The FORA European Training Network on Fog Computing for Robotics and Industrial Automation

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***Abstract*—Fog Computing for Robotics and Industrial Automation, FORA, was a European Training Network which focused on future industrial automation architectures and applications based on an emerging technology, called Fog Computing. The research project focused on research related to Fog Computing with applicability to industrial automation and manufacturing. The main outcome of the FORA project was the development of a deterministic Fog Computing Platform (FCP) to be used for implementing industrial automation and robotics solutions for Industry 4.0. This paper reports on the scientific outcomes of the FORA project. FORA has proposed a reference system architecture for Fog Computing, which was published as an open Architecture Analysis Design Language (AADL) model. The technologies developed in FORA include fog nodes and hypervisors, resource management mechanisms and middleware for deploying scalable Fog Computing applications, while guaranteeing the non-functional properties of the virtualized industrial control applications, and methods and processes for assuring the safety and security of the FCP. Several industrial use cases were used to evaluate the suitability of the FORA FCP for the Industrial IoT area, and to demonstrate how the platform can be used to develop industrial control applications and data analytics applications.**

***Index Terms*—Fog and Edge Computing, Industry 4.0, Deterministic Virtualization, Time-Sensitive Networking.**

I. INTRODUCTION

We are witnessing a new industrial revolution, *Industry 4.0*, which brings increased productivity and flexibility, mass customization, reduced time-to-market, improved product quality, innovations, and new business models. Although Europe has been undergoing a process of deindustrialization, 80% of its exports come from manufacturing, which is responsible for 33 million jobs. The European Commission has set as a target that 20% of value added should come from manufacturing.

Industrial systems use currently Operational Technology (OT), which relies on dedicated hardware and software that implement the control systems and process the control data with real-time requirements [1]. OT provides guarantees for real-time requirements and has a high degree of dependability. Examples of technologies used in OT are Industrial Personal Computers (IPCs), which are computers that have been ruggedized and configured for industrial applications, Programmable Logic Controllers (PLCs), which are computers that run real-time operations and control machines, and real-time safety-critical proprietary communication protocols.

The real-time requirements of industrial applications have so far been fulfilled via OT systems that are statically configured and use over-provisioning, with no support for dynamic changes and reconfigurations [2]. OT is not suited for business intelligence applications or Big Data and analytics due to technological constraints such as limited communication bandwidth and limited computation resources [2], [3]. Additionally, OT systems are often expensive due to the absence of open and standards-based solutions, the lock-in by specific vendors and the confines of their product development plans [2].

On the contrary, Information Technology (IT) uses different computation and communication technologies that are optimized for dealing with increased scalability and performance, storing and manipulating data. IT brings flexibility and capabilities for faster development and improvement with Cloud Computing, Artificial Intelligence (AI), and Big Data. However, IT is not directly applicable to industrial applications where non-functional properties such as timeliness and dependability have to be guaranteed [4].

A. *Fog Computing for the IT/OT Convergence*

The term "IT/OT convergence" refers to the IT and OT paradigms, which are using separated computation and communication solutions [2]. This convergence will bring effectiveness, flexibility, connectivity, interoperability, scalability, and capabilities for faster development and improvement with Cloud Computing, AI, and Big Data in industrial systems [5], enabling innovative Industry 4.0 solutions. Fog Computing is envisioned as an architectural means to realize the IT/OT convergence and deliver the vision of Industry 4.0. *Fog Computing* is a "system-level architecture that distributes resources and services of computing, storage, control and networking anywhere along the continuum from Cloud to Things" [6].

B. *Related Work and Contributions*

There has been already a lot of work on Fog Computing, and several surveys are available [6], [7]. Regarding reference architectures for Fog/Edge Computing, several have been proposed [8]–[10], including a couple that have been standardized [11], [12]. There are also commercial Fog/Edge Computing products and solutions on the market. However, there is limited work and solutions targeting application areas with real-time and safety-critical requirements.

