICASSO report (9) and takes some input from the BILAT 2.0 and BILAT 4.0 projects (24).

In the US, research and innovation is mostly funded by federal research programs that reflect directly the government’s R&I priorities and interests (9). Research funding is also available at the state level, but normally focuses on specific local needs and is not usable for international cooperation. According to research conducted by the BILAT 2.0 project, “nearly one-quarter of individual organisations’ policy measures provide funds to other countries as long as the leading organisation is a U.S.-based university or other research institution. About 40% of the measures do not provide funding to non-U.S. institutions. The remaining 40% have specific pre-requisites for allowing receipt of U.S. funds by third countries”. To our knowledge, no specific calls are published for foreigners’ participation (9), and normally international partnerships result more from existing and previous personal research collaborations than from a manifest encouragement in the call announcements.

A major contact point in the federal US funding landscape in the areas of IT, computing, networking, and software is the Networking and Information Technology Research and Development (NITRD) Program, a multi-agency program that coordinates the funding of all federal agencies in this area. It has a specific contact point that coordinates CPS research across all agencies.

The National Science Foundation (NSF) exclusively funds basic research and has a major CPS research program with more than 350 funded projects, plus funding for IoT research. The NSF has explored cooperations with the EU in the past, most successfully in the areas of environmental health and safety technology. In addition, there are several bilateral cooperation agreements with EU member states, such as the US-German IoT/CPS program. Potential collaboration mechanisms involving the NSF are e.g. joint workshops and mirrored calls.

The National Institute of Standards and Technology (NIST) is an important player in ICT funding and is active in a variety of technological areas and application sectors. In particular, it has a Cyber Physical Systems Program and a CPS Public Working Group that is currently developing a CPS framework (26). NIST has already shown significant interest in the PICASSO work.

The parent organization of NIST, the Department of Commerce (DoC), also promotes other activities in the IoT/CPS domain. In 2016, the DoC has set as a policy priority to engage with the EU Digital Single Market initiative in the area of the free and open internet.

Other agencies that are potentially of interest as US partners for PICASSO collaboration mechanisms are the Department of Energy (DoE) that supports research and development in areas such as clean energy, environmental cleanup, climate change, and other areas, has a strong track record in collaborations with European universities and research centers, and has shown interest in topics such as grid modernization and
integrating renewables, the Department of State (DoS), the Department of Homeland Security (DHS), Department of Defense (DoD) agencies such as DARPA, the Air Force Office of Scientific Research, the Army Research Office, and the Office of Naval Research, and US foundations such as Gordon and Betty Moore Foundation and the Blavatnik Family Foundation.

3.2. Barriers

This section summarizes barriers that must be overcome to implement successful EU-US collaborations. These barriers were identified in discussions with the PICASSO experts.

- **Collaborations that are based on joint funding** will be difficult to implement (money will generally not cross the Atlantic).

- Collaboration may be difficult on topics of high near-term commercial importance, i.e. innovation efforts that focus on products and services that may lead to large profitable businesses in the near term. We have identified this barrier as important in all considered application sectors, and this is also a major conclusion by the BILAT 4.0 project that has found a lack of bilateral funding agreements between the EU and the US in areas with immediate economic outcomes. They state that “one reason for the lack of joint funding agreements may be that there are immediate economic outcomes where the US has a competitive advantage compared to the EU in the areas of technology levels, entrepreneurship, supporting start-ups, and venture capital.” (24). It is thus arguably easier to collaborate on basic research than on applied research.

- Topics touching export control issues, sensitive or classified data / information, or privacy issues should be avoided. The EU and US national priorities, rules, and regulations are very different and will be difficult to harmonize, and generally legal and policy differences will be difficult to overcome in these areas.

- A lack of interoperability and (device) standards can be a barrier to collaboration. This is true for several of the application sectors, as described in section 2.5 and, in more detail, in (8). In addition, IoT/CPS systems were noted by our interview contacts as sometimes being highly regulated, which can stifle innovation.

- A lack of awareness and knowledge of EU and US funders of the other side is detrimental to collaboration. E.g., BILAT 4.0 found that US funders may be unaware of how EU funding schemes operate (including misconceptions on how US partners can participate in H2020), and are not aware of the R&I priorities of the other side. In addition, it is often straightforward to connect to other initiatives within the US, but the EC landscape is fragmented, and the responsibilities may not be clear to US agencies.

- Bureaucratic hurdles are seen as a major barrier to collaboration. One major hurdle was the need for US partners to sign H2020 grant and consortium agreements. This requirement has recently been removed under a new “Implementing Arrangement” that was signed in October 2016 by the EU and the US. Under this new agreement, US organizations that do not receive any funding under H2020 are allowed to partake in research efforts and other relevant activities in the scope of EU projects without having to sign grant and consortium agreements, thus providing a new basis for EU-US R&I collaboration.

