Literature Review on Cloud-Based Service-Oriented Architecture for IEC 61499 Distributed Control Systems

Tomás Torres[1], Gil Gonçalves[2][a] and Rui Pinto[2][b]

[1]*Department of Informatics Engineering, Faculty of Engineering, University of Porto, Porto, Portugal*

[2]*SYSTEC, ARISE, Faculty of Engineering, University of Porto, Porto, Portugal*

Keywords: Cloud Computing, IEC 61499, Service-Oriented Architecture, Cyber-Physical Production Systems.

Abstract: The 4th Industrial Revolution has driven innovations in integrating Information Technologies (IT) with Operations Technologies (OT). This integration is essential for developing Cyber-Physical Production Systems (CPPS), which enhance distributed automation and optimize industrial production processes. The IEC 61499 standard facilitates this integration through its modularity, reusability, and interoperability, making it crucial for distributed control and system automation. Despite its advantages, IEC 61499's application is predominantly at the Edge layer, limiting its functionality in higher layers such as the Cloud. To address this gap, Cloud-based Service-Oriented Architectures (SoA) have emerged as a key study area, offering modular, reusable, and scalable services extending beyond the Edge layer. This paper presents a comprehensive literature review focused on expanding the IEC 61499 applications to reconfigure CPPS, by integrating Cloud layer services through SoA. The review highlights advancements, challenges, and future directions in achieving greater modularity, interoperability, scalability, and abstraction within distributed control systems. By synthesizing current research, this work provides insights into the potential enhancements of CPPS using a Cloud-based SoA approach.

1 INTRODUCTION

The 4th Industrial Revolution, or Industry 4.0, has revolutionized manufacturing by integrating digital technologies into production systems. At its core, Cyber-Physical Production Systems (CPPS) (Lins and Oliveira, 2020) enable seamless interaction between physical and digital components, driving automation and optimization in industrial processes. The IEC 61499 standard (Vyatkin, 2011) has emerged as a foundational framework for distributed control in CPPS, offering modularity, scalability, and interoperability at the Edge layer. However, its application remains limited to Edge-layer operations, hindering advanced functionalities like large-scale analytics and Cloud-based machine learning.

With the development of Industry 4.0, the connection between the various layers of the system has been an aspect to be explored through CPPS using interconnection between the multiple layers present in a system. This interconnection results in greater productivity and speed, improving both decision-making and data collection. Figure 1 shows this structure with the 3 main layers and their interconnectivity.

In this structure, the connections between the devices in the Edge layer collect physical information, update status, and share this information with upper layers.

While IEC 61499 has advanced CPPS by enabling modular and scalable control systems at the Edge layer, its application is limited when expanding to the Cloud layer, where more complex data management and processing capabilities are essential. Service-Oriented Architecture (SoA) (Dai et al., 2014; Siqueira and Davis, 2021) has gained prominence as a cloud-centric paradigm to address the limitation of only Edge-layer operations. By leveraging SoA's modularity and scalability, CPPS can extend beyond the Edge, enabling comprehensive system management across Edge and Cloud layers. This integration promises to enhance system flexibility, improve interoperability, and enable dynamic reconfiguration to meet Industry 4.0 demands.

This paper presents a comprehensive literature review to investigate existing approaches for integrating

[a] https://orcid.org/0000-0001-7757-7308

[b] https://orcid.org/0000-0002-0345-1208

Torres, T., Gonçalves, G. and Pinto, R.
Literature Review on Cloud-Based Service-Oriented Architecture for IEC 61499 Distributed Control Systems.
DOI: 10.5220/0013293400003950

In *Proceedings of the 15th International Conference on Cloud Computing and Services Science (CLOSER 2025)*, pages 174-181
ISBN: 978-989-758-747-4; ISSN: 2184-5042

Figure 1: The main Industry 4.0 layers and their interconnection (Siqueira and Davis, 2021).

SoA with IEC 61499, aiming to address the following objectives:

- Identifying the potential of combining SoA with IEC 61499 in CPPS.
- Analyzing existing frameworks and case studies.
- Proposing strategies to address gaps in scalability, real-time performance, and data synchronization.