Fog Computing for Robotics and Industrial Automation, FORA[1], was a European Training Network, which trained 15 Ph.D. candidates in Fog Computing technologies applied to industrial automation and robotics. FORA has delivered a comprehensive training program and has proposed a curriculum for this emerging area. For the details of the training program, we refer the reader to the FORA website. The Ph.D. candidates were also trained via their own research performed in collaboration between academic and industrial partners.

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[1] For details on the FORA project, see the FORA website, http://fora-etn.eu.

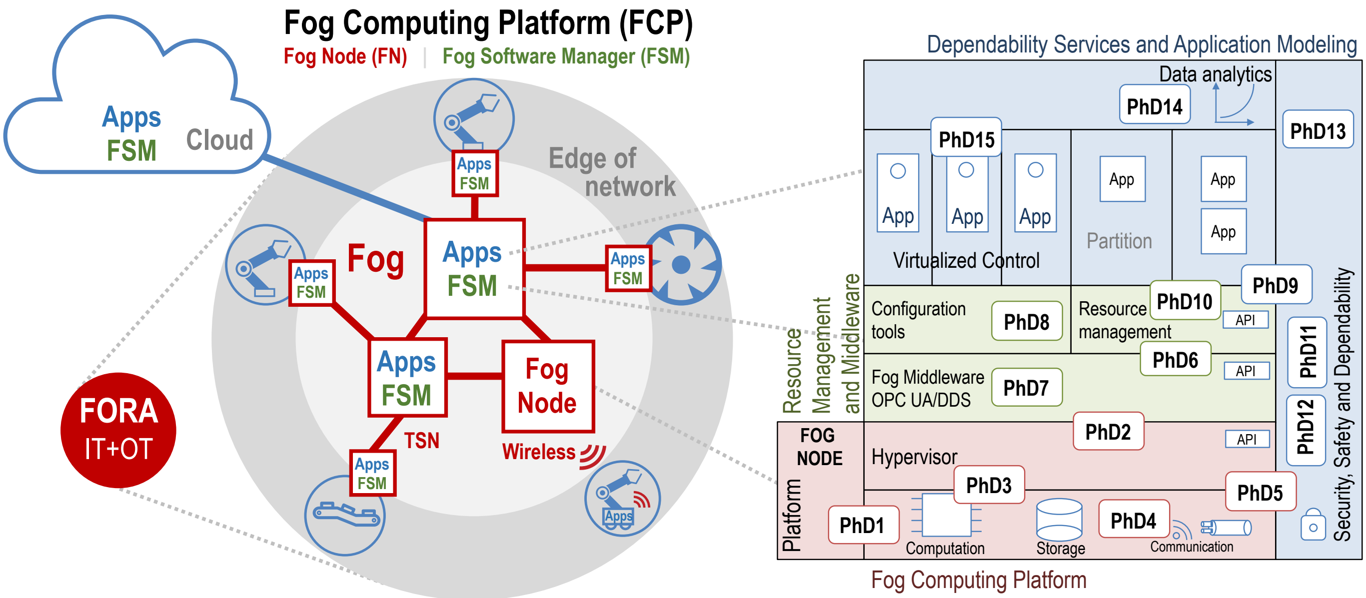

Fig. 1. Overview of the FORA Fog Computing Platform.

This paper reports the research results of the FORA project. We present the FORA Fog Computing Platform (FCP) that the project developed for Industrial Internet of Things (IIoT) applications, targeting mixed-criticality applications that have varying real-time and safety-criticality requirements. The FORA FCP is based on open standards and open source, achieves the IT and OT convergence, and enables novel Industry 4.0 applications and business models. The FORA FCP has been evaluated on several industrial use cases.

