cps summit

Action Plan

Towards a Cross-Cutting Science of Cyber-Physical Systems for Mastering all-Important Engineering Challenges

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Editors

Werner Damm
OFFIS - Institut für Informatik
Escherweg 2
26121 Oldenburg, Germany

Janos Sztipanovits
Vanderbilt - School of Engineering
1025 16th Avenue South, VU Box 351829 Sta B
Nashville,TN 37212, USA

Contributors

John S. Baras
Electrical & Computer Engineering
Institute for Systems Research
2247 AV Williams Building
College Park, MD 20742-3271, USA

Klaus Beetz
Siemens AG, CT TIM EC
Otto-Hahn-Ring 6
81739 München, GERMANY

Saddek Bensalem
Verimag Centre Équation
2 Avenue de Vignate
38610 Gières, FRANCE

Manfred Broy
Zentrum Digitalisierung.Bayern
Lichtenbergstr. 8
85748 Garching, GERMANY

Radu Grosu
Vienna University of Technology
Department of Computer Engineering
Treitlstrasse 3
1040 Wien, AUSTRIA

Bruce H. Krogh
Electrical and Computer Engineering
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213, USA

Insup Lee
Department of Computers and Information Science
University of Pennsylvania
3330 Walnut Street
Philadelphia, PA 19104, USA

Harald Ruess
fortiss GmbH
Guerickestrasse 25
80805 Muenchen, GERMANY

Alberto L. Sangiovanni-Vincentelli
University of California at Berkeley,
EECS Department
253 Cory Hall MC# 1770
Berkeley CA 94720-1770, USA

Joseph Sifakis
Verimag Centre Équation
2 Avenue de Vignate
38610 Gières, FRANCE

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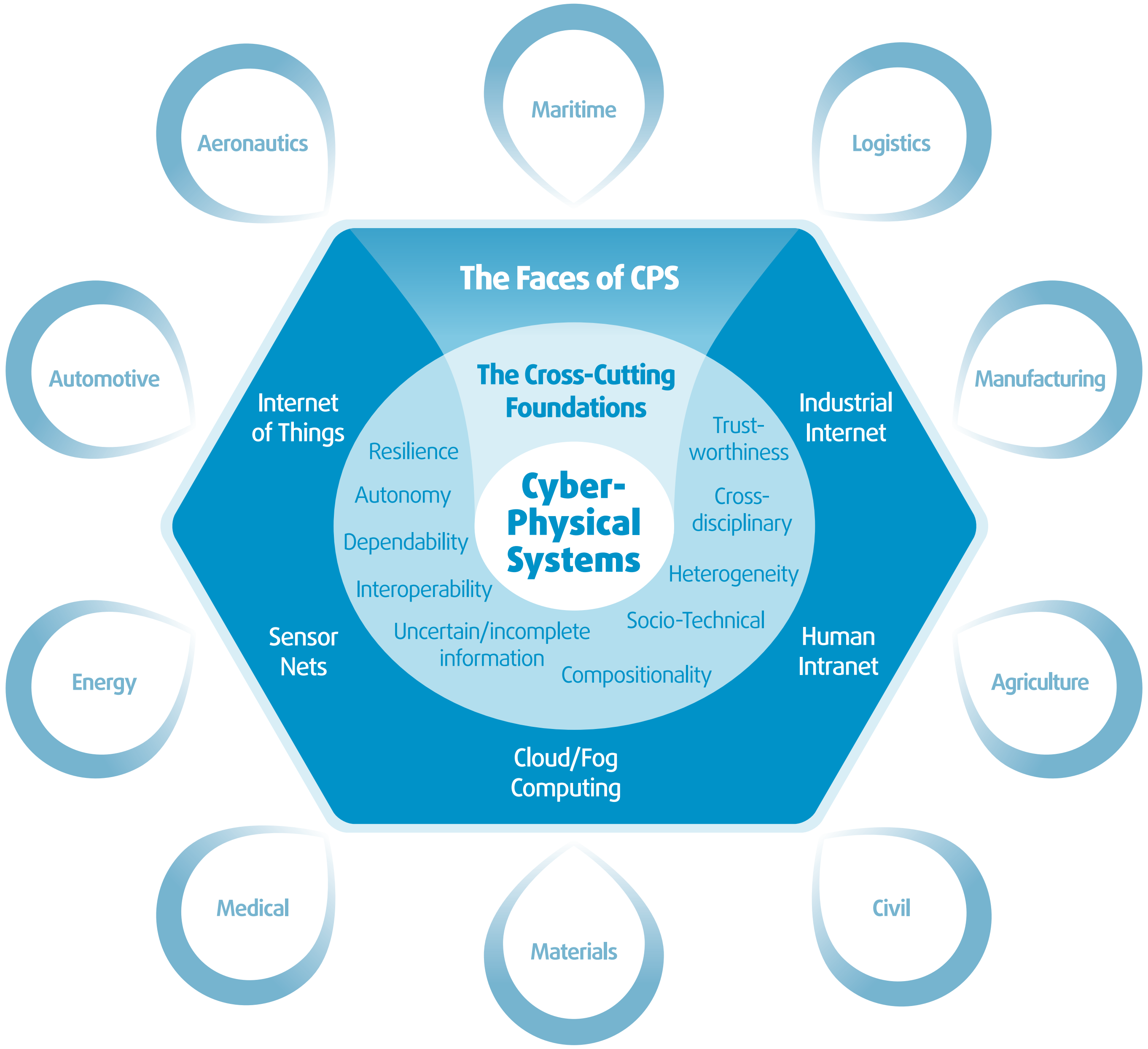
This is a call to launch a synergistic research campaign between the United States and Europe for solving cross-cutting scientific challenges of cyber-physical systems, needed to ensure safe, secure, and dependable delivery and operation of a new generation of digital technology and platforms with enormous economic and societal impact.

The CPS Landscape



Why we need to act now

The *emerging of new technology platforms* such as the *Internet of Things* (IoT), *Industrie 4.0*, the *Industrial Internet, Cloud/Fog Computing*, or the *Human Intranet* tremendously accelerate the adoption and commercialization of cyber-physical systems in domains such as highly automated vehicles, smart energy, smart manufacturing, smart cities, smart medical devices, smart logistics, and smart material. The more the intrusion of smartness in our physical world advances, the more we have to rely on their performance, their robustness, and their security. Delivery of a new generation of technology platforms that *perform well and are safe, secure, and dependable* therefore creates an ever-increasing *demand and urgency for new and expanded science and technology foundations.* What exactly seems to be missing is the foundational element, the glue between them, the force that should bring those elements together.

