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Open Continuum

The European vision and research directions in the Cloud-edge-IoT domain for 2025-2027

Distillation of the Consultation meeting in Brussels on 11 May 2023

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1. INTRODUCTION

The consultation event held in Brussels on 11 May 2023 aimed to bring forward thinking in the Computing Continuum. The meeting was organised by Open Continuum under the EUCloudEdgeIoT initiative[1] and the European Commission (EC). It gathered industrial players of all sizes, academic researchers, EC-funded projects and policymakers. New trends, visions, and tracks for research, from the most relevant papers received were presented at the event as well as the research roadmap developments of relevant initiatives (e.g., SW Forum, HiPEAC, NESSI, AIOTI, European Alliance for Industrial Data, Edge and Cloud, INSIDE, FIWARE foundation). The analysis of all the content resulted in the identification of the European vision for the cloud-edge-IoT domain and identifies four main research directions for the next Horizon Europe Work Programme (2025-2027). These research directions were presented in the wrap-up session at the end of the day and received strong support from the participants:

EU Computing Continuum Infrastructure: A transformation of the Computing Continuum Infrastructure is required, particularly in relation to European Cloud-Edge Servers. Digital autonomy in the Computing Continuum is only achievable with a strategic intervention leading to a paradigm shift. The adoption of RISC-V, an open-source Instruction Set Architecture (ISA), is widely proposed and supported as the only means to strengthen EU sovereignty in the Computing Continuum. The subsequent step following the EU investments in processors for HPC would be a cloud-edge server market. The importance of energy-aware computing and the creation of federated catalogues for effective resource sharing is also to be considered in line with Cognitive Cloud-Edge Continuum foreseen developments.

Cognitive Cloud-Edge Continuum: This section discussed and identified key challenges for the cloud-to-edge continuum imposed by the new emerging trends like the Virtual Worlds. To make the Industrial Metaverse/Virtual Worlds become reality, the digital and physical strands of a defined space need to be woven together into the fabric of a new universe that is orchestrated by an intelligent cloud-to-edge-to-IoT continuum. There is a need for end-to-end intelligent enablement for the orchestration of the data, computing, and Artificial Intelligence (AI) capacity across the cloud-to-edge/IoT continuum for trustworthy decision-making for business and private users. It presents several research challenges including end-to-end AI integration, dynamic data orchestration, new runtime management of the continuum, self-adapting clouds, decentralised optimisation and convergence with 5G/6G.

[1] Thank you to the rapporteurs for providing inputs to this document: Giovanni Rimassa (Martel/Open Continuum), Amjad Majid (Martel/Open Continuum), Golboo Pourabdollahian (IDC/Unlock CEI), Antonio Kung (Trialog/Open Continuum, Lara López (Atos-Eviden/Open Continuum), Juncal Alonso Ibarra (Tecnalia/SW Forum), and John Favaro (Trust-IT/SW Forum).

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Next Generation MetaOS for IoT-Edge: This part identified challenges about the merging of the physical and virtual worlds. Driven by the ubiquitous proliferation of IoT objects and connected systems, the complexity of data handling at the edge is characterised by data inflation, heterogeneity of data types, and task concurrency. It emphasises the role of emerging network functions, a transition from the Internet of things to Internet of digital twins, from cloud and central computing to spatial computing as well as the benefits of advanced technologies like Extended Reality (XR), going beyond system automation and robotics towards the vision of an Industrial Metaverse. Claiming that the Industrial Metaverse is more mature than the consumer-driven metaverse, emphasis was put also on the importance of distributed intelligence and collaborative industrial systems at the IoT-Edge Continuum as part of broader Cloud-Edge continuum challenges.

Cybersecurity, Privacy, Interoperability, Open Source and Software Engineering: The final section discusses the challenges of secure SecDevOps for complex systems, using AI for all phases of the Software Development Life Cycle (SDLC) and Service Operation Life Cycle (SOLC). It also highlights the importance of managing security in the software supply chain and ensuring data confidentiality in the cloud-edge continuum. The section concludes with a discussion on new software engineering mechanisms for the development of (hybrid) quantum software and the importance of open hardware and software.