The paper is organized as follows. Sect. II presents the FORA FCP, each subsection focusing on a specific aspect of the FCP. Thus, Sect. II-A introduces the reference architecture model of the platform. Sect. II-B presents the development of the Fog Nodes, the hypervisors and the middleware. Sect. II-C outlines the communication infrastructure considered. Sect. II-D details the results related to resource management, orchestration and configuration of the platform. Sect. II-E discusses how the platform is used to implement mixed-criticality applications, and the services needed for dependability and data analytics. Sect. III presents how the FORA FCP was evaluated in several realistic industrial use cases. Finally, the last section presents our conclusions.

II. THE FORA FOG COMPUTING PLATFORM

Regarding the research results, the main scientific objective of the FORA project was to develop deterministic Fog Computing technologies to be used in industrial automation and robotics solutions for Industry 4.0. FORA has proposed an FCP reference architecture targeting IIoT applications, see Fig. 1 for an overview. The FORA FCP is focused on the virtualization of industrial control, which is implemented as control applications.

In contrast to the related work, the FORA FCP has been developed to support the hosting *mixed-criticality* applications, e.g., critical control applications that are *safety-critical* (failure may result in harm or loss) and *real-time* (their correctness depends on the time when the results are produced) and dynamic Fog applications. Critical applications are typically configured at design-time, whereas Fog applications may be migrating in and out of Fog Nodes (FNs) and have to be handled at runtime.

We[2] have developed a reference system architecture for Fog Computing based on deterministic virtualization and networking, and implemented open-source prototype Fog Computing Nodes. We have developed Resource Management mechanisms and middleware (the FSM in Fig. 1) for deploying scalable Fog Computing applications, while guaranteeing the non-functional properties of the virtualized industrial control applications. We have proposed approaches for assuring the safety and security of the Fog Computing platform. Finally, we have demonstrated how the platform can be used to develop industrial control applications and data analytics applications. The relation of the 15 Ph.D. projects with these topics is illustrated in Fig. 1.

A. FCP AADL Model

FORA has proposed an FCP reference architecture targeting IIoT applications. The FORA FCP reference architecture was defined using the Architecture Analysis & Design Language (AADL), which is a well-known architecture description language in the domain of real-time embedded systems [13]. The AADL model captures the main components and their interconnections.

There are several tools developed for the AADL language to facilitate modeling and analysis of embedded systems from different perspectives such as real-time performance, resource consumption, security, etc. The most well-known one is OSATE [14], which is an open-source Eclipse-based modeling framework. In addition to the modeling environment for the AADL language, it provides a set of plugins for validating and analyzing the architecture of the system under study. We have chosen to use AADL as the core language for modeling FORA FCP reference architecture due to its non-ambiguous

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[2] In this paper, the pronoun "we" refers to all the FORA Ph.D. candidates and their supervisors (each Ph.D. candidate had three supervisors, from both the academia and the industry). The FORA partners, Ph.D. candidates and supervisors are listed on the FORA website.