This paper is organized to comprehensively explore the integration of SoA with IEC 61499 for distributed control systems. Following this introduction, Section 2 provides a theoretical framework and describes the key concepts of IEC 61499 and SoA, establishing the foundations for understanding their application within Industry 4.0. Section 3 presents a literature review, including the methodology, an analysis of IEC 61499 in distributed control, SoA principles for Cloud integration, and existing approaches for merging the two frameworks. Section 4 offers a discussion, synthesizing insights from the literature, identifying research gaps, and proposing future directions. Finally, Section 5 concludes the paper, summarizing the main findings and discussing implications for research and practice in the design of scalable, modular CPPS with integrated Cloud capabilities.

2 THEORETICAL FRAMEWORK

This section establishes the foundational concepts of IEC 61499 and SoA, essential for understanding their integration within CPPS to address Industry 4.0 challenges.

2.1 IEC 61499 Standard for Distributed Control

IEC 61499 is a standard for modular, event-driven control in distributed systems, employing Function Blocks (FBs) (Christensen et al., 2012; Lyu and Brennan, 2021) for reusability and scalability. Its decentralized approach supports real-time control at the Edge layer, enhancing flexibility in dynamic environments. However, its focus on Edge-layer operations limits advanced functionalities like large-scale analytics and machine learning, underscoring the need for cloud integration. Figure 2 exemplifies the architecture of an FB.

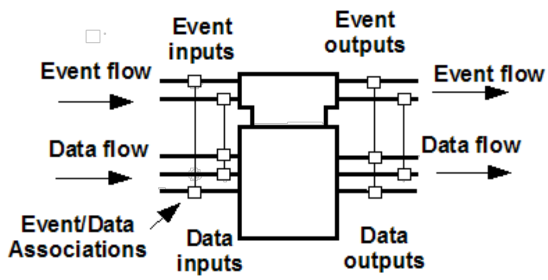

Figure 2: A Function Block structure (Christensen et al., 2012).

These FBs encapsulate logic and data in a modular format, allowing for reusability, portability, and scalability in complex systems. FBs can operate independently or be composed to form larger systems, enabling flexible and responsive control architectures suited to dynamic production environments typical of Industry 4.0.

IEC 61499 is especially advantageous for CPPS as it allows for real-time responses and improved interoperability between devices at the Edge layer. However, the standard's primary limitation is its confinement to Edge-layer operations, which restricts the scope for high-level data processing, scalability, and Cloud integration. Consequently, the full potential of CPPS cannot be achieved without an architectural framework that extends beyond the Edge, supporting advanced data analytics, storage, and processing in the Cloud layer.

2.2 SoA for Cloud Integration

SoA (Niknejad et al., 2020; Dai et al., 2016) organizes software into modular, loosely coupled services, enabling scalability, interoperability, and adaptability. In CPPS, SoA extends system capabilities to the Cloud, facilitating advanced analytics and real-time monitoring. According to (Siqueira and Davis, 2021), key SoA principles such as loose coupling, composability, autonomy, abstraction, and discoverability are central to enabling dynamic and scalable architectures suitable for CPPS, allowing seamless integration of diverse systems and third-party services, as represented in Figure3.

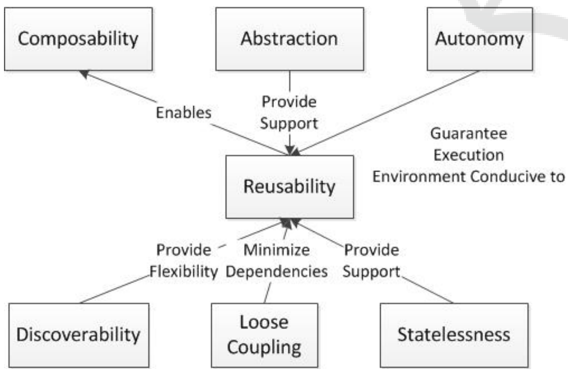

Figure 3: Service-oriented Architecture main principles (Dai et al., 2014).

By bridging IEC 61499's real-time capabilities with SoA's modularity and scalability, a holistic CPPS framework can emerge, addressing Industry 4.0's demands for smart and interconnected manufacturing systems. Despite its advantages, integrating SoA with IEC 61499 introduces challenges in maintaining real-time performance and consistent data synchronization.

3 REVIEW OF THE LITERATURE

This section provides an analysis of relevant literature focused on the integration of IEC 61499 with SoA in distributed control systems. The review is organized by thematic areas to capture various approaches and insights that contribute to the development of scalable, modular, and interoperable CPPS.