For EU-US collaboration, the following major conclusions can be drawn from these barriers:

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• EU-US collaboration on technological topics should focus on **low-TRL (Technology Readiness Level)** research efforts. However, despite the potential difficulties of close-to-market collaboration, some **innovation topics** can possibly be considered. One example of this that was identified in discussions is business model development.

• There may be an opportunity to collaborate on topics such as **energy, air, and water with a focus on developing parts of the world** (e.g., Africa, India, Latin America). Within this space, commercial opportunities may be more limited in the near term than in the US and in EU countries.

### 3.3. Potential Collaboration Mechanisms

This section provides an overview of potential mechanisms for EU-US collaboration that was compiled based on discussions with EG members, interview results, and an analysis of the results of projects that work towards EU-US collaboration development. It is supposed to serve as an inspiration for the definition of concrete collaboration opportunities and mechanisms within PICASSO. Note that this section is at this stage highly speculative, since the success probability of future collaboration mechanisms will depend on the regulatory framework and conditions that will be enacted by the new US administration.

There are different mechanisms for EU-US collaboration that can be considered, several of which have been successfully implemented before. The most promising partner for low-TRL research seems to be the NSF. The NSF will not cover EU costs, but it may cover costs for EU researchers visiting the US and vice versa. The NSF has already shown interest on collaborations on low-TRL research and is a good fit because it has a major initiative in CPS, in which energy aspects are of particular interest.

An option that was found by the **TAMS4CPS** project is to contact US national labs (such as Sandia) regarding funding for collaborations on more applications-oriented research.

In addition, the **NITRD Program** and **NIST** have already shown significant interest in the PICASSO work and are expected to be valuable contacts, and prospects could be explored with **Department of Defense** agencies (DARPA, the **Air Force Office of Scientific Research**, the **Army Research Office**, and the **Office of Naval Research**), as sources that we contacted indicated that there are no problems with having European institutes being subcontracted to regular research grants from the US.

While joint calls with the EC seem to be unrealistic, mirrored calls could be a viable path for many agencies as they do not require transfers of funds and full consortium agreements, although coordinating budgeting and planning cycles can be challenging.

Setting up a virtual network with institutional partners and a few leads who agree to help seek funding programs and do matchmaking may be a good approach to develop promising collaboration mechanisms in PICASSO.

The EU project **TAMS4CPS** has assembled a list of potential mechanisms that can be used as an inspiration for the development of proposed collaboration mechanisms by PICASSO. **TAMS4CPS** has proposed the following mechanisms - more details and examples for these mechanisms are given in (25):

- **Establishment of high-level bilateral agreements**, e.g. the 2016 Implementing Arrangement between the EU and the US[^3]

- **Thematic, targeted funding programmes**; the health sector is running a successful joint EC-NIH programme

• Joint calls, twinning of research projects
• Facilitating US participation in mainstream H2020 projects, enhancing framework conditions for trans-Atlantic collaboration
• Funding of joint workshops, conferences, and series of seminars
• Active support for the mobility of researchers, staff exchange, fellowships to students, trans-Atlantic training and education
• Access to research infrastructure, sharing of equipment
• Enhancing the visibility of EU/US programmes, as e.g. done via the BILAT 4.0 and PICASSO projects
4. Opportunities for Collaboration: R&I Themes

In the analysis in section 2.6, item (2), we have identified five CPS-focused R&I themes that have a high priority in both the EU and the US:

- Model-based systems engineering
- Trust, (cyber-)security, robustness, resilience, and dependability
- Integration, interoperability, flexibility, and reconfiguration
- Autonomy and humans in the loop
- Situational awareness, diagnostics, and prognostics

As illustrated in Figure 4 in section 2.6, these themes are related to the high-priority IoT topics, indicating that advancements in the state of the art in these topics will drive progress in both domains, in particular at the intersection of the IoT and CPS. The high relevance of these themes on both sides of the Atlantic makes them promising candidates for future EU-US collaborations.

This section presents draft summaries of these five R&I themes. These themes will be discussed, adapted, refined, and promoted during the remainder of the PICASSO project.

4.1. Model-based Systems Engineering

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Integrated, virtual, full-life-cycle engineering, system-wide design
- Engineering of high-confidence CPS, validation, verification, risk analysis and risk management
- System-wide management and coordination
- Models of heterogeneous large-scale systems
  - Stochastic models
  - Open simulation and model integration platforms
  - Model adaptation, maintenance, and validation
  - Data-based and grey-box modeling

Why EU-US Collaboration?

A consistent systems science and new integrated model-based engineering methodologies are of importance for the design, optimization, and operation of future IoT-driven CPS. The documents that were analyzed show that the US view on this topic focuses more on theoretical aspects of systems science for novel CPS (such as the formal conceptualization of the interdependencies of technical systems and the environment) and on reliability aspects while the EU view seems to promote the practical aspects (such as integrated engineering of novel CPS) more, as well as system-wide management and coordination. These somewhat differing views are an argument for collaboration as EU and US groups may complement each other well in systems engineering R&I topics. The challenges that are seen as important by both sides are similar (e.g. heterogeneous modeling of CPS), which may facilitate the identification of suitable collaboration partners.

