Cyber-Physical Systems

Recommendations for Cyber-Physical Systems

Accelerate cross-disciplinary joint research

The technology domains contributing to Cyber-Physical Systems research call for investment in tools, methods and cross-technology community initiatives to tackle the multi-stakeholder research barrier - especially arising for a technology bridging diverse complex knowledge domains and applied at higher levels of a system where there are many more interactions with the technology to consider - higher-order integrated research. This will accelerate progress towards the Next Computing Paradigm and CPS research as well as technology infrastructure updates by tackling the challenges of diverse knowledge domain perspectives and enabling access to the bigger picture. In particular: 1) A new R&D dimension to really boost our capability for highly complex and cross-domain integrated research activities. Just as we have different approaches for building windows and houses, there is need to establish tools and methods supporting higher order integrated research. This is especially a case in point for the highest integration levels of CPS research where most impact and value generation can be expected. Adapted or new tools and methods for convergence, with strong public engagement, should support terminologies (e.g. wiki-style trusted glossary), concept sharing (e.g. modelling), knowledge sharing (e.g. ontologies via Protégé), consistent evaluation approaches and global visualisations, including non-technical domains. 2) Existing communities should establish a centralised CPS association to unify efforts, promote knowledge exchange, and align standards; 3) Additionally, frameworks for integrating AI/ML into CPS must address safety, security, and ethics, ensuring dependable systems for sectors like healthcare and transport. These actions are vital to Europe's sovereignty and global leadership in CPS advancements.

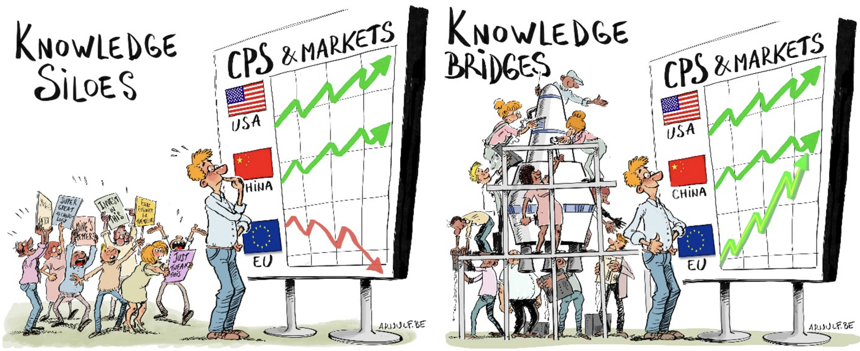
Redefining dependability for CPS adaptability and technology integrations

CPS depend on safety, security, and performance properties to govern what they can achieve and qualify technologies for use. CPS contributing communities encourage: 1) Solutions to migrate from legacy approaches that minimise interactions of these properties to instead maximised interactions for optimum system adaptability. These properties impose constraints on available choices we have at design and in operations, which are compounded by ruling out choices where trade-offs would be required. Techniques such as combined analysis, evaluation and knock-on effects should be advanced for handling these properties. Establishing an approach, considering tools and methods referring to best practice, is needed to account for the interdisciplinary integration overheads between these traditionally distant domains, but also with the rest of the system. This is crucial in CPS for enhancing scope of AI/ML and IoT usage, as well as other technologies. 2) A new way of thinking is needed for treating interconnected systems with CPS - dependability considered in a modular fashion - with hazard analysis techniques likes STPA extended, including for man-machine teaming and AI complexities. We encourage also frameworks for risk assessment in relation to AI/ML to be established and considering adaptive risk management strategies in the context of these interconnected critical systems. This moves forward with trustworthy CPS in sectors like AI-enabled autonomous systems.

AI-performance-defence guarantees for real-time interconnected systems

Future CPS require advanced technologies to address challenges in performance characterization, damage containment, and operational feedback. CPS contributing communities encourage: 1) Real-time methods ensuring deterministic multi-tasking environments and verifiable AI/ML performance. In complement, there should be an extension of defence mechanisms and feedback loops, which is essential for preventing damage propagation and enabling iterative improvement. Solutions should emphasize distributed architectures, particularly edge computing, and include digital twin capabilities for predictive insights. 2) Comprehensive uncertainty quantification, real-time monitoring, run-time verification, and data flow tracking will enhance trustworthiness. These advancements will support supervisory control and ensure dependable CPS operations, even in rapidly evolving and uncertain environments like AI-enabled applications.

These three recommendations are detailed next. Due to the multi-domain nature of CPS research they have also been extended as an associated white paper [1].