3.1 Literature Review Methodology

Regarding the search strategy, the review utilized main academic databases, namely IEEE Xplore, ScienceDirect, SpringerLink, ACM Digital Library, and Scopus, with the following initial query: [(”service-oriented architecture” OR ”soa”) AND ”iec 61499”]. This query ensures the inclusion of articles covering the two main scopes of the study's topic. Subsequently, to achieve greater thematic precision, the following query was used: [”cloud” AND (”cyber-physical production systems” OR ”cpps”)].

As a result, a limited number of studies were found, with approximately 344 articles identified in Scopus (the database that returned the largest number of studies) narrowed down to just 45 after adding additional queries. The full list of exclusion criteria follows:

- Not focused on integrating IEC 61499 with SoA.
- Lacked technical relevance or depth in solution proposal.
- Published before 2010.
- Do not address CPPS or distributed control systems.
- Do not present frameworks, case studies, or theoretical insights relevant to modularity, scalability, and interoperability in CPPS.

This approach allowed the synthesis of technological gaps, challenges, and possible directions for further study. Finally, the resulting works were collected and analyzed to conduct an initial assessment of the topic. Considering the number of articles identified, no highly rigorous methodology was applied, other than including more recent work (from 2010 onward), given that the intersection of both SOA and IEC 61499 topics is relatively new. Older articles cited were primarily those explaining foundational concepts of the technologies involved.

3.2 Integrating IEC 61499 with SoA in CPPS

Combining IEC 61499 with SoA introduces an architectural approach that leverages the strengths of both standards: the distributed control capabilities of IEC 61499 at the Edge and the scalable, modular service management of SoA in the Cloud. In this hybrid architecture, IEC 61499 manages real-time control and coordination at the Edge layer, while SoA facilitates Cloud-based services such as analytics, machine learning, and remote monitoring. The integration of IEC 61499 and SoA in CPPS offers multiple advantages:

- Enhanced Modularity: By segmenting functionalities into distinct, reusable services, the system can adapt more readily to changes or extensions in production requirements.
- Improved Interoperability: With SoA's standardized interfaces, CPPS components can more easily connect to external services and legacy systems.
- Scalability: Cloud-based services managed through SoA can be added or removed as needed, allowing the system to scale dynamically in response to operational demands.
- Abstraction and Flexibility: SoA encapsulates complex system functions as services, simplifying system design, maintenance, and evolution.

However, integrating these standards also presents challenges, particularly in achieving seamless communication and data synchronization between the Edge and Cloud layers, maintaining real-time performance, and ensuring security and reliability in distributed environments.

This theoretical framework sets the foundation for the literature review, which examines existing studies and solutions that explore this integration and identifies the gaps and opportunities for advancing CPPS design through a combined IEC 61499 and SoA approach.

Numerous frameworks and approaches have been proposed for integrating IEC 61499 with SoA. Next, some of the prominent methods discussed in the literature are presented.

3.2.1 DINASORE Framework

DINASORE (DIGI2-FEUP, 2024; Pereira et al., 2020) is a distributed platform that uses IEC 61499 for the reconfiguration of CPPS. Developed in Python, it utilizes 4DIAC (Strasser et al., 2008) and the OPC-UA protocol (Veichtlbauer et al., 2017) to create a modular and reconfigurable system architecture. DINASORE enables real-time reconfiguration of FBs through a graphical user interface, allowing for flexible and adaptable control systems. However, DINASORE currently operates primarily at the Edge layer, which limits its application in cloud-based environments. Expanding DINASORE with SoA could potentially enhance its scalability and allow for more extensive integration with external systems, providing additional services such as machine learning and advanced data analytics. Figure 4 demonstrates the architecture of DINASORE.

3.2.2 IEC 61499 Distributed Control Enhanced with Cloud-Based Web Services

(Demin et al., 2015) propose using NxtStudio (Deng, 2012) to model IEC 61499 control while leveraging HTTP for SoA message exchange. In their case study, a Pick-and-Place manipulator was integrated with Cloud computing services, enabling distributed data processing. The study demonstrated that integrating IEC 61499 with SoA could facilitate scalability and ease of maintenance in CPPS. However, limitations in cloud deployment performance indicate that further optimization is required to fully leverage cloud capabilities without compromising real-time control.

3.2.3 Arrowhead Framework for IEC 61499 Integration

The Arrowhead framework (Varga et al., 2016) offers a reference architecture based on SoA principles, specifically designed to facilitate integration and interoperability in IoT and CPPS environments. The framework is represented in Figure 5.