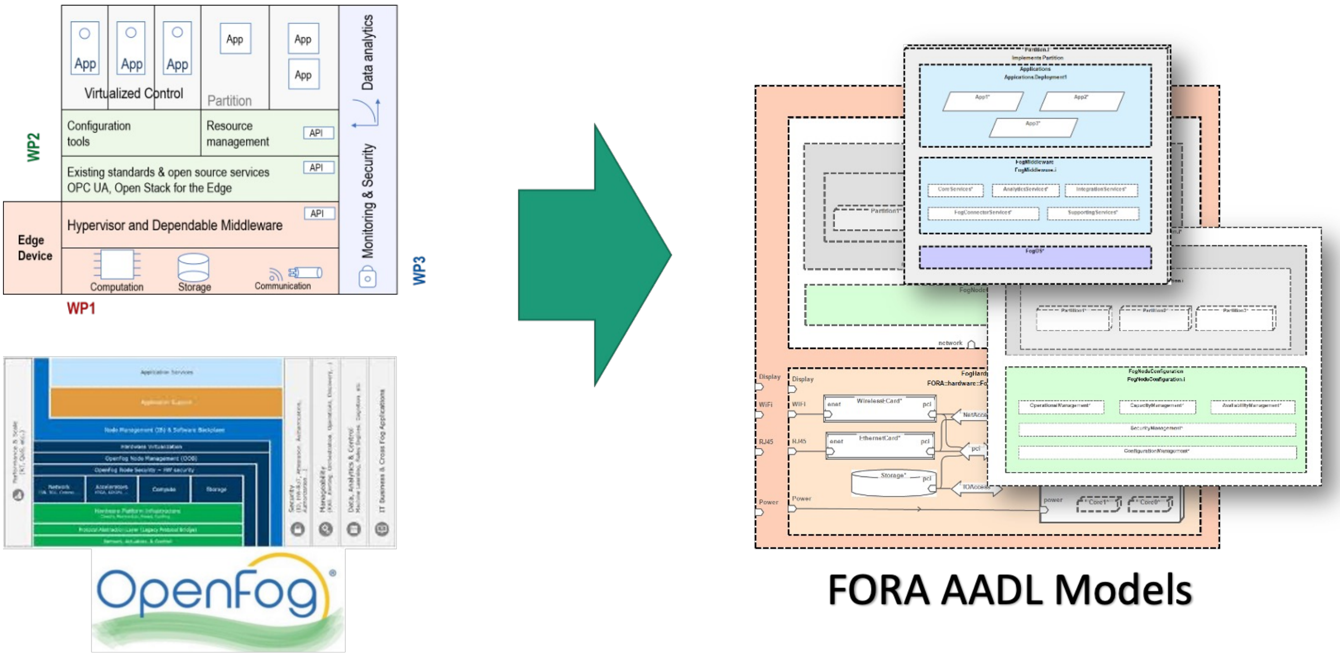

Fig. 2. The FORA AADL reference architecture definition process.

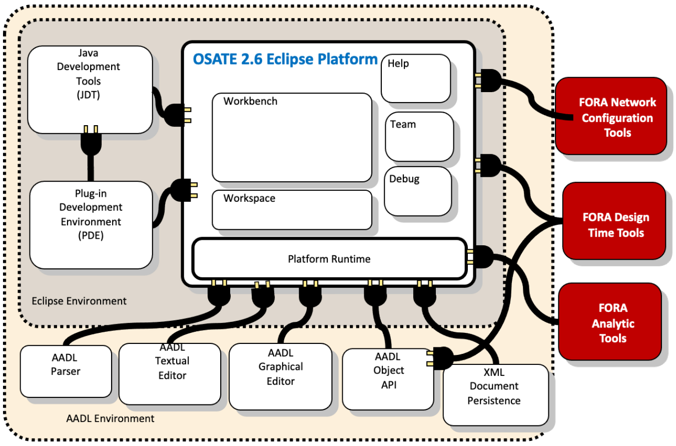

Fig. 3. OSATE for the FORA AADL modeling and analysis.

semantics, human readability, extensibility, and availability of a large set of analysis tools, e.g., scheduler, model checker, flow latency analysis, etc., as OSATE plug-ins, see Fig. 3.

The reference architecture was published as an open AADL model [15] aligned with the 1934-2018 IEEE Standard for Adoption of OpenFog Reference Architecture for Fog Computing [12], see Fig. 2 for an overview of the process. For the details on the AADL reference model we refer the reader to [15], which also presents the results of evaluating the reference architecture.

B. Fog Node, Hypervisors and Middleware

We have developed several versions of Fog Nodes (FNs), from low-end FNs operating close to the machines, sensors and actuators, to high-end FNs operating on the factory or enterprise level, connected to the Cloud[3]. FORA FNs come with an Intel x86-64 or ARM64 multicore processor that implements hardware virtualization extensions. FORA has also developed an open source FN by extending the T-CREST platform, which implements a time-predictable multicore that can synchronize on-chip networks with off-chip networks [16].

