EMPYREAN: Trustworthy, Cognitive and AI-driven Collaborative Associations of IoT Devices and Edge Resources for Data Processing

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ABSTRACT

The EU-funded EMPYREAN project (empyrean-horizon.eu) aims to establish a hyper-distributed computing paradigm, leveraging collaborative, heterogeneous IoT devices and federated resources. EMPYREAN focuses on developing technologies for efficient AI workload processing, secure distributed edge storage and cloud-native application development. It will offer open and standardised APIs and use open-source platforms. EMPYREAN's capabilities will be demonstrated through three use cases: advanced manufacturing, smart agriculture, and warehouse automation.

CCS CONCEPTS

• **Computer systems organization**; • **Computing methodologies** → **Distributed computing methodologies**; • **Information systems** → **Information systems applications**;

KEYWORDS

Edge, Cloud, IoT, AI, Associations

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1 INTRODUCTION

Internet of Things (IoT) devices equipped with various sensors and mobile or stationary units mounted with computing and storage capacity, like robots, are recognized today as key for the realization of cyber- physical systems, smart cities and spaces, providing critical services and business intelligence in a variety of user contexts and sectors [1]. At the same time, IoT devices and resources are subject to energy, processing and connectivity constraints and are vulnerable to security threats [2].

The conventional way of dealing with (big) data, generated and exchanged by IoT devices, is to continuously push them to

centralised cloud computing infrastructures, or utilize jointly on-device and on-premise/micro edge resources, edge computing nodes placed further from the end devices (far and deep edge), along with the traditional federated cloud resources, thus forming an IoT, edge-cloud continuum [3]. This approach can increase manifold the applications' performance and the efficiency of the infrastructures, overcoming the critical data collection, transmission, and processing bottlenecks present in the centralized systems. Nevertheless, when this continuum is implemented as a monolithic pipeline, it cannot efficiently serve the emerging hyper-distributed and AI/ML-based applications that are highly dynamic and whose performance requirements are increasingly strict (e.g., in terms of latency, geographic density, energy consumption).It is clear that to accommodate the explosive growth of IoT, more local decisions and a collective logic leading to system-wide welfare optimality are needed.

For this reason the EMPYREAN EU project proposes a new hyper-distributed computing paradigm encompassing heterogeneous IoT devices and computing, storage and connectivity resources that may belong to different providers at different segments of the continuum. EMPYREAN will build federations of collaborative resources (Figure 1), to be referred to as IoT-Edge Associations or simply Associations, that will be created and be operated autonomously and seamlessly using the EMPYREAN AI-enabled management scheme. This Association-based continuum will utilize distributed, cognitive and dynamic AI-enabled decision-making to balance computing tasks and data locally inside an Association and between federated Associations in a decentralized, multi-agent manner as well as across central computing environments. It will optimize resources and provide scalability, resiliency, energy efficiency, and quality of service.

An Association will constitute a secure execution environment where the trust between data-generating and data-processing entities will be continuously validated using distributed trust services, while identity and data access management will assure controlled access and confidentiality of data among different organizations. Automated tools and mechanisms for seamless interconnection, efficient data processing of ML workloads, and secure distributed edge storage will empower the EMPYREAN platform. EMPYREAN will also develop technologies for Associations-native application development and deployment that contribute to the entire application lifecycle and interoperability for AI-driven value extraction of high-volume and dynamic IoT data generated at the edge of the network from multiple sources.

2 EMPYREAN OBJECTIVES

EMPYREAN EU project has the following objectives:

- **Objective 1: Enable collaborative autonomy in the IoT-edge-cloud continuum**: An Association is a collection of IoT devices, multilayer edge resources and federated cloud platforms that dynamically and autonomously cooperate via a sophisticated coordination framework.
- **Objective 2: Cognitive Associations, speculative resource orchestration and AI-driven adaptability**: EMPYREAN's Associations operation will be empowered by a cognitive platform that involves distributed algorithms, decentralized AI-enabled decision-making and autonomous adaptations.
- **Objective 3: Ensure security, privacy and multi-party-trust in the IoT-edge-cloud continuum**: Associations will also be coupled with identity and access management mechanisms to assure controlled access and confidentiality of data. EMPYREAN will develop an S3 compatible distributed secure storage service operating autonomously inside an Association when needed, but also in the continuum.
- **Objective 4: Build mechanisms for efficient IoT data processing of ML-workloads and hyper- distributed applications**: EMPYREAN will provide a decentralized and distributed interconnection and data distribution service that supports decentralized data distribution, enabling services and data to interconnect seamlessly. Communication mechanisms will be developed for direct message and data transfer, using an FPGA-based RDMA device driver that drastically improves small-message transfer performance.
- **Objective 5: Workflow-based, AI-augmented application development and seamless deployment on the edge-cloud continuum**: EMPYREAN also contributes to workflow-based, AI-augmented application development and seamless control and deployment
- **Objective 6: Demonstrate the capabilities of the EMPYREAN platform in supporting hyper- distributed, highly- demanding and dynamic applications**: EMPYREAN will demonstrate its advanced innovative capabilities through three well-defined use cases that involve device- and data-rich applications in advanced manufacturing, smart agriculture and warehouse automation that involve continuous federated learning from distributed data. These use cases evolve high-demanding, safety-critical, dynamic, greatly impactful applications that pose heterogeneous demands.