Cyber-physical systems (CPS) provide such a *cross-cutting foundational framework*. They are merging the physical with digital worlds by means of integrating software-intensive *embedded systems* with (potentially global) *information systems* for recording physical data using sensors and affecting physical processes using actuators, for evaluating and saving recorded data, and for actively or reactively interacting with and controlling both the physical and digital worlds. CPS are connected with one another and in global networks via digital communication facilities, use globally available data and services, and have a series of dedicated, multimodal human-machine interfaces.

CPS is a pervasive *key enabling technology,* impacting all industrial branches and almost all aspects of life (US PCAST 2010 , ARTEMIS SRA , Acatech's CPS Agenda). A recent study by McKinsey for the US administration estimates up to an additional 1.5 trillion US$ to the GDP of the United States by 2025, and the on-going digitization of industry is estimated to potentially add 1 Trillion EUR to the GDP in Europe. The scale of impact of CPS exceeds the already substantial changes initiated by the business information systems and embedded systems alone, and the *impact of CPS is cutting across almost every societal and industrial domain.* Indeed, many industrial technology leaders are already in the midst of a global race of repositioning and reinventing themselves by developing and implementing these novel CPS-based business models.

However, we do *not yet have a mature science and technology* for the rigorous engineering of CPS. The area still lacks the maturity of established engineering and scientific disciplines; it also lacks scalable principles of combining large heterogeneous ensembles of physical systems, humans, and cyber-systems; and it lacks suitable methodologies and systems engineering processes applied to cross-domain CPS, and consequently, a lack of suitable open standards and supporting tools (e.g. for smart cities).

The *lack of foundations and methodologies* creates barriers that may *prevent market success* of new CPS applications and hinders the implementation of cross-sectorial, horizontal value chains. Since current CPS are engineered and maintained at very high cost and sometimes with unknown risks we are about to make our economy and society completely dependent on a technology, whose risks have been insufficiently reflected upon.

The *United States* and the *European Union* face a number of *common challenges* to push forward the limits of the science and technology, including:

- *Technical challenges for designing and operating trustworthy CPS to which we do not have adequate solutions, at the state-of-the-art;*
- *The lack of accepted open and interoperable technology and platforms for CPS (such as in smart cities);*
- *Differences in technical standards across domains, including for safety and security, make it more difficult and costly to produce end-to-end quality and assurance;*
- *It is uncommon for engineers to be trained with the right mix of skills to address the technical issues in CPS;*
- *Fragmented eco-systems of CPS platforms prevent and limit the implementation of many new business ideas.*

There are a number of on-going CPS initiatives, programs, and large-scale projects both in the United States and in Europe for addressing these key CPS challenges. In the United States, the CPS research program of the NSF has funded over 350 research projects and established a new systems science for CPS, including the Secure and Trustworthy Cyberspace program, the creation of a thriving CPS Virtual Organization (CPS-VO), the National Robotics Initiative, and expedition projects such as CMACS, exCA-PE, CycerCardia, and the Science of Integration of CPS. There is also a broad range of large research projects at DARPA including AVM, SIMPLEX, HACMS, the Connected Vehicle and Intelligent Transportation Systems program by the Department of Transportation, the CPS test bed program and the CPS Public Working Group at NIST, with several subgroups - including CPS Reference Architecture and CPS Security - a range of mission-specific programs at OSD, the DoE and DHS specifically targeting the areas of CPS security and resiliency, and the smart city initiative by NIST and by the NSF. In addition, there are a large number of industry-driven initiatives, including the Industrial Internet Consortia, and the industry-academia CPS research partnership program iCyPhy.

In Europe, the EU-level initiative for the Digitalisation of European Industry is complemented by a number of multi-regional and national initiatives and programs including Embedded France, Plattform Industrie 4.0 in Germany, or Produktion der Zukunft in Austria. The ECSEL/ARTEMIS joint undertaking and its lighthouse initiatives play a key role in creating CPS reference technology platforms and open interoperability standards through large-scale projects such as CRYSTAL, CESAR, EMC2, D3COS, and ENABLES. Foundational research on CPS design is being supported through the EU-level Horizon 2020 framework program and by individual programs of the member states. EU-level innovation activities such as Smart Anything Everywhere facilitate the creation of ecosystems for dedicated CPS platforms, and a number CPS-related public-private partnerships (PPPs) including Big Data, Robotics, and Cloud Computing are preparing the supply of digital technologies across value chains.

Scientific-technological challenges that are being worked-on in both the EU and the US include the *cross-disciplinary* and *socio-technical character* of CPS; the lack of a common, integrated *systems theory* including *cross-domain modeling* and *integration of large-scale, heterogeneous CPS;* the *interoperability* between platforms, infrastructures, frameworks, methods, and tools; predicting the complex, evolving behavior of *autonomous* systems to exclude emergence of unintended behavior; technology platforms concerning protection of data *privacy* in CPS applications; *dependability* technology for CPS to avoid propagation of faults or cyber-attacks; new design paradigms such as *data-driven development* for resource-optimized operation of CPS; provable *robust* abstraction between real-world artefacts and its digital models; and a systematic approach to collect, aggregate, and apply *incomplete* and *uncertain information* to ensure provision of services with sufficient level of confidence, specifically in the interaction with humans.

The biggest part of the CPS avenue is still in front of us. Despite tremendous progress in the last ten years on developing an integrated CPS science, there are still mountains of questions and challenges to be solved, some of them fundamental and rooting in mathematical science and logic. And we still have to get the design principles and fundamentals right for *mastering the engineering of trustworthy CPS. Indeed, the magnitude of the CPS* foundational challenge is so great that a collaboration would prove to be *beneficial for industry, academia, and governments*, including:

- *A synergistic research campaign boost developments by facilitating collaboration of the best research teams across the Atlantic on some of the hardest CPS research challenges.*
- *Creation of industrial CPS platforms, standards, and applications on the basis of cross-cutting design principles enables the sound end-to-end implementation of cross-domain CPS-based value chains.*
- *Together we are able to set global and cross-domain open standards for the interoperability and trustworthiness of CPS-related platforms and applications.*
- *Lifting the synergetic potential of sharing research infrastructure and large-scale test beds for experimenting with and validating, possibly, cross-domain CPS applications.*
- *Preparation of the future workforce/engineers by facilitating and promoting an integrated education program on CPS engineering.*

The CPS Summit therefore recommends to *pool resources* between the US and Europe on *pre-competitive CPS research and development,* including (1) joint research for establishing a new systems science for predicable and trustworthy CPS, (2) driving open standards and platforms for capitalizing on synergies in building CPS, (3) creating and coordinating the operation of joint platforms and living labs for testing and experimenting with CPS, and (4) the exchange of best practice for CPS training and education. This transatlantic research program shall promote *synergistic* and *added-value collaboration based on results obtained in research projects from both sides of the Atlantic,* as outlined above.