In FORA we advocate for the use of hardware-supported virtualization implemented via hypervisors, which separate mixed-criticality applications in different partitions (e.g., virtual machines, containers). We have evaluated several hypervisors such as Xen, KVM, ACRN and PikeOS. FORA FNs can use any hypervisor, but for safety critical applications we use PikeOS or Xen. We have developed a table-driven VM scheduler for Xen, a new clock mode and tracing hooks to handle safety-critical applications that have real-time requirements and have to synchronize their activities across FNs [17]. PikeOS has been extended with container capabilities and with continuous monitoring services for security [18].

Partitions can host any operating system, depending on the requirements of the applications. FORA applications communicate via a middleware developed in FORA and via standard interoperability solutions such as OPC Unified Architecture (OPC UA) and Data Distribution Service (DDS). OPC UA is a platform-independent secure and reliable industrial communication architecture for and semantic interoperability; DDS is a real-time interoperability data sharing solution for any kind of network.

For non-critical applications, FORA has developed a distributed fog middleware that self-organizes the FNs; two versions are available, a hierarchical setup and a peer-to-peer solution [19]. For critical applications, we are using an extension of MotionWise [20] developed for the fog. We have developed an OPC UA to DDS gateway to enable interoperability between a large class of applications [21]. These solutions can be used in conjunction with application layer protocols such as MQTT-SN and CoAP.

C. Deterministic Communication

There are several standardization efforts to bring timeliness and dependability to wired and wireless networks. The trend in wired networks is towards the use of Deterministic Ethernet solutions that integrate mixed-criticality traffic on the

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[3] Due to a lack of space, we have not added references for the products, solutions and standards; these can be found online based on their names.

same medium (e.g., IEEE 802.1 Time-Sensitive Networking (TSN), TTEthernet, AFDX, Profinet), using gateways towards legacy bus-based protocols (e.g., EtherCAT, Profibus). Future wireless networks will support time-critical communication, with redundant communication channels over 5/6G and Wi-Fi 6/7. The FORA FNs can support a variety of communication solutions, but our focus was on using TSN [22] for the wired communication targeting critical applications and low-energy long-range wireless communication [23] for non-critical applications.

TSN is a set of standards developed by the IEEE Time-Sensitive Networking Task Group of the IEEE 802.1 Working Group [22]. TSN defines mechanisms for the time-sensitive and dependable transmission of data over switched Ethernet networks. A TSN network guarantees bounded latency communication between FNs of an FCP and its environment. This guarantee enables the relocation of real-time critical applications from machines to FNs [15]. We have shown how different traffic shapers in TSN can be used and configured to support the mixed criticality and timeliness requirements of FORA applications [24]. FORA can also use WirelessHART or 5G for remote FN installations. In the future, it will be interesting to explore the use of Wireless TSN, as such a solution is envisioned in IEEE 802.11be (WiFi 7) and 5G 3GPP, which have industrial use cases [25].

D. Resource Management, Orchestration and Configuration

The goal of resource management and configuration techniques in the FORA FCP is to provide the necessary computation and communication resources to all applications, balance the overall resource utilization landscape, and provide real-time guarantees for critical applications [15]. To this end, the FORA FCP uses application deployment techniques [26] for submitting applications to the FCP and application migration methods [27] for migrating application between FNs. The FORA FCP provides cross-layer resource allocation mechanism [28], so that resources all over the FCP can be exploited if necessary and based on the demands of these applications, especially in the cases where the FCP is dynamic, i.e, FNs may enter and leave the FCP.

Besides, each FN implements an extensible configuration method [29] as a hierarchical scheduling framework represented as a tree, or a hierarchy, of levels, where each level represents a scheduling approach that assigns resources to the applications submitted to the FN, and the remaining resources are allocated from a parent level to its childrens' levels. The FORA extensible configuration method generates design-time configuration for critical control applications and can host dynamic Fog applications in runtime, see [29] for more details.

