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Extended Recommendations for Advances on Cyber-Physical Systems: A white paper in relation to the HiPEAC Vision 2025

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Cyber-Physical Systems (CPS) research continues support across many contributing technology domains as a facilitator for their integration into domains like transport, health, manufacturing and space. The Next Computing Paradigm will play a key supporting role for future CPS research, providing an established alignment of enabling technologies around computing. Meanwhile, there is a need to look at research that eases the complexity of traversing the research itself and raising awareness that this work opens the markets for contributing European technology fields.

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Introduction

The Cyber-physical Systems (CPS) research field focuses on supporting the convergence of technologies across a multitude of other fields[1] into products like trains, life-support systems and production plants. It is therefore a spectrum supporting integrations across knowledge domains. This is particularly impacting closer to the product-side, whilst the cumulative effects of earlier integrations are at least of equal importance. It represents the technology-to-system continuum centered around computing as well as the dependability for safe operation in the real world. An overview of domains providing core functionalities to CPS are described in the associated white paper Bridging the Stakeholder Communities that Produce Cyber-physical Systems[2]. The recommendations in this paper come directly from these domains representing both individual and global challenges with respect to CPS.

In this context, the infrastructure provided by the Next Computing Paradigm (NCP) plays an important role for future CPS. It provides a foundation of already many technology interfaces and federations (as described in this Vision). This brings many new functionalities and opportunities for CPS development whilst opening new challenges, especially in relation to managing the complexity to orchestrate within the big picture while managing the increased responsibility of a much more interconnected environment.

Uptake of integrating\orchestrative technologies is often greater than 10 times more difficult than component technologies, particularly in relation to dependable systems[3][4]. This is especially in relation to satisfying the needs of interactions across the whole system including dependability, of stakeholders and of given environments, including accounting for associated knock-on effects, diverse time and spatial scales. Consider the analogy of technology types represented as a window, a room and a house and the degree of interactions to realise each. There are many more dimensions for the latter and building such technologies require scaffolding including support technologies and policies to enable them to be impactful for industry.

Thus for advancing complex and critical systems research there are proposed two axes to be considered. The first is a new axis emerging recently[2], Support R&D, advancing method and tool technologies enabling more advanced treatment of complex research across technology fields and its uptake. There is also the more familiar Applied R&D, considering technology inside the CPS and their integrations.

The recommendations for these two axes are classed as either technology (for instance can be used to inform a research call), or challenge (where treatment will enable for instance helping to transfer understanding between communities, policy structuring, provide representation, etc e.g. creating an association). They extend on those presented for CPS research in the main HiPEAC 2025 vision document.

Axis 1 Support R&D Recommendations for Research on Complex and Critical Systems

Technology Recommendation A – Launch **support R&D technologies** facilitating integrations between contributing CPS knowledge domains.

Rationale: CPS are the assembly of technologies into higher-order technologies for real-world interactions. This means they represent EU capacity to absorb new technologies, but they also face distinct challenges from typical component technologies, as advances must satisfy many stakeholders. Research often operates in isolated silos, hindering the effective combination of advances from diverse fields like IoT, AI, and those related to dependability for CPS development. We also have increasing integration challenges for the Next Computing Paradigm, as well as sovereignty so CPS are ready for new EU technologies.

This calls for a new dimension of R&D with a different mindset, encompassing research, production, and policy. It will investigate technologies supporting particularly integrative R&D. Just as we have more advanced support tools for complex construction, like JCBs, we can establish more advanced technologies supporting complex\integrative research that will greatly bring down the related effort. These will facilitate integration between contributing CPS knowledge domains, broaden access to the bigger picture for greater impact, and prepare the destination for complex new technologies. Developing these integrating solutions will provide smoother knowledge transfer and boost collaboration between researchers. They should focus on support of assets identified by projects, programmes, and industry that have been traditionally outside their scope and be refined in applied R&D projects.

This will enhance the ability to address multi-dimensional challenges, including those arising from differing values, time and space needs from stakeholder knowledge domains, for integrative work destined to sectors like transport, healthcare, and manufacturing. In parallel, applied R&D projects on complex systems would benefit by reserving effort to use and enhance these support R&D technologies. Such work transcends the traditional expectation that one person or group can advance a technology, requiring us to rethink approaches to multiple group solutions.