(Derhamy et al., 2016) explored the application of Arrowhead for orchestrating services in IEC 61499-based systems. Their case study on a Festo MPS manufacturing system (SE, 2024) that combines Arrowhead's orchestration and authorization systems with IEC 61499 provides greater control and flexibility. By bridging protocols between the Edge and Cloud layers, Arrowhead enables dynamic service management and enhances interoperability within distributed automation systems.

3.2.4 OPC UA and IEC 61499 Integration with Arrowhead

(Cabral et al., 2020) examined an integration model using OPC UA to enable seamless communication between IEC 61499-based control systems and Arrowhead's core services. This approach demonstrated

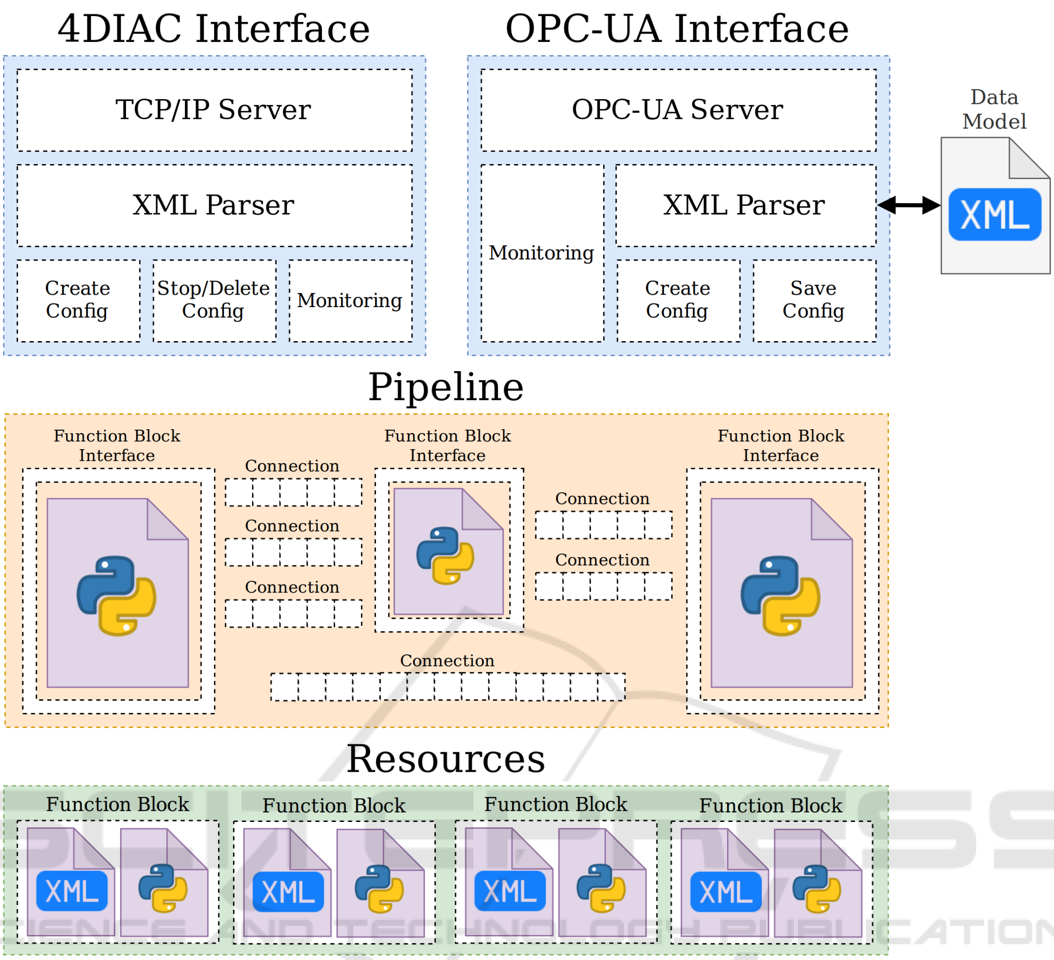

Figure 4: DINASORE architecture with Function Blocks, 4DIAC and OPC-UA (Pereira et al., 2020).

how OPC UA servers could facilitate interoperability by connecting Cloud-based services and Edge-level control systems. In their case study, a traffic light management system was used to test the integration, showing that this approach supports flexible service discovery and management. However, the study also highlighted challenges in synchronizing data across layers, particularly in real-time applications.