Introduction

Cyber-Physical Systems (CPS) bridge diverse technologies into cohesive wholes that interact seamlessly with the physical world. CPS research fosters the integration of disciplines across domains like healthcare, manufacturing, transportation, and space, transforming fragmented innovations into dependable, real-world applications. This interdisciplinary effort relates to the continuum of technology-to-system and centered around computing. It transitions from lower-stage cross-domain integrations within a system up to final product-oriented outcomes. The Next Computing Paradigm (NCP) provides a pivotal foundation for CPS research advances, building already on a mature infrastructure of connected technology domains.

However, the increasing interconnectivity of systems presents significant challenges, including the interaction complexity of diverse stakeholder knowledge domains (across technology specialisations, end-users, policy, regulation, standards, the public, etc.), orchestration, dependability and the scalability of solutions. This means CPS research, while playing an important role as a market generator for a multitude of technologies, has specific challenges compared with most other research domains, including a slower R&D cycle. This longer time to maturity can be compared with building windows, rooms and houses – where CPS research is positioned especially towards the later part in terms of integration complexity and calling for scaffolding in the form of supportive tools, frameworks, and policies. This chapter promotes two key axes for advancements: Support R&D, focusing on enabling methodologies and tools to integrate research across knowledge domains, and Applied R&D, which examines integrated technologies within CPS. Together, these axes provide key ingredients for CPS research supporting the success of the NCP and technology uptake in European markets.

Due to the scope of CPS research there are two connected white papers with this chapter. One supports the advice offered here, with three extended recommendations for the first one in this chapter and two supporting recommendations for both the second and third ones of this chapter[1]. The other is a positioning paper – many research domains characterise a CPS[2].

Accelerate cross-disciplinary joint research

The CPS specialists and contributing technology domains consider this the most urgent of the CPS recommendations. The complexity of technology integrations towards CPS demands a new R&D dimension to address the challenges especially of multi-stakeholder environments and prepare for the NCP, ensuring Europe's sovereignty in advanced technologies.

One aspect is that the time to develop and adopt such technologies is several times longer than for technologies from a single domain. We need to look at bringing down this time. Just as we have more advanced support tools for complex building construction, like cranes or vehicles for digging, we can have R&D providing also more advanced technologies that support doing complex/integrative research. That is, building technologies - support R&D - that helps researchers to carry out more advanced (applied) R&D.

Research collaboration approaches taken for granted inside single disciplines suddenly become multiple times more difficult where definitions, concepts, methods, priorities and evaluations can be quite different related to the involved domain perspectives. This is also compounded for elements higher up in a system where they normally have many more interactions with the system and related standards to taken into account. The effort and time required to surmount these cause collaborations to grind to a halt and significantly impact success, even where there is a strong motivation between researchers[3].

Reducing this hurdle will play a significant role in European market capture and global competitiveness. This is because ultimately CPS represent markets of integrated technologies, culminating for instance in railway systems or satellite constellations, and CPS research permits easier integrations so these infrastructures (technologies in themselves) are ready for the latest developments from the contributing technology domains. Technology integrations can play a profound role in market capture, take for example as an infrastructure technology the American Android phone, which represents a wide market place – not only for the technology components that make the phone, but for all the applications that sit on top of this.

Another aspect is that technologies higher up in a CPS face unique integration challenges that require cohesive collaboration across domains. Like industry relies on continuity programs to manage complex projects, CPS research needs a unifying structure to prevent fragmentation and address long-term goals. Europe currently misses a centralized association for CPS research or even system engineering that represents European interests. The question of how our technology components come together into technology wholes\systems is an important element for supporting successful European markets – CPS are markets. We have a unique (CPS) infrastructure landscape on the global market both in terms of physical implementations of transport, etc, and also in terms of policy focusing on ethical, sustainable development, with a strong emphasis on regulation and societal impact. Without a central means to take the pulse at European level and act, we miss a unified advocacy in relation to needs and priorities: supporting policies, funding allocation, or regulatory decisions; missed opportunities for knowledge sharing and efficiencies; supporting Europe market capture via European CPS; workforce development and education; public awareness supporting trust. The community should work to draw together national system engineering bodies into such an association that will also provide platforms for knowledge exchange, align research with emerging standards, and foster common approaches to interdisciplinary education and shared strategies across Europe. It will support CPS advancements in transport, healthcare, and manufacturing, ensuring Europe's leadership in aggregative technologies (like motors and cars composed of other technologies).

Finally in relation to the rapidly changing AI landscape, there is a need to facilitate collaboration among AI researchers, dependable systems experts, and domain specialists to address safety, security, and ethical challenges to address integration of AI/ML into CPS. Frameworks and guidelines for AI/ML safety, security, and ethical integration, supported by a European network of excellence should be developed. This will help accelerate AI/ML integration into CPS, and align innovations with Europe's ethical and regulatory standards, particularly for high-stakes sectors like healthcare and autonomous systems.