Expected Outcomes:

- **Integrative Support R&D:** Especially tools and approaches easing knowledge transfer between domains in CPS, but also evaluation techniques supporting new complex cross-domain work, project progress and post-project impact.
- **Cross-domain Data Sharing Platforms:** Create data-sharing platforms to improve access to the big picture across CPS contributing domains for joint analysis.
- **Implementation Readiness Research:** Understanding and preparing the complex multi-stakeholder environment of CPS-technologies, with TRL advancement and uptake.
- **Early Users:** New regular users established with projects or programmes and across the contributing CPS domains. Feedback loops should be established.

Scope: This work will focus on promoting knowledge sharing by developing integrating tools, methodologies, and platforms to enhance collaboration across domains in complex systems. These technologies should promote access to the bigger picture and be open source as a baseline. Such resources will directly support advanced research projects across CPS sectors.
Preparing the environment is essential for industry and researchers to engage effectively with diverse stakeholders. Projects should focus on facilitating collaboration on multi-dimensional challenges. This includes tools for iterative improvement, such as incentives, performance measures, and mentoring schemes, ensuring continuous advancement. Managed contributions like open-source results should align with business models and sustainable maintenance strategies.
The work should also consider industrial processes adaptations to integrate new technologies, lifting constraints on the product side to maximize innovation. A complementary approach to Technology Readiness Levels (TRLs), termed "aggregative-TRLs," is encouraged to assess the maturity of technologies formed by the integrations of others, rather than individual components or interfacing. Moreover, studies should guide industry towards long-term strategies, potentially advocating regulatory changes that balance short-term competitive goals with sustained, long-term value generation. Such studies would fill a gap in technology aggregation research, supporting long-term strategic adaptation to technological advancements.

Community and Policy Recommendation B – Create a **pan-European research association** to represent needed advances in complex and critical systems.

Rationale: Higher-order technologies, or technology integrations for real-world applications, face unique challenges different from traditional domain-specific developments. A key issue is cohesion; while industry has programs to ensure continuity and integration, similar support is needed in advanced aggregative research. Another challenge is representing these advanced technologies in research programs, crucial for Europe as such technologies are ultimately infrastructures representing significant markets towards which many of our technology investments are destined – domains like transport, health and space.

There is need for an association to unify cross-domain research integrations, providing cohesion among academia, industry, and regulatory bodies. It should include focuses on knowledge management, supporting longer development cycles, and refining cross-disciplinary collaboration. Without higher-level guidance, progress in complex CPS research is limited, much like construction projects that change teams frequently. Additionally, disruptive technologies like quantum computing can shift global development directions, requiring adaptable guiding strategies.

It will enable European representation providing a missing element for supporting European market capture, supporting and retaining European technologies, and fostering longer-term value generation including points typically beyond the direct scope of industry efforts.

Expected Outcomes:

- **Centralized Collaboration Platform:** Create a platform for cross-domain knowledge exchange and joint initiatives among European CPS researchers and industry partners.
- **Standardization Advocacy:** Develop guidelines and best practices to align research outputs with emerging European standards and certification needs.
- **Educational Programs:** Coordinated agreements on normalised approaches for training to equip researchers with skills in cross-disciplinary CPS methodologies.
- **Funding Access:** Both in terms of the association operation and also advising on funding for aggregative CPS research projects across Europe.

Scope: This work aims to establish a research association that connects European researchers, industry stakeholders, and policymakers that contribute to aggregative technologies in complex and critical systems. The association will have a unifying influence supporting collaboration and defragmentation of research silos; public understanding of the importance of CPS; supervisory support to draw together a common body of knowledge; and developing talent in order to maintain Europe's leadership and sovereignty of diverse technology aggregations for multi-domain applications including transport, manufacturing and health.

The association should rally Europe's existing national engineering bodies calling also on support from international groups like INCOSE, the IET and HiPEAC, as well as related focus groups like Modelica and INTO-CPS in order to have a representation of CPS and System research interests at the Europe level.

Key areas of focus will include analyzing how CPS-specific and integrative technologies are advancing and assessing the flow of funding to the contributing communities, highlighting both benefits and risks of underfunding. Lighthouse initiatives in various programs may offer valuable insights for structuring and managing such collaborations. The association will also prioritize building a comprehensive body of knowledge and promoting engineering education for multi-group aggregative technologies. Additionally, it will balance local, national, and European interests, with cross-border digital innovation hubs complementing regional or national initiatives.