3.2.5 Manufacturing Service Bus as a SoA-Based Integration Platform

The Manufacturing Service Bus (MSB) (Schel et al., 2018) is an SoA-based integration platform that provides functionalities for reconfiguration, loose coupling, and asynchronous communication in production environments. Developed as an Enterprise Service Bus (ESB) for manufacturing, MSB supports multiple communication standards such as RESTful API, WebSocket API, OPC UA, and MQTT (Breunig and Götz, 2018). The modularity and protocol support offered by MSB makes it a promising solution for integrating IEC 61499-based systems with cloud services, especially in highly dynamic CPPS environments.

4 DISCUSSION

This section synthesizes the findings from the literature review, focusing on the potential and challenges of integrating IEC 61499 with SoA in distributed control systems. The discussion is organized around key themes, including modularity, interoperability, scalability, and the real-time performance required for effective CPPS.

4.1 Synthesis of Findings

The literature reveals multiple approaches to integrating IEC 61499 with SoA, each contributing unique

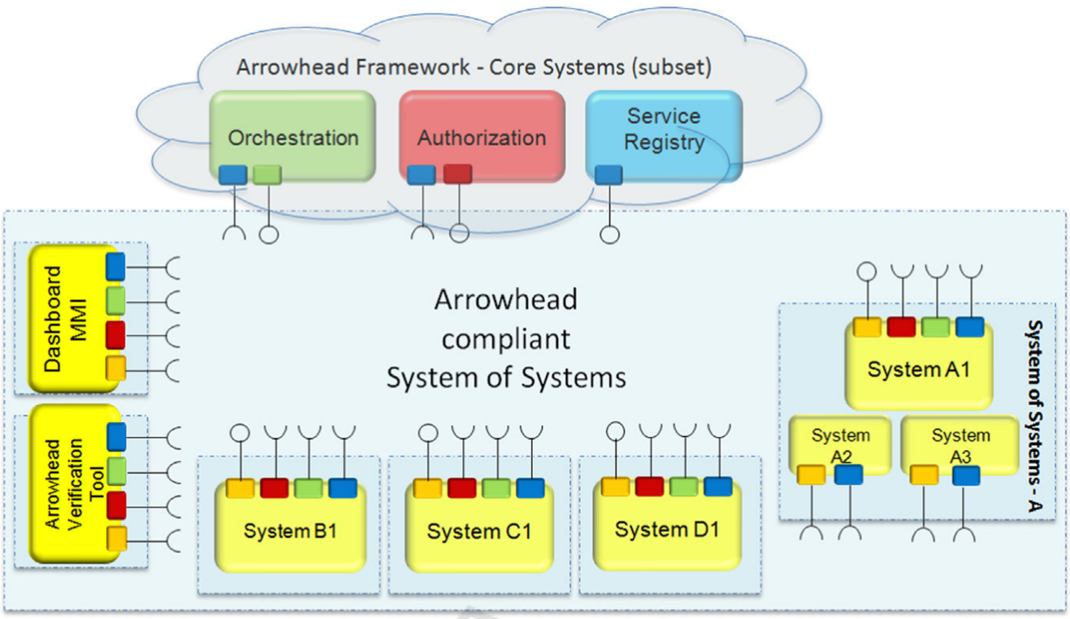

Figure 5: Arrowhead main Core Systems integrated with Systems of Systems (Varga et al., 2016).

solutions and insights, as represented in Table 1.

Modularity is a key benefit of integrating IEC 61499 and SoA. IEC 61499's function blocks enable reusable, adaptable control logic at the Edge layer, while SoA's loosely coupled services enhance flexibility at the Cloud level. Frameworks like DINASORE and Arrowhead demonstrate how modularization improves system adaptability, simplifies maintenance, and supports independent updates and scaling.

Interoperability is another significant advantage, as protocols like OPC UA and frameworks such as Arrowhead facilitate seamless communication through service discovery, orchestration, and authorization systems. However, consistent data exchange and protocol bridging remain challenges, particularly in heterogeneous environments.

SoA's Cloud-based service management enhances scalability, enabling systems to adjust dynamically to shifting production demands and support more devices and data streams without architectural overhauls. Frameworks like the Manufacturing Service Bus (MSB) illustrate how SoA supports flexibility through multi-protocol communication and asynchronous models. Despite these advantages, ensuring scalability without compromising real-time performance or data synchronization remains a critical challenge.