Together we *boost the rate of achieving resilient, reliable, predictable CPS maximizing cross-sectorial re-use* through synergies obtained by closed loop cooperation between US and EU team in key strategic areas sharing substantial body of experience and R&D in both the US and EU. In this way, the proposed collaboration is significantly accelerating R&D for engineering trustworthy CPS, and it promotes and facilitates the application of rigorous CPS design principles in a multitude of industrial applications through open standards, interoperable platforms, and needed skill sets.

The impact of this joint CPS initiative is expected to be global by reaching out beyond the United States and Europe; thereby *facilitating and promoting a globalized CPS eco-system and marketplace.*
In summary: joining the outstanding systems engineering and IT engineering expertise in the United States and in Europe collaborative research activities will *boost progress* in laying the foundations for engineering trustworthy CPS and for synthesizing and instantiating common cross-domain guidelines and principles for mastering the complexity of large-scale, heterogeneous CPS. The costs of the proposed *one-time investment* for creating a single reference architecture for systems of CPS (around 300 M€ or US$) needs to be contrasted with the reinvention of concepts for establishing reference architectures in each domain (200 M€ per domain), the costs for cross-domain interfacing lacking shared interoperability standards (100 M€ per link), and the costs for global failures exploiting weaknesses in ad hoc integration (several Billions or Trillions €/US$). An attack exploiting such a weakness could amount to a *perfect digital storm* causing, for example, the collapse of traffic, black-out of the energy grid, and a digital blackout of our medical infrastructure - and *we won't be able to reboot a hospital, an energy system or a smart city, and we won't be able to reset a digitized world.*

The *alignment* of the proposed EU-US collaboration campaign *with on-going industry-driven initiatives* and *platforms.*

- *Ensures a rapidly accelerated timeline and huge savings in the creation and operation of new technology platforms;*
- *Fosters end-to-end resilience against cyber attacks and failures;*
- *Prepares the future workforce by defining and facilitating education on CPS engineering.*
- *Enables the sound implementation of novel CPS-based value chains on the basis of open de facto standards;*
- *Promotes competitive ecosystems and cross-domain market-places based on open and interoperable CPS platforms.*

Implementation of the CPS Summit action plan therefore directly contributes to the *sustainable success* of a large number of *industry-driven initiatives and platforms* in the US and Europe, including the IIC (goal: increase of 3% of GDP), ECSEL (goal: create 250.000 new jobs), and IoT (projected global market volume in the trillions €/US$).

Why we need to join forces

One of the grand challenges for cyber-physical systems (CPS) is the construction of *societal-scale systems* that are *safe and secure.* Examples for these systems are in the application categories of *Smart Cities*, *Smart and Integrated Transport*, *Smart Energy Systems*, etc., and are increasingly enabled by platforms such as the *Industrial Internet*, the *Internet of Things (IoT)*, *Industrie 4.0* or *Fog Computing.*

Societal-scale systems are motivated by societal needs, must conform to social norms and respond to expectations. In addition, many of these systems integrate humans as part of their operation as decision makers continuously interacting with physical and cyber components. *If* these *systems evolve independently* in the US and EU, they will "hard-wire" the social context in which they are created. That will make *interoperation hard or impossible, decrease reusability of results*, and *narrow the market for products and services.*

Progress in the design of societal scale-systems should be initiated and informed by a *social context* and refined into a progressively deeper CPS *foundation agenda. A joint research activity focusing on systems that are "parameterized" by social context* (such as operation policies, incentive mechanisms and others) *would offer an important contribution to CPS.* The agenda should extend to fundamental principles (abstractions, architectures, composition, dynamics) and test beds for major application domains. *This research would be ineffective or unfeasible without a joint action.*

For example:

- *Acceptance of self-driving cars in different social environments will depend on their solution to ethical/legal constraints as they relate to safety, security and privacy. These constraints can be and should be mapped into technical agendas related to certifiability and verifiability of safety, security and privacy requirements.*
- *Architectures and services in connected vehicles should be driven by privacy and security constraints that are informed by very different cultural expectations.*
- *Dynamic properties of traffic flows (stability, flow-rate, etc.) are increasingly dependent on connected vehicle services (e.g. real-time routing) and the way individual drivers utilize those services in their decision making. Optimization of system operation by including methods for influencing human decision making (such as incentive mechanisms) is becoming integral part of the control hierarchy.*

Similar arguments can be found in all other societal-scale system categories.

Therefore, besides the many other reasons, it is a real *need to initiate US-EU collaboration in this system category where influence of social, cultural expectations has strong impact on technical agendas.* Understanding this impact and architecting technical solutions such that differences in social expectations can be accommodated easily by products is an important goal.

"The US and Europe face common challenges to push forward the limits of science and technology for engineering trustworthy cyber-physical systems."

Launch of an ambitious transatlantic CPS research campaign

Cyber-Physical Systems (CPS) integrate systems and products perceiving, analyzing, and acting upon their environment in a highly automated way (smart systems), with cloud-based services, in order to address societal and business needs. Humans are essential elements of CPS and the modeling of humans and their interactions with other components of CPS provide new critical challenges. CPS constitute a core technology in the ongoing process of digitization of our society, creating a global market of several trillion US $. The sheer scale of CPS-business opportunities has created a momentum that is completely changing the market dynamics, through penetration of traditionally separated market segments. The holistic approaches made possible through CPS enable smart-energy management, smart transportation, smart production and manufacturing, smart cities, smart health-care management, smart logistics ... and thus promise to solve key societal challenges.

The CPS Summit gathers US and EU scientists with the goal of assessing the CPS market dynamics and of recommending harmonized policies for the development of reliable, safe, secure, and sustainable solutions. Although we are today observing the uptake of CPS technology in many application domains, CPS conception and design, production, operation and life-cycle management follow ad-hoc, domain-specific approaches. The area lacks the maturity of established engineering and scientific disciplines making it possible to predict properties of the constructed systems from their blueprints. It also lacks scalable principles of combining large heterogeneous ensembles of physical systems, humans, and cyber-systems while assuring that their emergent properties and behaviors meet the overall system objectives within quantifiable tolerances. In short: we are about to make our society completely dependent on a technology, whose risks have been insufficiently reflected upon.
To address this concern, we propose the following lines of cross US-EU harmonized actions:

1. *Making CPS predictable and dependable across their whole life-cycle: joint research*
2. *Capitalizing on synergies in building CPS: driving open, horizontal standards*
3. *Testing and experimentation with CPS: open platforms and living labs*
4. *Training and education for CPS: exchanging best practices for training and education.*