In terms of policy, the association will consider how EU business data protection (such as a B2B equivalent to GDPR) affects CPS advancements, ensuring that these policies support technological progress. By facilitating access to funding opportunities, the association will empower aggregative research, driving innovation in critical system applications throughout Europe.

Community and Policy Recommendation C - Foster **collaborative R&D efforts** between AI, dependable systems research, and domain application experts.

Rationale: The integration of Artificial Intelligence and Machine Learning (AI/ML) - technologies that enable systems to learn from data and make intelligent decisions - into Cyber-Physical Systems (CPS) demands a focused and collaborative approach to address emerging challenges while aligning with Europe's goals of technological sovereignty and ethical AI development. To achieve this, coordinated efforts are essential in developing domain-specific guidelines, standards, and certification processes for AI safety, security, and ethics that adhere to regulations such as the EU AI Act and industry best practices. This collaboration is particularly crucial in domains including autonomous vehicles, smart grids, and medical devices, where AI experts must work in close conjunction with domain specialists and safety engineers.

Drawing parallels from the aviation industry's successful integration of fly-by-wire systems, a similar multidisciplinary approach is imperative for AI/ML in CPS. By adopting this collaborative model, stakeholders can ensure that A/MLI-enabled CPS meet stringent dependability requirements while effectively leveraging the capabilities of AI/ML.

Expected Outcomes:

- Establish a European network of excellence in AI/ML-enabled CPS to foster cross-domain collaboration.
- Develop domain-specific AI/ML safety and security frameworks for high-impact CPS sectors.
- Create standardised (ethical) guidelines and certification processes for AI/ML integration in critical systems.

Scope: This initiative aims to establish collaborative platforms that unite AI researchers, dependable systems experts, and domain specialists across Europe. By fostering cross-disciplinary events, shared resources, and tools, it will support collaborative research and accelerate AI/ML integration into dependable CPS. The program will facilitate joint academic-industry research endeavours and develop a comprehensive repository of best practices and case studies. To ensure long-term sustainability, the initiative will support the development of interdisciplinary curricula focused on AI/ML-enabled dependable systems. Furthermore, it will cultivate partnerships with European regulatory bodies to align research outcomes with emerging AI regulations, thereby bridging the gap between innovation and policy.

Axis 2 Applied R&D Recommendations inside Complex and Critical Systems

Technology Recommendation D – Open-up **safety-security-performance interactions** to maximize system resilience and to support EU technology markets. For the specific joint-research challenges, technology to apply interdisciplinary best practices is also essential.

Rationale: The need for automated, trustworthy management of safety, security, and performance (SSP) in complex systems is well-recognised. However, the traditional methods are still widely spread separating in particular the safety and security. This creates inefficiencies and barriers to industrial adoption of technologies that enable their joint treatment and governance. This in turn limits advances in automation and technology uptake. SSP represent separate disciplines, however in parallel there is an increasing pressure for advanced integrative research and management approaches to promote adaptability and resilience in both design and operational phases. Dedicated expertise should be encouraged to find solutions that maximize SSP interactions relevant for resilience. This is in contrast with general systems engineering that, due to a very wide scope, seeks to minimise SSP interactions, as for system architects, they are considered among the hardest decisions to make[5]. A balanced solution needs to be found to avoid overly restricting uptake of all the contributing technologies to CPS and for system adaptability.

These innovations should be used to evolve regulations towards adopting credible safety and security combined techniques and mediation. Due to the significant hurdles as a topic traversing knowledge domains, support R&D technologies should be established based on interdisciplinary best practice. The capacity to evaluate and compare SSP jointly is expected to bring major enhancements to design, operations and technology transfer, crucial for Europe's ability to adopt digital technologies effectively and address the needs for trustworthy systems. This will be as a result of significantly enlarging the permitted interactions between SSP mechanisms and benefitting from the increasingly pervasive interconnectivity. It will support many other technology advances such as AI/ML integration and the need to enable IoT systems to automatically integrate and coordinate within larger Systems of Systems (SoS), ensuring resilient operation and enhanced system capabilities.