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2. EU COMPUTING CONTINUUM INFRASTRUCTURE

Keywords: *autonomy, RISC-V, federation, energy-aware, advanced mechanisms, hyperdistribution, business model*

In order to respond to the dynamic challenges of a rapidly evolving digital landscape, a transformation is required within the Computing Continuum infrastructure, specifically in relation to European cloud-edge servers. This transformation is centred around achieving autonomy within the Computing Continuum. A series of strategic interventions and paradigm shifts were identified to address this challenge.

A central aspect of this challenge is the race to develop and deploy new hardware as outlined by HiPEAC. It implies the urgency to advance in hardware technology, leveraging cutting-edge processing capabilities to handle the increasing demands of computational tasks across the continuum. This advancement in hardware serves as a foundation for achieving autonomy in the Computing Continuum. As part of this shift, the adoption of RISC-V, an alternative open-source Instruction Set Architecture (ISA), was proposed by Semdynamics for use throughout the Continuum. Such adoption could strengthen the EU's sovereignty in the cloud-edge server market while fostering new research and development (R&D) and business opportunities.

The federation of cloud ecosystems to support heterogeneous hardware platforms is another significant aspect of the challenge. A potential solution, according to the Karlsruhe Institute of Technology, could be the novel X-by-Construction (XbC) paradigm, which focuses on automatically generating system implementations with guaranteed properties. However, its current limitation to the design phase makes it less suitable for highly adaptive systems. Thus, extending XbC's applicability to dynamic systems is a key research question. Furthermore, the development of a European Processors family, which includes a European Cloud Processor, European Edge Processor, and European IoT Processor, will lead to seamless interoperability and integration of computing continuum components and enable optimising the performance across the computing continuum layers.

Energy-aware computing is an essential dimension of the challenge, aiming at fostering an environment of sustainability and efficiency. The Alliance for Internet of Things Innovation (AIOTI) is set to make the Computing Continuum cognizant of its energy consumption, promoting strategies that optimise power utilisation and minimise environmental footprint. Furthermore, to improve operations in the continuum, there is a need for advanced mechanisms. This includes the miniaturisation and context-aware self-configuration of workloads (UNIVERSITAT POLITÈCNICA DE VALÈNCIA). We also need new algorithms to enable virtual machines to follow policy settings. The management of hyper-distributed resources is another priority, with a particular focus on migrating AI operations closer to data sources to reduce latency and improve efficiency.

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Finally, the creation of federated catalogues is crucial. These would feature services and data from cloud, edge, and IoT resources and enable effective publication and discovery of resources. FIWARE is one of the organisations spearheading this initiative, promoting interoperability and data sharing across multiple sectors. These federated resources call for the development of effective business models. These models would encourage resource sharing and cooperation among different stakeholders, fostering a robust, resilient, and self-sustaining Computing Continuum. In this context, the role of effective business models becomes pivotal in aligning the interests of various stakeholders towards a shared vision of achieving autonomy in the Computing Continuum.

In conclusion, strengthening sovereignty in the Cloud-Edge Server Market through open-source software and hardware, with a particular focus on building on RISC-V, is an imperative task in navigating the rapidly evolving digital landscape. Initiatives such as the federation of cloud ecosystems, energy-aware computing spearheaded by AIOTI, and the creation of federated catalogues under the leadership of FIWARE are crucial components in this transformative journey. These initiatives, along with the evolution of effective business models, are all set to drive robust and resilient operations in the continuum, fostering a computing environment that is sustainable, efficient, and conducive to innovation. These are ambitious, yet achievable targets, that will consolidate the EU's position as a leader in the global cloud-edge server market, and ultimately ensure that the European Computing Continuum stands out as a benchmark for technological autonomy and innovation.