While frameworks like DINASORE and Arrowhead highlight the potential of SoA for CPPS, they also underscore the need for improved integration strategies to balance modularity, scalability, and real-time performance. Advancing these frameworks requires addressing technical challenges in data consistency, communication, and latency across Edge and Cloud layers.

4.2 Identification of Research Gaps

Despite the advances noted in the literature, several research gaps remain in the integration of IEC 61499 with SoA for CPPS. Real-time performance is a significant challenge, as many Cloud-based SoA services may not support the low-latency requirements of real-time control systems. While IEC 61499 is designed for event-driven, real-time operation at the Edge, extending this capability to the Cloud layer without latency disruptions is a challenge. Future research should investigate optimization techniques or hybrid solutions that maintain real-time capabilities across both Edge and Cloud layers.

Another notable gap is in security and data privacy. Although some frameworks, such as Arrowhead, address aspects of authorization and secure communication, a comprehensive security strategy for CPPS that integrates both IEC 61499 and SoA is still lacking. Given the sensitivity of industrial data, especially in multi-vendor environments, future research should address mechanisms for secure data exchange and robust authentication protocols across the Edge and Cloud.

Data synchronization and consistency across layers also pose challenges, particularly in distributed control systems that rely on continuous, real-time data flow. Several studies discuss protocol bridging (e.g.,

Table 1: Summary and Comparison of Literature Findings.

Study	Framework	Integration Focus
(Demin et al.,2015)	NxtStudio with IEC 61499 and SoA.	Cloud-based web services.
(Derhamy et al.,2016)	Arrowhead with IEC 61499.	Orchestration and protocol bridging.
(Cabral et al.,2020)	OPC UA and IEC 61499 with Arrowhead.	Cloud-enabled service management.
(Breunig & Götz,2018)	MSB with XML-RPC.	Multi-layered communication.
(Varga et al.,2016)	Arrowhead core systems.	System of systems for Cloud automation.
(Pereira et al.,2020)	DINASORE with IEC 61499.	Real-time reconfiguration of FBs.

OPC UA integration), but real-world implementations often face issues with data lag or inconsistency when operating across Edge and Cloud environments. Developing more efficient data handling and synchronization methods could further enhance the reliability of IEC 61499-SoA integrated systems.

4.3 Future Directions

Future research should focus on hybrid architectures that seamlessly integrate Edge and Cloud capabilities. Critical real-time processing can be offloaded to the Edge layer, while non-time-sensitive tasks like analytics and machine learning are handled in the Cloud. This approach retains IEC 61499's low-latency advantages at the Edge while leveraging SoA's scalability and processing power in the Cloud.

Developing standardized interfaces and protocols for interoperability between IEC 61499 and SoA is another essential direction. Industry collaborations can help establish standards for protocol bridging, data formats, and communication models, enabling efficient and secure data exchange across heterogeneous CPPS devices and reducing integration complexity.

Lastly, security must be prioritized in IEC 61499 and SoA integration. Frameworks with robust encryption, authentication, and access control are critical for ensuring safe deployment in industrial environments. Multi-layered security protocols can mitigate risks in distributed systems, particularly as they scale into cloud environments.

5 CONCLUSIONS

This paper presents a comprehensive review of integrating IEC 61499 with SoA in CPPS, a promising approach to enhancing scalability, modularity, and interoperability in Industry 4.0. The review examines the foundational principles of IEC 61499 and SoA, highlights their complementary strengths, and analyzes frameworks and case studies that illustrate the benefits of their integration for distributed control systems.

The findings demonstrate that combining IEC 61499 and SoA addresses key challenges in CPPS. Reusable function blocks (FBs) enhance modularity, while SoA's scalable, loosely coupled architecture enables flexible Cloud-based services. This integration facilitates seamless communication between CPPS components and external systems, allowing distributed systems to adapt more effectively to dynamic industrial requirements.

Despite these advantages, several challenges remain. Real-time performance in Cloud-integrated systems is a critical issue, as many SoA frameworks are not optimized for the low-latency needs of real-time applications. Additionally, security, data synchronization, and standardized protocols require further development to ensure secure and reliable integration of IEC 61499 and SoA across distributed systems.

In conclusion, this review underscores the transformative potential of integrating IEC 61499 and SoA for Industry 4.0 applications while outlining a roadmap to overcome current limitations. Advancing these integrations will enable the development of flexible, scalable, and secure CPPS capable of meeting modern industrial demands. Future research should focus on hybrid architectures, robust security frameworks, and efficient data-handling mechanisms to bridge the gap between Edge and Cloud layers, unlocking the full potential of CPPS for smart manufacturing and beyond.