Expected Outcomes:

- **Advanced SSP Approaches & Mechanisms:** As a high-level support technology, establish an approach for joint SSP research. Extend applied technologies for coupling and combined analysis of safety, security, and performance, especially focused on AI\ML and IoT within systems of systems contexts.
- **Regulatory Alignment:** Propose updates to regulatory frameworks, supporting a convergence of SSP solutions and evolving industry standards and security requirements.
- **Interdisciplinary Teaching and Collaboration:** Foster educational programs and training to engage industry stakeholders, regulators, and researchers, facilitating a shared understanding of SSP trade-offs and adoption.

Scope: The work will focus on developing and demonstrating advanced SSP coupling mechanisms and approaches including co-engineering in key sectors like transport, nuclear, oil, gas, first response and other safety-critical systems or extreme environments where dependability is essential. It will draw together the relevant building bricks for managing safety, security, and performance (SSP) and converge strategy for resilience. This includes assessing methodologies for aligning SSP with certification standards like the EU Cybersecurity Act, ISO 21443 and ISA/IEC 62443. The work will include system modelling, conducting scenario-based evaluations to demonstrate the benefits of advanced SSP coupling and propose solutions to barriers in certification and policy processes. Additionally, it will foster interdisciplinary collaboration and life-long learning schemes among stakeholders, including researchers, industry partners, and regulatory bodies, to ensure alignment with the future industry needs and regulatory requirements. As cross-disciplinary technology development – R&D preparing the destination environments is a particular challenge outside of normal exploitation actions.

Technology Recommendation E - Advance **proactive risk management and analysis solutions** for enhanced dependability of systems interactions and for AI/ML.

Rationale: The growing complexity of interconnected critical systems and AI/ML integration in CPS necessitates a paradigm shift in dependability engineering. Traditional approaches treating safety only as a non-functional property are no longer adequate. A new perspective is required that considers Reliability, Availability, Maintainability, Safety, and Security (RAMS2) as functional properties at the system-of-systems level. Functional properties are typically treated as modules within a system, such as sensing, with a similar call now being made for orchestrating\governing properties like safety across many connected systems. This shift is necessary for addressing unique challenges posed by AI/ML-enabled CPS, where system-level specification flaws can lead to major incidents/accidents. Across critical sectors like smart energy grids and autonomous transportation, the integration of AI/ML introduces new vulnerabilities that traditional risk assessment methods may overlook. Historical examples, such as the Mars Climate Orbiter mishap and accidents like the autonomous taxi of Cruise a subsidiary of General Motors, underscore the need for more sophisticated, proactive risk management strategies in the age of AI/ML-enabled CPS.

Expected Outcomes:

- Develop advanced, model-based functional hazard analysis techniques like STPA especially on man-machine teaming functions and AI/ML-dependant CPS.
- Create comprehensive risk assessment frameworks addressing ethical, safety, and security implications of AI/ML in critical systems.
- Establish dynamic, adaptive risk management strategies and European standards for AI/ML safety and reliability in CPS.

Scope: This research initiative will develop cutting-edge proactive risk management and analysis solutions for AI/ML-enabled CPS. It will advance model-based System-of-Systems engineering techniques for hazard analysis, creating methodologies to capture complex interdependencies. The program will foster sophisticated simulation environments, incorporating adversarial testing and chaos engineering, to test complex system interactions before real-world deployment. A major focus will be integrating advanced diagnostics, prognostics, and health management capabilities for proactive fault detection and predictive maintenance in AI/ML-enabled CPS. The initiative will establish frameworks for continuous risk monitoring and automated contingency management, ensuring CPS can respond dynamically to emerging threats. Throughout, special attention will be given to aligning these enhanced risk analysis methods with European values and regulations, promoting ethical and responsible AI/ML-enabled CPS development.

Technology Recommendation F – With higher critical system interconnectivity, new and advanced systemic technologies for **performance characterization** and for **isolation of hazards and threats** are needed.

Rationale: Modern CPS are evolving toward unprecedented levels of autonomy and interconnectivity, demanding increasingly sophisticated responses to variable physical environments. This evolution necessitates systems capable of highly dynamic behaviour, adapting their responses based on complex contextual factors with respect of real-time constraints imposed by the environment. The integration of AI technologies, coupled with advanced solutions for energy management, connectivity, new computing NCP platforms and digital twins, has dramatically increased the complexity of performance management across distributed systems.