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3. COGNITIVE CLOUD-EDGE CONTINUUM

Keywords: *end-to-end AI, any-to-any infrastructure, reinforced learning, traceability, optimisation, 5G/6G, distributed AI, Virtual Worlds/Industrial Metaverse*

To actualise the concept of the Industrial Metaverse or Virtual Worlds, we must intertwine the digital and physical aspects within a specified environment, crafting the foundation of a novel realm. This should be managed by an intelligent, trustworthy, and context-aware continuum, stretching from the cloud down to the IoT devices. This continuum is expected to evolve into an any-to-any infrastructure, with AI playing a crucial role in optimising global outcomes (Fraunhofer). However, this vision presents several research challenges.

One of the primary challenges, as indicated by Tecnalia, is the orchestration of data, computing, and AI capacity across the continuum. This involves the development of a self-adapting cloud that can sense, learn, optimise, and adapt. The cloud should be energy-aware and equipped with new runtime management solutions that feature reinforced learning. Traceability of data and usage across the continuum is another critical aspect that needs to be addressed.

AI is expected to play a significant role in enhancing the continuum. Experts argue that AI should be applied to all the components of the continuum to integrate and compose services. However, the integration of AI into the continuum presents challenges such as ensuring the alignment of AI models, agent coupling, and negotiation for cooperation and resource utilisation (6G Flagship).

With the continuum likely to involve multiple stakeholders, integrating decentralised identity and access management becomes a key priority for ensuring data security and privacy. Furthermore, the need for decentralised optimisation techniques becomes apparent as we seek to leverage resources across this vast continuum effectively (University of Oslo). In addition to this, establishing a cognitive system of systems for global optimisation that intrinsically upholds values of resilience, safety, security, autonomy, and trust, brings another level of intricacy. This necessitates pioneering research to overcome such complexities.

The convergence with 5G/6G is a crucial aspect of the continuum. This involves the integration of the emerging 5G/6G infrastructure to optimise AI computations across the Cloud/Edge/IoT continuum (the focus should be on developing distributed AI systems enabled by 5G/6G instead of AI-enabled 5G/6G; the University of Patras and π-NET). However, the current dependence of data on 5G legacy infrastructure presents a challenge in accelerating cloud migration to the edge for data processing. Furthermore, the combined application of 5G/6G technologies and standardisation efforts could transform the Computing Continuum into a space where domain-specific vertical solutions can

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effectively cohabit (Trust-IT Services). This would enable cross-sectoral exchange and semantic interoperability, leading to more integrated and efficient computing environments (TRIALOG).

In conclusion, the vision of a cognitive cloud-to-edge continuum presents several research challenges that need to be addressed. These challenges span various aspects of the continuum, including data orchestration, AI integration, decentralised intelligent management, decentralised and global optimisation, energy and resource heterogeneity support, data management, security/privacy, and convergence with 5G/6G. Addressing these challenges is crucial for realising the vision of a cognitive cloud-to-edge continuum as a key enabler for any emerging trend like the Virtual Worlds, Industrial Metaverse, AR/VR/XR, etc.

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4. NEXT GENERATION METAOS FOR IOT-EDGE

Keywords: *Industrial metaverse, distributed intelligence, digital twins, metaweb, reinforcement learning, any-to-any, metaverse standard form*

The merging of the physical and virtual worlds is a significant trend in the technological landscape spurred by explosive growth of IoT objects and connected systems (AIRBUS). The latter leads to data inflation, heterogeneity of datasets, and task concurrency at the edge. This convergence presents challenges in managing and processing vast amounts of data generated by edge nodes, seizing the opportunity of an increasing computing capacity and decentralised intelligence, however, it comes along with the need for seamless interoperability across diverse systems, and handling concurrent tasks efficiently.