Action Line 1 addresses the fact, that, while CPS research is conducted within the established funding schemes in the US and the EU, there is no instrument to bring together US and EU scientists to assess jointly the fundamental design, production, operation and life-cycle management principles, methods and associated risk assessments in CPS. In particular, bringing together researchers in this field will significantly contribute to making CPS predictable, safe, resilient and secure. CPS will need to meet stakeholder aspirations over entire value chains (example: information security and traceability over entire logistic chains). Models have to be developed for methods, which enable cross-value-chain system and outcome qualities. Through a joint understanding of the basic principles and methodologies required to build robustness and reliability into such systems we will be able to provide concrete guidelines and also test criteria for proposed open standards as addressed below. The action line calls for funding of such joint R&D projects over a five-year period, giving particular attention to foundational research that supports:

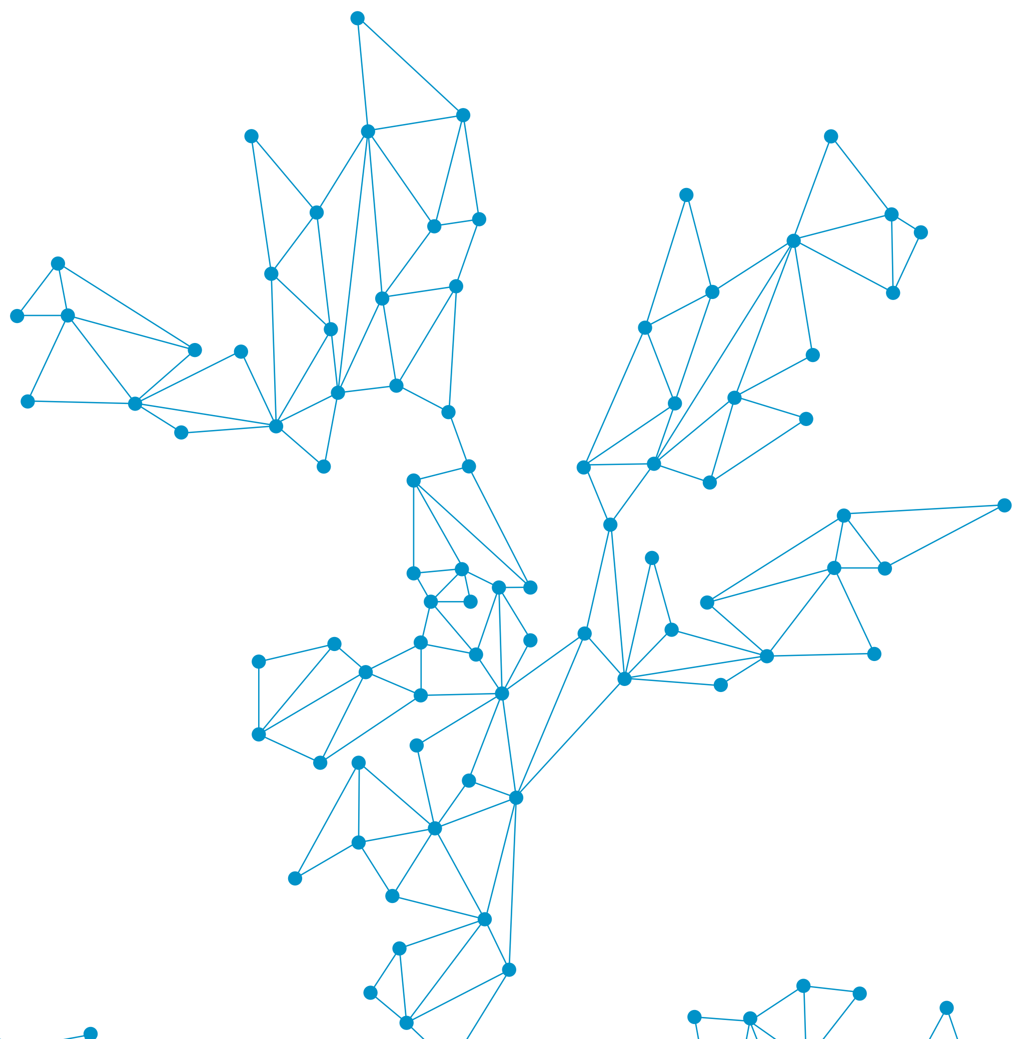
- *Construction of composable and predictable (within quantifiable tolerances) CPS*
- *Assessment of the resilience of CPS against failures and cyber attacks*
- *Consideration of humans as elements of CPS in an integrated approach*
- *Large scale orchestration of CPS, including a taxonomy of architectures, and Design, production, operation, life-cycle management and evolution of CPS*

This research can benefit from substantial previous research projects both in the US (NSF-CPS- Expeditions project CMACS, NSF-CPS-Frontiers project CyberCardia, Science of Integration of CPS.....) and EU (ARTEMIS project CESAR, MBAT, CRYSTAL, EMC2, ECSEL project SEMI40, ENABLES, ...).
In bringing together US and EU scientists driving these initiatives, we expect significant synergies and robustness to the answers, thus providing blueprints for guidelines in leveraging the potentials of CPS in a safe and predictable way.

Action line 2 addresses the need to break domain barriers in unrolling the potentials of CPS in areas where cross-domain standards are a necessary basis for this. The term "standard" is intended to subsume any activities leading to a harmonized industrial position, paving the way for a potential future formal standard. As an example, NIST purposely pushed Smart Cities as a topic because of its cross-cutting nature, involving smart energy, smart health, smart mobility, and smart crisis management. On September 14th, 2015, President Obama launched a new initiative on smart cities , whereby $160 Million were committed to the development of this technology. Within this action line, we propose to capitalize on the findings of action line 1 to promote the creation of open, cross-domain standards for building predictable CPS, building on cross-domain initiatives such as those driven by NIST in US or by Artemis or the AIONI platform in Europe. To support the stimulation of cross US-EU evolution of such open standards we propose to fund this action line over a period of five years.

Action Line 3 addresses the fact, that innovation cycles for CPS solutions can be dramatically boosted by providing open platforms for CPS components to be used in precompetitive R&D&I adhering to industrially accepted open standards. It also addresses the fact that we can gain further trust in building predictable CPS through living labs providing facilities for testing and experimenting with CPS, in particular for critical applications such as health, transportation, and mobility, in sufficiently realistic scenarios so that further confidence in their predictability, safety and security can be gained. The living labs will be the one-stop-shop for the CPS development e.g. for Startups/SMEs to find the technology, the development processes, and test beds and they could also play a role in disseminating the knowledge of the CPS application creation processes by organizing workshops, seminars, master classes. This action line calls both for financial support for creating, and above all maintaining, such platforms, and for linking together (nationally funded) living labs so that repeatability of tests and validation of test-suites for establishing predictable, safe, secure, and reliable CPS innovations is possible. We suggest to install such shared living labs in the area of smart health, smart energy, smart cities, and smart transportation, and to foster the development of applications in these living labs capitalizing on the guidelines provided by action line 1 and the open standards provided by action line 2. Already today, there is significant investment in test beds worldwide, such as the ones coordinated through the Industrial Internet Consortia (IIC) or the Industrie 4.0 initiative, the NSF CPS Virtual Organization, smart city and urban smart grid test beds, the DriveMe fleet of self-driving cars in Sweden, and the medical device interoperability labs in Massachusetts.