E. Services and Applications

The FORA FCP provides platform services for assuring the safety, security, and dependability of the FCP utilizing virtualization of computation and communications. The FCP implements the Precise Time Protocol Multi-Domain Aggregation for safe and secure clock synchronizations [30]. The security services are implemented as the lightweight authentication protocols for secure and efficient TLS Session Resumption, rTLS [31] and a host intrusion detection system integrated to the FCP [18]. The dependability services are based on a framework for recovery using fault-tolerant mechanism [32] and fault tolerant scheduling solutions for multi-criticality TSN traffic [33].

Additionally, the FCP offers applications for data analytics since it benefits form the FN's proximity to the sensors and machines. These applications perform data analysis using the distributed active learning method that distributes data processing among the FNs in a federated fashion [34], [35].

III. EVALUATION OF THE FORA FCP

In FORA, we have setup an technical management process to guide the development and evaluation of the FCP. The management process followed a structure typical to many European Union (EU) projects.

Use Cases: We started from a set of Use Cases (UCs), see below, which drove the identification of the project-level Key Performance Indicators (KPIs) and requirements.

UC1—*Electric drives as fog nodes*: Electric drives, alternatively called drives, are used to alter characteristics of the electric current such as frequency and voltage to control the motor speed, torque and position. In UC1, an electric drive is developed as an FN which receives required motor output via TSN network and is able to run various applications as well as the motor control application [44].

UC2—*Fog-based industrial robotics systems*: In a multi-robot system, a number of robot controllers are connected to each other to form a local network and programmed together to accomplish a process application such as welding and painting. In UC2, the controller functionality is provided by the FORA FCP and the robot controllers are connected via TSN [45].

UC3—*Data analytics using real-time machine data*: On modern factory floors, there is a multitude of machines and sensors producing huge quantities of data. In UC3 equipment such as PLCs and industrial PCs are replaced by FNs that can integrate their functionalities and has access to data. The FNs are connected to each other and to the management Cloud for data analytics using machine data [46].

Requirements, KPIs, metrics: The requirements are elicited based on industrial automation requirements for the implementation of the FORA FCP and provided the specific constraints and problems that had to be solved by the FORA FCP. Since the methodologies, platforms and tools developed in FORA would be applicable to various industrial areas, we consolidated the requirements into a coherent set of structured requirements, presented in detail in [47]. Table II presents the list of FORA project-level KPIs, see [47].

Technology Bricks: The concrete outputs of FORA were gathered as a set of "Technology Bricks" (TBs) that are implemented as prototypes and integrated via the FORA AADL model. The TBs are documented in the prototype deliverables [48]–[51], where for each TB we also list the repositories where the TBs are available for download[4].

Integration into demonstrators: The technical work was evaluated based on demonstrators, one for each UC. The initial integration work was done at the level of AADL modes. We modeled each demonstrator using AADL, highlighting the integration required. This was followed with the integration of the TB prototypes into the demonstrators, focusing on specific aspects of a use case.

Evaluation: The evaluation of the FORA FCP started from the KPIs that were identified during the requirements elicita-

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[4] See also http://www.fora-etn.eu/people/ for links to the prototype TBs.

TABLE I
FORA FCP EVALUATION OVERVIEW.