The advent of the Industrial Metaverse emphasises the critical role of network infrastructure and advanced technologies like Extended Reality (XR), digital twins, and robotics (Nokia). These technologies demand enhanced and dynamic network capabilities, managing network functions on the fly and at a local level including tailored bandwidth, reduced latency, and high connection density on demand (SIEMENS AG). AI embedded into edge nodes and distributed systems are integral to the Industrial Metaverse, facilitating its dynamic and collaborative Industrial Internet of Things (IIoT) systems. The Industrial Metaverse, which is evolving ahead of the consumer variant, presents numerous opportunities for innovation, collaboration, efficiency, and enhanced interaction with the physical world, all of which are driven by advances in technologies such as Augmented Reality, the embedding of graphical computing processors and large-scale semantic language models). As stated, it also poses challenges including the need for immersive training, personalised interaction with operators/workers, implementation of fungible and non-fungible tokens, seizing opportunities by combining physical data with simulated data and system models (twin models) with down-scaled AI algorithms at the edge, reducing energy consumption, and security threats (ATOS/Eviden).

Distributed Intelligence and collaborative systems at the IoT-edge continuum are crucial for optimising operations and decision-making processes at the edge of the Metaverse according to EVIDIEN. However, the development and implementation of these systems present challenges in terms of ensuring seamless integration, interoperability, and efficient collaboration. The transition towards an Industrial MetaWeb, characterised by any-to-any connectivity (e.g., cloud to cloud, cloud to edge to IoT, device to device etc.), presents additional challenges in terms of developing a data manager and resources orchestrator adapted to distributed and dynamic edge architectures. Among the promising technologies to manage and optimise the IoT-edge continuum are swarm computing and (deep) reinforcement learning as they enable autonomous learning of collaborative, adaptive behaviours with minimal prior knowledge by reacting to dynamic, complex physical events as emphasised by Inria and Politecnico di Milano respectively.

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To be noted, the establishment of a recent Metaverse Standard Forum would be instrumental to drive industrial standards at an early stage for ensuring interoperability and standardisation. The establishment and operation of such a forum could present challenges in terms of ensuring critical participation, collaboration of key industries, and consensus among diverse stakeholders across the value chain.

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5. CYBERSECURITY, PRIVACY, INTEROPERABILITY, OPEN SOURCE AND SOFTWARE ENGINEERING

Keywords: *AI, DevOps, secure software engineering, secure supply chain, access management, low code, open source, quantum computing*

The availability of secure DevOps (SecDevOps) for complex systems, using AI (e.g., Reinforcement learning) and including security techniques in all phases of the SDLC and SOLC, is a significant research challenge. This involves integrating AI into all aspects of software development and operations, from initial design to deployment, operation, and maintenance. Automation with ZeroTouch provisioning of resources and services is a key aspect of this. Realising such systems will reduce manual intervention and increase efficiency (Fraunhofer). Such AI-managed systems can be further advanced to feature self-learning and self-healing capabilities (SW Forum). With these capabilities, systems can learn from their experiences and adapt to changes, improving non-functional characteristics such as performance, over time. They can also detect and fix problems automatically, reducing downtime and improving reliability. The complexity of the development of complex systems can be reduced by adopting a low code development approach where developers create applications with minimal coding, increasing efficiency and reducing the time and effort required for the development (Harokopio University of Athens).

Management of security in the complete software supply chain, using a DevOps approach or not, is another important challenge. This involves implementing measures to ensure that the software supply chain is secure, protecting it against vulnerabilities and threats, especially when third-party components are being used (NESSI). Automatic software composition analysis, dependency analysis and automatic maintenance of a Software Bill of Materials can alleviate this challenge.

In the cloud continuum, developing federated Identity and Access Management (IAM) and ZeroTrust mechanism can help in addressing the challenge of ensuring security (Foundation for Research and Technology - Hellas). They ensure that only authorised individuals have access to resources, services, and data and that all users are treated as potentially untrustworthy, regardless of their location or network. Ensuring data confidentiality in the cloud-edge continuum is crucial. This requires implementing measures to protect data as it moves between the cloud and the edge, ensuring that it remains confidential and secure.

Open hardware and software can also reduce security risks. They enable anyone to test and discover vulnerabilities in the hardware and software stack and thereby improving them and making them more robust. Open source development will also increase collaboration and innovation (ECLIPSE Foundation; Open Nebula).

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Finally, the Computing Continuum will also include specialised hardware such as quantum computers. This will call for new software engineering mechanisms as quantum computers operate very differently from traditional computers.

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