Relevance to Application Sectors
Model-based systems engineering approaches and methodologies, as well as novel approaches for system-wide management and coordination, have been identified as a major need in all of the application sectors that we have analyzed.

Proposals for Collaboration Actions
To be added after feedback collection.

4.2. Trust, (Cyber-)security, Robustness, Resilience, and Dependability

Research and Innovation Topics
Potential topics in this area for EU-US collaboration are:
- Exception handling, fault detection and mitigation
- Intrusion detection and prevention, resilience to cyber attacks
- Trust in technical systems
- Secure real-time and mixed-criticality systems

Why EU-US Collaboration?
Cyber-security is currently one of the dominant topics in the US, and is seen as important in the EU as well. Although collaboration on data-sensitive or privacy-related topics is most likely not feasible, there does not seem to be any reason that technology-oriented R&I collaborations on related topics may be feasible, such as attack resilience and intrusion detection or secure real-time and mixed-criticality systems. In addition, the topics of fault detection and mitigation in large-scale technical systems, in which faults are the norm and not an exception, are seen as important in both the EU and the US. This large overlap in interests is a good basis for R&I collaborations.

Relevance to Application Sectors
The topics of cyber-security and safety are seen as the key challenges in all of the application sectors that we have analyzed. Thus, EU-US collaborations will benefit all sectors.

Proposals for Collaboration Actions
To be added after feedback collection.

4.3. Integration, Interoperability, Flexibility, and Reconfiguration

Research and Innovation Topics
Potential topics in this area for EU-US collaboration are:
- Semantic interoperability and semantic models (which ensure that different physical artefacts and computing elements ‘understand’ each other)
- Pushing openness and open standards, harmonization of standards
- Automatic configuration, reconfiguration, and plug-and-play integration of IoT and CPS components
- Joint testbeds and large-scale pilots for CPS and IoT systems, shared access
- IoT and CPS architectures and cross-domain infrastructures
Why EU-US Collaboration?

We have identified the topics of integration, interoperability, flexibility, and reconfiguration as being of the high relevance in the EU and the US in both the CPS and the IoT domains. In particular, semantic interoperability and the need for open standards are seen as important in all domains and on both sides of the Atlantic. This large overlap in interests is a good basis for R&I collaborations.

Joint infrastructures and test beds, or shared access to infrastructures and test beds, have been included there since they can be an important tool to promote interoperability between heterogeneous infrastructures (as was e.g. found by the TAMS4CPS and CPS Summit projects), and since the US and (in particular) the EU are currently working on large-scale demonstrators, e.g. in the areas of the IoT and smart cities.

Relevance to Application Sectors

The areas of interoperability and integration are of crucial importance in all of the application sectors that we have analyzed. Novel methodologies for (automatic) reconfiguration will be necessary for the development of future industrial infrastructures and networks, e.g. to reflect the increasing requirements for flexibility in manufacturing systems or to implement future smart grids with a large penetration of renewables.

Proposals for Collaboration Actions

To be added after feedback collection.

4.4. Autonomy and Humans in the Loop

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Autonomy in large-scale, complex, open systems, taking into account that such systems are not domain/knowledge-“contained”
- Models of autonomous CPS systems and humans
- Socio-technical aspects of IoT-driven CPS
  - Humans in the loop and collaborative decision making
  - Analysis of user behavior and detection of needs and anomalies
  - Novel approaches for analysis, visualization, and decision support

Why EU-US Collaboration?

Modern large-scale CPS are socio-technical in nature, and taking their interaction with humans into account has been identified as a challenge in both the EU and the US, as has the increasing trend towards autonomy in many areas and the need to predict how autonomous systems will behave when interacting with human actors. The significant overlap of the needs and interests in the EU and the US in this area is a good basis for R&I collaboration.

Relevance to Application Sectors

Our analysis has shown that the need to consider the interactions of humans with technical systems is seen in several application sectors, and that there is an interest in the area of increased autonomy that cuts across all domains, in particular smart cities and smart transport.

Proposals for Collaboration Actions
4.5. Situational Awareness, Diagnostics, and Prognostics

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Large-scale real-time data analytics and data management
- Data-based operation
- Machine learning, learning methodologies, adaptive behavior
- Predictive condition monitoring and maintenance
- Self-diagnosis tools

Why EU-US Collaboration?

With the increasing pervasiveness of affordable sensing devices in future IoT-enabled CPS and, the intelligent use of data will become crucial to deal with the increasing complexity and to ensure efficient and optimal operation. This fact has been recognized in both the EU and the US, and the large overlap of interests and needs in this area will facilitate the successful establishment of R&I collaborations.

Relevance to Application Sectors

The increasing use of data and of real-time data analytics for the optimization and monitoring of technical systems is seen as a major opportunity, or even a prerequisite, in all of the application sectors that we have identified. Thus, novel theories, tools, and methodologies in this area will benefit all of these application sectors.

Proposals for Collaboration Actions

To be added after feedback collection.
5. References