Action Line 4 addresses the challenge, that CPS design is inherently interdisciplinary, requiring competences from computer science, electrical engineering, systems engineering, human-machine collaboration, networked collaborative systems, economics and business models, on top of deeply understanding the needs of the targeted application classes. The action line will bring together leading universities in the US and the EU that are involved in teaching CPS design to share best practices and recommend curricula. An important aspect of these activities will be careful development of hands-on courses and laboratories for teaching and learning the new foundations.



> “Together we boost the rate of achieving resilient, reliable, and predictable CPS by means of closed-loop collaboration between US and EU research teams in key strategic areas.“

Action Line 1: Making CPS predictable and dependable across their whole life-cycle: joint research

Large scale Cyber-Physical Systems are built from millions or even billions of unreliable components often not originally designed for the purpose of jointly serving overarching objectives, use unreliable communication media, are vulnerable to failures and attacks, integrate humans both as decision makers or users. Yet this assembly is to act like a multiform entity in providing live-long dependable services, with typically strong quality of services guarantees, exhibiting, in spite of the inherent non-determinism of its constituent systems, only behaviors meeting overarching safety and dependability requirements within precise margins. How can we guarantee that the often highly automated decision process of a CPS is based on sufficiently precise real-time images of the world in which it acts? How can we orchestrate the interactions of its thousands or millions or billions of constituent systems with its thousands of human actor so that their mutual plans and strategies blend synergistically to achieve the overarching objectives of the ensemble and avoid the chaos resulting from undesired, unplanned interactions, leading to failures of large scale infrastructures, thus causing a complete state to be out of power, or in traffic chaos.

This action line will build on background projects carried out separately in the US and EU to synthesize common EU-US crossdomain guidelines in mastering the complexity of large scale heterogeneous CPS. We propose to focus on five complementary topic areas, and launch for each cross US-EU projects integrating teams from the 10 leading US sites with teams from the 10 European leading sites in each topic area.

A. Construction of composable and predictable (within quantifiable tolerances) CPS

B. Assessment of the resilience of CPS against failures and cyber attacks,

C. Consideration of humans as elements of CPS in an integrated approach,

D. Large scale orchestration of CPS, including a taxonomy of architectures, and

E. Design, production, operation, life-cycle management and evolution of CPS.

Topic Area A will study and develop a set of mathematical models and operators rich enough to formally describe all emergent behaviors relevant for the design, orchestration, and continuous evolution of CPS. Such models will be able to express a number of aspects, ranging from the health state and capabilities of participating technical systems, to states and capabilities of humans, to beliefs about the (both humans and technical) evolutions of such states, to expressing uncertainties about beliefs of world models (created by humans and technical systems, or based on information taken from the cloud), to orchestration principles. The refinement, abstraction, composition and decomposition principles developed will allow predicting the emerging behavior of such systems on different level of abstractions. They span both the vertical dimension (systems build on “lower-level” components, be they processors, actuators, engines, or realized in software, complete physical systems, or abstracted into aggregates representing flows of physical systems) and the horizontal dimension (systems are dynamically entering areas of physical proximity demanding their orchestration). Overall, topic area A thus defines the mathematical essence for assembling large scale predictable and dependable CPS from constituent systems. The challenges in building these models and operators cannot be overestimated: heterogeneity makes it hard to compose subsystems and to build models of the ensemble given the models of its constituent parts as the mathematics of composition is not well defined, the sheer number of components makes it imperative to organize the design and operation of the ensemble in a hierarchical fashion where the levels of abstraction play a fundamental role and their choice is part of the design process, the uncertainty of the surrounding environment makes it mandatory to develop statistical models that yield non-deterministic models and behaviors. Albeit some research has been carried out in this domain in Europe and the US, much works remain to be done both in mathematical terms and to develop software and hardware frameworks. We believe that the combination of skills and knowledge base of Europe and US are necessary to shift gear in such a difficult domain.

This "genetic code of CPS" will be made available in *The Handbook of CPS Design: Fundamental Principles* – reflecting the joint US-EU consolidated expertise.

Topic Area B will study and develop online and offline compositional methods and tools for assessing and ensuring resilience of CPS against failures and cyber attacks, and provide architectural guidelines which must be observed to achieve the indispensable capability of carrying out such analysis compositionally. While security has been the object of intense research and scrutiny for cyber systems, not much has been done in the area of security for CPS. Here we must cope with limited resources and with hard performance constraints that make implementing security measures without compromising the operation of the system difficult. Modeling attacks and other hardware and software failures is an issue since by definition cyber attacks are very hard to predict. Yet given the present social situation, guaranteeing some degree of security is a must to develop the market. This task will involve experts in security including law enforcement agencies to make sure that the models are representative of the attacks that have been observed over the years. The maturity and scalability of these methods will be demonstrated using platforms and living labs as provided by Action Line 3, in close cooperation with industrial partners supporting such living labs. Teams participating in this topic area must own or have significant access to such living labs. The resulting processes and methods for demonstrating resilience will be made available in *The Handbook of CPS Design: Demonstrating Resilience*. Contributions are also expected to action line 2, e.g. in proposing standardized processes for certification taking into account criticality of the system.

Cyber-physical systems will support humans in daily routine tasks, have humans in the loop for continuous control of evolution of subsystems, and ask humans for high-level decision-making. Topic Area C addresses the overarching challenge of achieving an intuitive mutual understanding of state and intent of both humans and technical systems so as to optimally blend their competences in jointly acting towards overarching objectives, while respecting privacy. Topic Area C will blend US and EU experts in cognitive modeling, human-machine communication and interface design, with experts from holistic system modeling and sociology to provide empirically validated guidelines. The challenge here is to model human behavior interactions with the system and to provide the appropriate uncertainty characteristics related to the often unpredictable behavior of humans under unforeseen circumstances. The results of this research will be made available in *The Handbook of CPS Design: Human Factors*.