Research contribution	KPIs						
	Increased safety	Increased security	Reduce latency of virtualized critical control	Reduction in installation, configuration and software management costs	Reduction in hardware spending	Increased access to machine data edge analytics	Shorter time-to-market for new industrial applications
Fog Node, Hypervisors and Middleware							
Clock synchronization for virtualization [36]	✓	●	✓	✗	●	✗	✗
Time-triggered hypervisor [17]	✓	✓	✓	●	●	✗	✗
Container reconfiguration technique [21]	✗	✗	✗	✓	●	✗	✓
Deterministic Communication							
Time-triggered networking [16], [37]	✓	●	●	✓	✗	✗	●
Wireless networking [38]	✗	●	✓	●	✗	✗	●
TSN configuration optimization [24]	●	✗	✓	●	●	✗	●
Resource Management, Orchestration and Configuration							
Orchestration method [19]	✗	✗	✗	●	●	●	✓
Routing configuration optimization [39]	✗	✗	✗	✓	✓	●	✓
Control virtualization method [40]	✓	✗	✓	●	●	✗	✗
Extensible configuration optimization [29]	✓	✗	✓	●	✓	●	✓
Application migration method [27]	✗	✗	●	✗	●	✗	✓
Scheduling algorithm for elastic applications [41]	●	✗	✓	✗	●	✗	●
Services and Applications							
Fault recovery mechanism [32]	✓	✗	✗	✗	✓	✗	✗
Fault-tolerant architecture [42]	✓	✗	●	●	✓	✗	✗
Authentication method [31]	●	✓	✗	●	✗	✗	✗
Intrusion detection method [18]	●	✓	✗	●	✗	✗	✗
Fault detection mechanism in TSN [33]	✓	✗	●	●	●	✗	✗
Safety services [43]	●	✗	●	●	●	✗	✗
Decomposed deep training solution [35]	✗	✗	✗	✗	✗	✓	●
Data analytics solution [34]	✗	✗	✗	✗	✗	✓	●

TABLE II
KPIS COVERAGE IN FORA UCS.

KPIs	UC1	UC2	UC3
Increased safety	✓	●	✓
Increased security	✗	●	✓
Reduced latency of virtualized critical control	✓	✓	✓
Reduction in installation, configuration and software management costs	●	✗	●
Reduction in hardware spending	✓	✓	●
Increased access to machine data and edge analytics	●	✗	✗
Shorter time-to-market for new industrial applications	✓	✗	✗

tion process. To evaluate if a KPI was achieved, we identified how the KPI was addressed using TBs in the FORA UCs.

Table I shows an overview of the evaluation results. The columns are the FORA KPIs as defined in [47] and the rows are the research contribution of FORA[5]. For each of the KPIs in the table, ✗ means "no relevant/not considered", a ● means "relevant", and a ✓ means "strong relevance". We also present in Table II how the KPIs have been evaluated via the UCs.

The evaluation stage of the technical management process has concluded that the targets of technical project-level KPIs have been achieved. Due to a lack of space, this section has only presented an overview of the evaluation results. For details, the reader is directed to [44]–[46].

IV. CONCLUSIONS

This paper has presented the FORA Fog Computing Platform developed in the FORA European Training Network, targeting industrial and robotics applications. The FORA FCP is open and public, built on open source and open standards, e.g., TSN, OPC UA and 5G. FORA has made available the concrete results for the project, i.e., an open AADL reference architecture for Fog Computing, prototypes for the technology bricks developed, demonstrators for the use cases considered, and all the scientific publications and project reports, accessible via the project website. The FORA project has addressed Industry 4.0 challenges, from several different angles: system architectures, resource management and middleware, safety and security, industrial control and data analytics applications.

The universities have exploited the training materials and the results in their graduate-level teaching and by strengthening their academic profiles. The company partners in the project have exploited the results as follows. TTTech Computertechnik AG has exploited the results in their Nerve product, via an improved reference architecture focusing on deterministic virtualization solutions based on hypervisors and dynamic separation kernels. SYSGO GmbH has exploited the results in their PikeOS hypervisor product extended with hardware-assisted security techniques for safety and real-time critical devices, via an integration of the implemented techniques as module in the existing real-time hypervisor. ABB Ltd. has exploited the results to evaluate the benefits of the fogification of the next generation of industrial robotics applications, with the aim of transitioning from single core platforms to more complex architectures in automation applications.

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