Critical systems now face a fundamental challenge: balancing the need for enhanced computational capabilities with strict certification requirements. For instance, in avionics, safety requirements demand failure rates as low as 10^{-10} for catastrophic events. Similar ultra-high reliability requirements are emerging across sectors as autonomous systems interact more directly with human lives. This creates a paradox where systems must simultaneously become more dynamic and demonstrably deterministic.

These competing demands—enhanced adaptability versus dependability—require breakthrough technologies. We need new approaches to characterise and verify real-time behaviour in multi-tasking environments, especially when dealing with AI/ML components. Traditional methods of performance analysis and hazard isolation become inadequate when systems must dynamically reallocate resources while maintaining strict safety guarantees.

Expected Outcomes:

- Advanced real-time performance methods to master demonstrably deterministic multi-tasking environments, enabling precise monitoring and control of system behaviour across distributed architectures.
- Robust isolation mechanisms for containing hazards and threats detection in interconnected critical systems, particularly focusing on edge computing scenarios where performance demands meet safety requirements.
- Verifiable performance bounds for AI/ML-enabled components in critical systems, ensuring predictable behaviour while maintaining operational efficiency.

Scope: This research addresses two critical challenges in modern cyber-physical systems: performance management and risk isolation. Advanced methodologies will be developed for real-time performance analysis in interconnected distributed and multicore architectures, with particular attention to variable workload scenarios and AI/ML integration. The work extends existing defence mechanisms in edge computing to prevent fault propagation across interconnected critical applications. New verification and validation techniques will be proposed for multi-tasking environments where current timing analysis methods prove insufficient. These methods will support systems with mixed-criticality levels and dynamic resource allocation. The research will produce analytical frameworks for early detection of performance limitations and security vulnerabilities, with specific emphasis on systems incorporating AI/ML components. This integrated approach to performance characterization and safety isolation aims to advance the development of dependable CPS.

Technology Recommendation G – Extend **online feedback mechanisms** for testing and validation in dependable systems.

Rationale: This will permit the uptake of new technologies especially for the field of AI/ML. In addition, development of these technologies will enable Digital Twin technologies with supervisory control capabilities and provide advances for enabling prediction capabilities in order to enable Dependable Systems to perform better. This is in particular important when increased levels of autonomy is desired. In order to avoid new certifications if the lessons learned from AI/ML shall be deployed autonomously it is necessary to ensure the trustworthiness of the system-wide solution in relation to safety and security-related requirements dynamically. Here uncertainties from sensors and from the environment can affect the perception of the real situation for the CPS (a physical twin) and consequently any control aspects (also supervisory) needs to be able to compensate for such uncertainties.

Expected Outcomes:

- New digital twin capabilities enhancing the ability to increase autonomy for digital twin-enabled systems.
- New technologies for coping with uncertainties enabling trustworthy decision-making from supervisory control levels.
- Use of machine learned data that can be dynamically verified to be safe to use in an operational setting.

Scope: Establish both R&D support and applied technologies in the area of digital twins that will enable prediction capabilities when a CPS (its physical twin) can perform better and provide services that will increase the value of the CPS. Use comprehensive uncertainty quantification, real-time monitoring, run-time verification, data flow tracking, and automated compliance checks to ensure the reliability, fairness, and security in high-risk dependable systems applications. This will also enable the establishment of new frameworks and assets that will make it easier to get started producing digital twins.

Conclusion

Cyber-Physical Systems are the cornerstone of future innovation, integrating diverse technologies across domains such as transportation, healthcare, and manufacturing. The recommendations outlined in this white paper address critical challenges in CPS research, focusing on enabling tools, managing collaboration across knowledge domains, and aligning technologies with emerging standards.

By advancing Support and Applied R&D, the proposed strategies aim to simplify the complexities of integration, enhance dependability, and promote scalable, trusted solutions for highly interconnected systems. Centralised platforms, AI safety frameworks, and advanced methodologies for system dependability will play an important role for Europe's commitment to sovereignty.

The vision for CPS requires collaboration among researchers, industry stakeholders, and policymakers, bridging gaps between disciplines and accelerating the adoption of transformative technologies. Through collective effort, CPS can unlock unprecedented advances, ensuring European leadership in global technology markets while addressing societal needs for safe, dependable, and adaptable systems.

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