Cyber-physical systems render the physical world into smart coordinated objects by bringing even remote and broadly distributed physical processes into the sphere of human and computer control. As individual spheres of control may overlap arbitrarily, there is a pronounced need for orchestrating these processes such that they jointly serve not only a single human, but can best-possibly multi-task in serving arbitrarily large groups at the same time despite uncorrelated requests and uncoordinated missions. *Topic Area D* extracts such novel forms of coordination and distributed control, addressing dynamically changing overlap and competition between control functions. It will develop principles for designing distributed hierarchical evolvable architectures capable of adapting to changing baselines (regulations, technical capabilities, objectives) while scaling from thousands to millions of component systems depending on application domain, meeting orchestration requirements on availability, safety, security, evolvability, timeliness, performance, recourse usage, etc. This activity is thus of key relevance for action line 3, in providing key principles to be observed in platform design. The maturity of such architectural principles and principles of coordination and control will be evaluated in living labs with supporting industrial partners, and documented in *The Handbook of CPS Design: Architectural Principles, Coordination, and Control*.

Given the expected lifetime of large-scale CPS, such systems must be designed to cope with changing underlying technologies, changing regulatory settings, changing system requires, and yet provide the same high level of dependability and quality of service throughout their evolution. *Topic Area E* focuses on the methods and processes for achieving such adaptability while guaranteeing the overall integrity and coherency of the system. It will determine what methods for demonstrating compliance for technology upgrades are mandatory so as to maintain system integrity as well what additional capabilities and guarantees the upgrades can offer. It will develop processes and methods for assuring that newly deployed services addressing changing requirements do not violate integrity and coherency requirements of the running system. It will define procedures for maintaining certification evidence of the resilience of the system against failures and cyber attacks under such evolutions. To this end Topic Area E will strongly build on findings of the Topic Areas A to D. Topic Area E is expected to have strong contributions to Action Line 2. Methods and processes proposed will be evaluated for their maturity in realistic settings in cooperation with industrial partners using the living labs provided by action line 3. The principles for assuring such life-long evolvability will be documented in *The Handbook of CPS Design: Evolvability*.

“Driving open, horizontal standards for creating new kinds of cross-industry structures for lateral value creation based on de facto standards for open CPS platforms.“

Action Line 2: Capitalizing on synergies in building CPS: Driving open, horizontal standards

The technological developments underlying CPS evolution require the development of standards in the individual application domains, as well as basic infrastructure investments that cannot be borne by individual companies alone.

The creation of such quasi standards, less in the traditional mold of classic industry norms and standards is an essential part of the proposed activities under this Action Line. For that *Interoperability and Integratability of CPS* is critical. Thus, by building on background projects and on-going efforts carried out separately in US and EU, this action line will develop a framework to facilitate interoperability and integratability of CPS via *Open Standards and Platforms.* This framework will have several critical components, and will allow freedom for various instantiations of the components, in order to accelerate development and acceptance by industry world-wide. As platforms are unbundling conventional vertical value chains, they are also creating new kinds of horizontal cross-industry structures for lateral value creation. In doing so, platforms are also radically reshaping the skill sets required of employees in different industries, as job descriptions are gravitating towards higher and higher degrees of cross-industry overlap.

An additional goal of developing and publicizing such a framework is to solicit feedback on the proposed framework, from the broader CPS technical community towards improving and strengthening this Framework and as well analyzing the implication on cross-industry structures and skills required in the future. This action line will build on background projects carried out separately in US and EU to synthesize a Framework that will catalyze the development and use of standards and interoperable methods and tools for the design, manufacturing and operation of CPS, often including human agents.

We propose to focus on four complementary topic areas, and launch for each cross US-EU projects integrating teams from leading US sites with teams from leading EU sites.

A. CPS Architectures

B. CPS Integrated Modeling Hubs

C. Linking CPS Integrated Modeling Hubs with Tradeoff Analaysis and Design Space Exploration

D. CPS Requirements Representation and Management

We believe that the combination of knowledge base and expertise from US and Europe are essential for progress. This activity is of key relevance for both Action Line 1 and Action Line 3.

Topic Area A will investigate *architectures for CPS* and develop a taxonomy of such CPS architectures. This is a critical challenge towards a framework for standards and interoperability. Generically the architecture of a system consists of: (1) A description of the arrangement of entities that constitute the system; (2) A description of the relationships between these entities. The architecture of a CPS must describe the interfaces between the cyber and the physical components at different scales. Furthermore as many CPS are networked systems describing and classifying the relevant network architectures adds to the challenge. CPS create core technological challenges for traditional system architectures, especially because of their high degree of connectivity. This is because CPS are not constructed for one specific purpose or function, but rather are open for many different services and processes, and must therefore be adaptable. Every system has at least one architecture, whether it is stated explicitly or not. In fact, a typical system has more than one architecture depending on the intended purpose for describing it. The architecture of a system is essential to: Understand, model and analyze complex systems; Design and validate complex systems; Manufacture complex systems; Evaluate the cost and other financial concerns about a system and its potential markets; Design standards and protocols to guide the evolution and maintenance of long-lived systems; Manage complex systems. These are especially true for CPS, where the physical and cyber (e.g., computation, communication, control) components have their own architecture(s).

Results on methods and tools for describing CPS Architectures, taxonomy and representative examples will be made available in *the Handbook of CPS: Taxonomy of CPS Architectures and Frameworks for Their Description* – reflecting the joint US-EU consolidated expertise and knowledge base.

Topic Area B will investigate and develop and demonstrate a Framework for developing cross-domain integrated modeling hubs for CPS. Model-based Systems Engineering (MBSE) has emerged as a promising methodology for the systematic design, performance evaluation and validation and verification of complex engineering systems. Several key components have emerged within this Framework but much work remains to be done. One key building block is the use of a modeling backplane and languages that describe components of structure and behavior in a formal semantic way with easy development of annotations for such block diagrams. One such instantiation is provided by SysML, but there are other possibilities. Another key component of the emerging Framework is a metamodeling environment with its associated languages and semantics based on sophisticated versions of annotated block diagrams (e.g. bond graphs). At the metamodeling layer model transformations take place.

There are several possible instantiations of this component, but none is satisfactory for the challenges imposed by CPS modeling. CPS puts additional challenges in this integration of models and views due to the fundamental heterogeneity of CPS components and the hybrid (logic-analog) nature of CPS. There is need for new mathematical foundations for this model integration. One of the major challenges in modeling CPS and for performing MBSE of CPS, is the heterogeneity of physics involved in CPS. Thus there is need for a framework and methods and tools to integrate these diverse logics.
A key challenge in multi-physics modeling and simulation is the handling of geometry, constraints across geometry, geometry across scales. Regarding CPS the interface of the components of multi physics models with the cyber models is also challenging. Since most CPS are actually networked CPS additional challenges are generated from the networks involved, their semantics and models.

Results on methods and tools for describing CPS Model Integration and representative examples will be made available in the *Handbook of CPS: CPS Model Integration* – reflecting the joint US-EU consolidated expertise and knowledge base.