3 EMPYREAN CONCEPT

To achieve its objectives, EMPYREAN will introduce and develop innovative technologies and approaches that bridge existing technology gaps, enabling a cognitive computing continuum that integrates intelligence and automation to achieve more efficient data processing. EMPYREAN will develop a platform of high novelty and openness realize EMPYREAN Associations, utilizing open-source platforms, open standards, and interoperability models. The continuum, empowered by EMPYREAN, will fulfil the stringent demands of future hyper-distributed applications and services. EMPYREAN will contribute to key factors such as intelligence, automation, trustworthiness, security, heterogeneous IoT edge mesh connectivity, interoperability, elasticity, and energy efficiency that are required to shift in practice the paradigm from cloud-native towards continuum-native applications that will fully leverage the highly anticipated X-continuum paradigm [4].

The EMPYREAN concept is founded on two primary pillars that underscore the project's core activities along with the development of the EMPYREAN Aggregator that will support the formation, coordination, and collaboration of Associations leveraging the EMPYREAN technological advancements. The first pillar, Security, Trust and Seamless Data and Computing Management, builds a

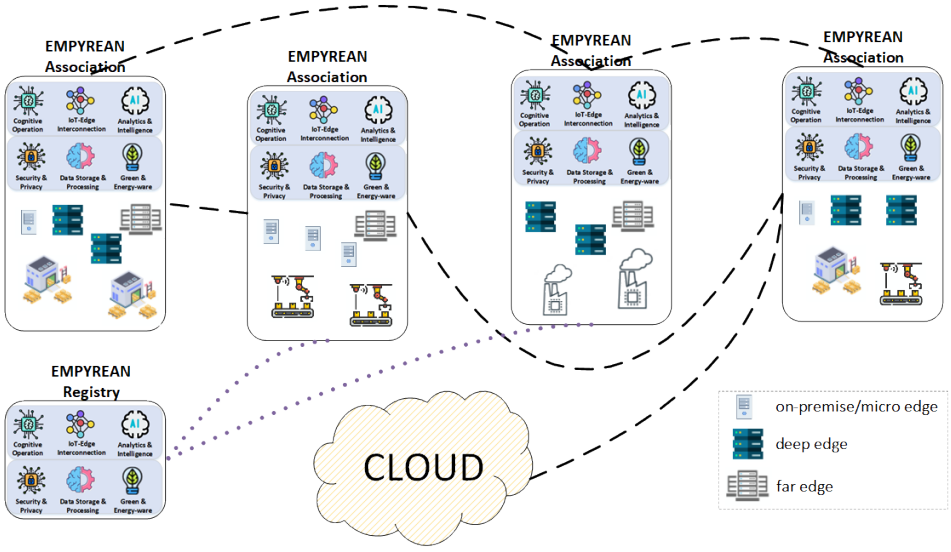

Figure 1: EMPYREAN general concept and vision

distributed trust management framework that operates inside an Association and between Associations, coupled with identity management mechanisms. A distributed edge-cloud storage service along with mechanisms that assure controlled access and confidentiality of data are also implemented. Moreover, this pillar creates mechanisms for the dynamic management of computing resources in an Association and their software-defined interconnection that creates a unified memory layer. The second pillar, Decentralized Intelligence and Application Development and Deployment, concentrates on the cognitive orchestration of resources and hyper-distributed applications and the provision of AI-enabled service assurance and autonomous adaptations across the EMPYREAN Associations comprising the continuum. Moreover, it includes novel solutions for designing, deploying, and managing continuum-native applications, facilitating scalability, elasticity, adaptability, and interoperability by empowering the "develop once, deploy everywhere" approach.

4 EMPYREAN USE CASES

The capabilities of the EMPYREAN platform and developed technologies will be demonstrated through three distinct use cases (UCs). All three UCs are end-user driven and represent significant economic segments, ensuring innovation portability and a clear commercialization roadmap.