Redefining dependability for CPS adaptability and technology integrations

Technology advances for cyber-physical systems are strongly tied to the triad of safety, security and performance properties within a critical system. These properties each can influence governance of thousands to millions of interactions between parts of a system from many contributing technology domains, which permit the transformation of digital intentions into trusted real-world actions. As such, they act as a form of gateway determining which technologies and combinations are acceptable for use within CPS. The size of this gateway, i.e. how much technology is qualified to get through for usage, is dependent not only on the permitted interactions by each of these properties, but also between them. Advancing on this latter part is where we could expect a high impact, since interaction engineering between safety and security in systems is currently very limited across industry.

Figure 1: Enhancing technology access to the real world. Source: Generated via Dall-E.

There are two aspects agreed by the community to be tackled in order to advance, drawing on existing safety-security interaction research. For applied R&D, it would be beneficial to investigate the means for a system itself to be able to evaluate safety, security and performance through common evaluation criteria. From the support R&D perspective, there is need for a new research dimension, building the means to bridge the safety and security research domains themselves. This should draw upon interdisciplinary best practices to create a tailored approach for managing the research integrations. Remember that a technology is the application of scientific knowledge to the practical aims of human life (Britannica). No dedicated interdisciplinary approach currently exists to support technologies for advanced interactions between these domains. This is considered a key reason why there is not yet widespread adoption by industry. It qualifies for such an approach as the two domains have historically developed independently (traditionally distant disciplines), emerging as two distinct domains. They have separate specialist definitions, concepts, standards, certification processes, values and priorities. This presents very specific bridging hurdles for successful joint research, which does not exist for standard technology development approaches inside disciplines.

Enlarging the permitted interactions between safety and security mechanisms by enhanced research integration approaches, in addition to boosting technology uptake in critical systems, should be used to particularly support advanced AI/ML integration and to enable IoT systems to automatically integrate and coordinate within larger Systems of Systems (SoS), ensuring resilient operation and enhanced system capabilities. More generally, there is need for new ways to be established for managing dependability for AI/ML-enabled CPS and highly interconnected systems. Frameworks for continuous risk monitoring and automated contingency management will be needed, as well as advances in modelling techniques that modularize the dependability between systems and the methodologies to capture these complex interdependencies, including man-machine teaming capacities.

AI-performance-defence guarantees for real-time interconnected systems

With unprecedented levels of autonomy and interconnectivity, future CPS face fundamental challenges, particularly in higher-level orchestrative and autonomy technologies. Key hurdles include performance characterisation, containment of damaging events and establishing comprehensive operational online feedback mechanisms.

This calls for advanced real-time performance methods to master demonstrably deterministic multi-tasking environments and verifiable performance bounds for AI/ML-enabled components. Existing defence mechanisms must be extended, alongside performance characterisation, to prevent damage propagation across interconnected critical applications. Solutions will require consideration in the context of distributed architectures and particularly from the edge computing perspective.

Mechanisms providing system-level feedback are also essential, in general for enabling advances of contributing technology domains, to catch an understand weaknesses, and especially for rapidly changing landscapes like AI Feedback results must return directly to developers, enabling iterative improvement. Technologies should provide new digital twin capabilities providing predictions when a CPS can perform better with associated services to increase the value. They should include comprehensive uncertainty quantification, real-time monitoring, run-time verification, data flow tracking, and automated compliance checks for trusted machine-learned data and supervisory control during operations.

Figure 2: New feedback capacity for engineering with AI and Digital Twins. Source: HSE.AI.

Conclusion

As CPS evolve to meet the demands of an interconnected world, the need for cohesive strategies to navigate complex integrations is critical. By leveraging the foundations provided by the Next Computing Paradigm, CPS research will tackle challenges in dependability, scalability, and cross-domain innovation. Focusing on Support R&D and Applied R&D encourages a strategic approach to technology orchestration and integration for future complex and critical applications. This dual-axis strategy empowers stakeholders to bridge the gaps between knowledge domains, which will unlock transformative potential in diverse fields such as healthcare, manufacturing, and transport. The journey forward demands collaboration, innovation, and a commitment to managing complexity.

References

1: Charles R. Robinson et al. (2025). Extended Recommendations for Advances on Cyber-Physical Systems. Zenodo. https://doi.org/10.5281/zenodo.14624958

2: Charles R. Robinson et al. (2025). Bridging the Stakeholder Domains that Produce Cyber-physical Systems. Zenodo https://doi.org/10.5281/zenodo.14693254

3: D. Gooch & L. Benton. (2015). Impact in Interdisciplinary and Cross-Sector Research: Opportunities and Challenges. Journal of the American Society for Information Science and Technology.. https://doi.org/10.1002/asi.23658