Topic Area C will investigate and develop and demonstrate a framework for linking the integrated CPS modeling hub of Area B with powerful and diverse tradeoff analysis methods and tools for design space exploration for CPS. Addressing the design, manufacturing and operation of CPS requires such a linkage; modeling and simulation alone will not suffice. Progress in this area requires developing the foundations for such an integration, together with associated algorithms and frameworks. Key concepts here are: the integration of multi-criteria, multi constraint optimization with constrained based reasoning. Although progress to date in MBSE facilitates the integration of system component models from different domains, we still need an integrated environment to optimize system architecture, manage the analysis and optimization of diverse measures of effectiveness (MoE), manage the various acceptable designs and most than anything else perform tradeoff analysis. Tradeoff is an essential part of system design, as it implements design space exploration. The framework should enable performing trade-off analysis for both the behavioral and the structural model of a system and its components, as well as of the allocation of behavioral components to structural components. Important technical challenges in such a framework include: run time interaction between the model and the user, ability to handle metrics and constraints with both numerical and logical variables. Further- more effective design space exploration and tradeoff analysis require the ability to compute sensitivities to proposed changes and evaluate "what if" types of questions. In the SysML-based instantiation the linkage is implemented through the Requirements Diagram (RD) and the Parametric Diagram.

Results on methods and tools for describing the framework for linking tradeoff analysis and design exploration to CPS modeling hubs and representative examples will be made available in the *Handbook of CPS: CPS Tradeoff Analysis and Design Space Exploration* – reflecting the joint US-EU consolidated expertise and knowledge base.

Topic Area D will investigate and develop and demonstrate a framework for translating textual requirements to mathematical representations as constraints, rules and metrics involving both logical and numerical variables and the automatic (at least to 75%) allocation of the resulting specifications to components of the CPS and of processes, in a way that allows traceability. In other words we will include in the proposed framework formal ways to represent and manage requirements. This means specifically formal methods to automatically annotate the structure and behavior components of the CPS by the mathematical representations of the specifications via constraints and metrics.
This is currently done manually and as such it represents a scalability problem. As the complexity of the CPS increases, our inability to rigorously model the interactions between the physical and the cyber sides creates serious vulnerabilities. Systems become unsafe, with disastrous inexplicable failures that could not have been predicted. This is the most difficult challenge in the Action Line 2 program as very few results and tools exist in this direction. The proposed framework for checking and validating specifications, after they have been translated to their mathematical representations as constraintsand metrics with logical and numerical variables, will involve integration of multi-criteria optimization, constrained based reasoning, model checking and automatic theorem proving.
Contract-based design appears to be a promising methodology to be included, coupled with formal model-checking tools and methods like UPPAAL, efficient computation and approximation of reachable and invariant sets of set-valued hybrid systems and automatic theorem proving tools and methods like Isabelle.

Results on methods and tools for representing and managing requirements included in the Framework and representative examples will be made available in the *Handbook of CPS: CPS Requirements Management* – reflecting the joint US-EU consolidated expertise and knowledge base.

"Creating and operating open research test beds organized in open platforms and living labs with coordination across the US and EU research teams and federating a range of nationally funded test beds enables larger-scale experimentation and validation in critical areas such as connected mobility, smart energy, smart cities, medical CPS, and food/water management systems."

Action Line 3: Testing and experimentation with CPS: Open platforms and living labs

CPS are engineered by composing tightly integrating physical and computational components. Delivered functionalities emerge from the networked interaction of physical and computational processes. Their tight integration enables new capabilities, but the resulting heterogeneity inevitably leads to enormous complexity increase in most engineered systems. To deliver a new generation of systems that perform well, safe, secure and reliable, we need new suitable scientific foundations and new standardized technology and execution platforms. The Industrial Internet (II), the Internet of Things (IoT) are examples for emerging new technology platforms that tremendously accelerate progress and create an ever increasing demand for new and expanded science and technology foundations.

Progress in CPS technologies cannot be achieved without extensively experimenting with this new generation of engineered systems in a wide range of application domains. This is a direct consequence of the fact, that current scientific foundations, design tools, and make processes are insufficient to predict salient properties of upcoming real-life systems. Rapidly emerging application domains such as connected vehicles, transactive smart energy, smart cities, or smart medical devices provide huge application pull but also represent a significant risk in case the needs for safety, security, and reliability are not answered. Since CPS are *engineered systems,* we need credible test beds that serve as *living laboratories* for CPS research and development. Given the world-wide interest in smart mobility, smart healthcare, *smart energy systems, smart home, smart cities, intelligent transportation systems, smart production and management of food and water* and *smart manufacturing* with strong requirements on dependability, these areas strong candidates for creating test beds that are built in international collaboration and widely shared by the research community.

Test bed organization: A fundamental issue is the test bed organization that directly linked to its goal and accessibility. Industrial test beds, such as those created under the Industrial Internet Consortium (IIC) are driven by a business case and help a group of companies in understanding use cases, interoperability issues and technology needs for a new product category. IIC test beds are subject to range of architectural, security and interoperability constraints and have a defined management structure. IIC test beds are not open, access is restricted to IIC members. Open research test beds such as those created by various NSF and DARPA programs are driven by some specific technology challenge, provide open access to test bed resources and frequently serve as repositories for a research community. Appearance of Software as a Service and Platform as a Service technology infrastructures are significant enablers for creating and operating open research test beds. Examples for open research test bed organization are the NSF funded CPS Virtual Organization (CPS-VO) and NanoHub, the DARPA Deter test bed, NIST's federated CPS test bed program, and the Industrie 4.0 SmartFactoryKL in Germany.

Creating and operating open research test beds organized in open platforms and living labs with coordination across the US and EU research teams and federating a range of nationally funded test beds would offer much advantages and enable the construction of larger scale living laboratories in critical areas.

Test bed types: There are three types of test beds that have significance in CPS research: (a) virtual test beds, (b) hybrid test beds and (c) living laboratories. Virtual CPS test beds are created as multi-model distributed simulators of networked physical and computational processes. They are extremely important because of low cost, easy reproduction and distribution and potential for using a wide range of open source software. Hybrid testbeds extend the virtual testbeds with integrated physical components to improve fidelity. Living laboratories include live physical systems (such as an instrumented transportation network, such as the U.S. Department of Transportation connected vehicle research pilots) that offer live data streams and capabilities to run controlled experiments on large-scale systems. In all cases, reproducibility and open interfaces are essential requirements.

Setting up and providing access to living laboratories in strategic areas such as transportation, energy, smart cities and food/water management systems are extremely important. Since these facilities are expensive their coordinated development and operation would be highly effective.