4.1 Process Monitoring and Anomaly Detection in Robotic Machining Cells

This UC aims to develop a system that can perform process monitoring in robotic machining cells, composed of robots performing drilling and milling operations that are managed by specialized personnel. High-precision sensors mounted on robots are used to measure various variables, such as temperature, vibration, cutting force and tool wear, in order to create a unique fingerprint for each process, which can be used for future comparison with similar operations. The system will detect anomalies based on a previous process fingerprint analysis and will alert the operator in real-time to take corrective actions.

EMPYREAN's Association will provide a secure and trusted execution environment for the interactions between robots and edge resources. Also, resource orchestration and autoscaling mechanisms will efficiently and dynamically handle the increased demands inside or across multiple Associations (e.g., remote plants of the same organization) for processing and storage in a multi-agent manner. Remote Direct Memory Access (RDMA) operations for small messages will further support the UC's latency-sensitive (transaction) processing operations. Finally, EMPYREAN will provide efficient and secure storage for generic and time-series data from various sensors of the robotic cells. These developments will demonstrate EMPYREAN's platform as a key enabler for the ongoing industrial revolution.

4.2 Proximal Sensing in Agriculture Fields

This UC aims to develop a Soil Organic Carbon (SOC) process to dynamically assess the soil state in agriculture fields dynamically. Proximal sensing is a method for assessing the soil's real health and fertility conditions, using proximal and remote sensing devices and other tools, stationary or mounted into robots. Proximal sensing technologies can generate large amounts of data, which have to be analysed. Federated AI makes possible to develop robust and accurate models for estimating soil organic carbon content, to support data-driven decision-making concerning the use of inputs such as nutrients and water, enabling low-input farming.

The EMPYREAN Associations will enable groups of farmers to share the expenses for buying and maintaining computing and storage equipment in the fields, organising them into Associations, and sharing the available capacity on demand. Also, a number of federated AI algorithms will be developed to assess SOC content using proximal and remote sensing sensors that will be validated in a relevant environment for different crop types and cultivation

periods. The EMPYREAN platform will support the execution of federated AI mechanisms, train machine learning (ML) models on decentralised data sources and enabling the development of accurate SOC prediction models on the spot.

4.3 Robotic Semi-autonomous and Lights Out Logistics Order Picking

Order picking can comprise nearly 30% to 40% of a warehouse's activity and runs parallel with stocking inbound goods on the shelves. As a lot of "dead-time" occurs just to reach the goods location. Swarms of robots can be deployed to scale with goods volume while reducing dead-time of human resources. Moreover, in the so-called lights-out order picking (LOOP) environments, the entire order picking is handled by a heterogeneous robot fleet with specialized functions for shelf picking (picker), transport (tugger), and pallet replenishment (forklift).

This UC EMPYREAN will showcase a fleet of robots, part of an Association, comprised of a picking robot that cooperates with the towing robots. The EMPYREAN Data Distributor service will be tuned to work in highly constrained network environments by developing intelligent ad-hoc routing strategies between robots to compensate for network losses. EMPYREAN Edge Storage service will also be utilized for low latency store and retrieve operations, coupled with multi-cloud storage service for scalability. Resource orchestration mechanisms based on swarm intelligence will be used for collaborative workload execution from the Associations' robots and edge resources.

5 EMPYREAN IMPACT

EMPYREAN will a highly impactful project in various directions:

- EMPYREAN will play a crucial role in the EU's strategic autonomy and its effort for edge/cloud dominance. EMPYREAN's Associations will enable any European organization, groups of organizations, or groups of EU citizens to make their own choices regarding the processing and storage of data in line with their interests and values. This will also strengthen their independence from cloud providers since an EMPYREAN Association can operate independently when required.
- EMPYREAN's unique technological advancements and their application in diverse key sectors (manufacturing, agriculture and warehousing) through the UCs and the candidate services and products identified by industrial partners will substantially contribute toward the realization of Europe's Digital Decade targets by 2030 while benefiting EU industry roadmap.
- EMPYREAN is committed to promote interoperability and portability, towards an EMPYREAN-based open ecosystem based on Associations that (i) renews and expands edge-based infrastructure foundations across Europe, (ii) supports the establishment of a mature, leading and competitive European supply chain on global market focusing on trustworthy data exchange and cybersecurity, and (iii) contributes to the shaping of worldwide standards and practices.
- EMPYREAN partners will promote the strategic industrial cooperation in AI/ML-based data storage and processing that can benefit the EU industry roadmap. Also, EMPYREAN aims to assess various business models and roles so that EMPYREAN-based services will significantly contribute to the global IoT-edge-cloud services market in the coming years, not only within the EU but also in non-EU regions.

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