Test bed scope: Well-designed network of CPS test beds serve as widely accessible infrastructure for (1) inspiring and grounding CPS research in reality, (2) hosting and evaluating new solutions and (3) validating methods and tools. Because of the pervasiveness of CPS technologies, test beds can be horizontally or vertically scoped. Horizontal test beds cut across application domains and supply physical and software building blocks via test bed platforms, frameworks and services that can be used for constructing vertical test bed solutions. Horizontal test beds are technology layers offering alternative solutions for achieving interoperability, resilience, privacy, scalability in CPS application domains. Vertical test beds address an application category and provide a customizable environment for experimenting with use cases and capabilities.

The primary challenge of an effective CPS test bed program is the selection and coordinated development of a coherent set of horizontal and vertical test beds organized in from open platforms and living labs that provides an infrastructure for open, pre-competitive CPS research.

“It is our goal to establish an educational framework for preparing and enabling the future workforce for designing, operating, and maintaining trustworthy CPS, and to contribute in establishing a thriving, independent, and internationally recognized new CPS discipline.”

Action Line 4: Training and education for CPS: Exchanging best practices for training and education

CPS theory and applications build on a rich set of disciplines that have been traditionally taught in a variety of diverse academic programs in engineering and computer science. These roots of CPS include elements of both discrete and continuous mathematics, physical systems and dynamics, real-time systems, networking, optimization, performance analysis, systems integration, and many others. Advanced topics in CPS research include networked CPS and the interfaces to and integration of humans in the loop. It is the distinctive blend of these diverse intellectual developments that has led to the emergence of CPS as a new discipline requiring a new approach to education to develop the experts in CPS that will be needed for future innovation and leadership in this field.

New CPS courses and programs have begun to emerge in the U.S. and Europe, typically anchored in traditional programs in computer science or engineering, trying to address the challenge of training students in the broad set of skills that have traditionally each been developed in separate programs that would take students a number of years to acquire, were they to follow the traditional prerequisite streams in the relevant, disparate disciplines. Recognizing this inherently interdisciplinary nature of CPS, the short-term goals of Action Line 4 are to:

A. *The taxonomy of CPS:* identify the fundamental elements of CPS that need to be addressed in training and educating CPS engineers and scientists.

B. *Educational module database:* create a shared set of course and laboratory modules that make it possible for universities to introduce effective CPS undergraduate and graduate programs within the distinct contexts of each institution.

C. *CPS projects repository:* create a project repository enabling CPS faculty to share concepts, materials and industry contacts for projects that can be incorporated into CPS curricula.

D. *CPS education assessment:* put in place an ongoing activity for learning from the experiences in CPS education across Europe and the U.S. and to use this information to continually refine and improve the CPS taxonomy and modules.

The long-term goal of Action Line 4 is to contribute in *establishing a thriving, independent, and internationally recognized new CPS discipline.* In most American and European universities, the current curricula for computer science and computer engineering emphasize discrete mathematics topics, such as, automata theory, algorithms, logic, programming languages, and software engineering. This focus partially covers the cyber (controller) component of CPS. However, traditional CS ignores the fact that controllers do not act alone, but in conjunction with the physical part within the CPS loop. On the other hand, traditional engineering curricula (mechanical, electrical, civil, biomedical, etc.) relevant to CPS theory and applications emphasize continuous mathematics to address the issues of modeling and designing mechanical and electrical systems, the physical component of CPS, while ignoring the details of the computational (cyber) elements that actually implement the monitoring and control functions for systems.

As a consequence, CPS courses emerging from computer science and computer engineering need to provide background, tools and laboratories to provide students with the requisite “physical” material, whereas the engineering programs need to provide the essentials on the “cyber” side. To address the critical need for holistic, integrated education in CPS that cuts across the traditional disciplinary boundaries, we propose the following initiatives that will build on the work already being done in European and U.S.

universities and institutions. While the consensus on what constitutes the elements of CPS education is still emerging, these initiatives provide solid steps in the evolution of CPS as recognized independent discipline.

Topic Area A: the taxonomy of CPS. A joint Europe-U.S. CPS education initiative with experts in current CPS education along with domain experts from across the spectrum of applications will work together to create a structure for the elements of CPS education, including mathematical foundations, application domains and current research frontiers. We envision this structure to be a taxonomy or directed graph showing these elements as they relate to each other. The goal will be to create frameworks for how CPS education can be developed and integrated into the programs of universities. The proposed activities build on the recent U.S. National Research Council project to define the 21st Century CPS Education by incorporating the input and activities in CPS education in Europe. For example, computer science and computer engineering curricula would need to expand the coverage of continuous mathematics, which is currently restricted to Calculus 1-2 and some introductory courses in physics, with new courses, such as, signals and systems, control theory, and the stochastic foundations of cyber-physical systems. These courses are typically taught in electrical and mechanical engineering curricula, and allow students not only to cope with uncertainty in CPS, but also to have a complete view of a CPS.

Topic Area B: educational module database. Building on the taxonomy of CPS, we propose to create curricular modules, including laboratory modules, which can become components of CPS courses and programs across the spectrum of programs seeking to expand into CPS. Models for full CPS curricula will also be developed using these modules. Such combined curricula are offered these days within the EECS departments of American universities. They are also offered, starting already at the bachelor level, by the computer-engineering track of the faculty of informatics at the Technical University of Vienna. These courses are typically aided with laboratory-classes, where the taught concepts are applied especially on robotics (agents)-related applications. By working in conjunction with all universities providing CPS-related courses, we plan to establish a freely accessible database of course materials, home-works, and projects. A distinctive feature of this database will be the addition of instructional information for faculty who are not currently involved in CPS education, helping with the development of new courses at institutions wishing to introduce CPS into their curricula.

Topic Area C: CPS projects repository. Hands-on experience applying CPS concepts, technologies and tools in the context of real problems is essential to CPS education. Some universities in the U.S. and Europe have introduced substantial project experiences into their CPS curricula, often including industry mentors and sponsors. To leverage these existing CPS project initiatives and encourage the development of new project experiences for students, a project repository will be developed for faculty share concepts, materials and industry contacts for projects that can be incorporated into CPS curricula. Sharing projects that build on common tools will be encouraged.

Topic Area D: CPS education assessment. As CPS training and assessment is in its nascent stage, in conjunction with the above activities, a database of all education and training initiatives will be developed as a resource for accessing the materials developed in the above activities, and also as a mechanism for collecting data about educational initiatives that use these resources. The objective will be to put in place an ongoing activity for learning from the experiences in CPS education across Europe and the U.S. and to use this information to continually refine and improve the CPS taxonomy and modules.

Cyber-Physical Systems:
Boosting cross-domain value creation, products, and services

CPS Summit

Coordinated Support Action

Goal:

Facilitating and creating an enduring and sustainable collaboration campaign on CPS research and development between Europe and the US.

Scientific Coordinators:

Josepf Sifakis, Manfred Broy

Project Coordinators:

Harald Ruess, Saddek Bensalem

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See also:

http://cps-vo.org/node/19159 (group: cps-summit)