ACKNOWLEDGEMENTS

This work results from Agenda "GreenAuto: Green innovation for the Automotive Industry", nr. C644867037-00000013, investment project nr. 54, financed by the Recovery and Resilience Plan (PRR) and by the European Union - NextGeneration EU.

REFERENCES

Breunig, D. and Götz, B. (2018). Simultaneously acting network layers in an iec 61499 modeling system at the example of eclipse-4diac, the cloud-oriented msb and xml-rpc. *Procedia CIRP*, 72:928–933.

Cabral, J., Dorofeev, K., and Varga, P. (2020). Native opc ua handling and iec 61499 plc integration within the arrowhead framework. In *2020 IEEE Conference on Industrial Cyberphysical Systems (ICPS)*, volume 1, pages 596–601.

Christensen, J., Strasser, T., Valentini, A., Vyatkin, V., and Zoitl, A. (2012). The iec 61499 function block standard: Overview of the second edition.

Dai, W., Huang, W., and Vyatkin, V. (2016). Enabling plug-and-play software components in industrial cyber-physical systems by adopting service-oriented architecture paradigm. In *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, pages 5253–5258.

Dai, W. W., Vyatkin, V., and Christensen, J. H. (2014). The application of service-oriented architectures in distributed automation systems. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 252–257.

Demin, E., Patil, S., Dubinin, V., and Vyatkin, V. (2015). Iec 61499 distributed control enhanced with cloud-based web-services. In *2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, pages 972–977.

Deng, Y. (2012). *Applying IEC61499 for Building Management System*. PhD thesis, ResearchSpace@ Auckland.

Derhamy, H., Drozdov, D., Patil, S., van Deventer, J., Eliasson, J., and Vyatkin, V. (2016). Orchestration of arrowhead services using iec 61499: Distributed automation case study. In *2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1–5.

DIGI2-FEUP (2024). Dinasore: Distributed industrial automation and control system. https://github.com/DIGI2-FEUP/dinasore. Accessed: 2024-11-16.

Lins, T. and Oliveira, R. A. R. (2020). Cyber-physical production systems retrofitting in context of industry 4.0. *Computers & industrial engineering*, 139:106193.

Lyu, G. and Brennan, R. W. (2021). Towards iec 61499-based distributed intelligent automation: A literature review. *IEEE Transactions on Industrial Informatics*, 17(4):2295–2306.

Niknejad, N., Ismail, W., Ghani, I., Nazari, B., Bahari, M., and Hussin, A. R. B. C. (2020). Understanding service-oriented architecture (soa): A systematic literature review and directions for further investigation. *Information Systems*, 91:101491.

Pereira, E. M., dos Reis, J. P. C., and Gonçalves, G. (2020). DINASORE: A Dynamic Intelligent Reconfiguration Tool for Cyber-Physical Production Systems. In *SAM IoT*, pages 63–71.

Schel, D., Henkel, C., Stock, D., Meyer, O., Rauhöft, G., Einberger, P., Stöhr, M., Daxer, M. A., and Seidelmann, J. (2018). Manufacturing service bus: An implementation. *Procedia CIRP*, 67:179–184. 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 19-21 July 2017, Gulf of Naples, Italy.

SE, F. D. (2024). Didactic infoportal. [Online; accessed 2024-11-16].

Siqueira, F. and Davis, J. G. (2021). Service computing for industry 4.0: State of the art, challenges, and research opportunities. *ACM Comput. Surv.*, 54(9).

Strasser, T., Rooker, M., Ebenhofer, G., Zoitl, A., Sunder, C., Valentini, A., and Martel, A. (2008). Framework for distributed industrial automation and control (4diac). In *2008 6th IEEE International Conference on Industrial Informatics*, pages 283–288.

Varga, P., Blomstedt, F., Ferreira, L., Eliasson, J., Johansson, M., Delsing, J., and Martínez de Soria, I. (2016). Making system of systems interoperable – the core components of the arrowhead framework. *Journal of Network and Computer Applications*, 81.

Veichtlbauer, A., Ortmayer, M., and Heistracher, T. (2017). Opc ua integration for field devices. In *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)*, pages 419–424.

Vyatkin, V. (2011). Iec 61499 as enabler of distributed and intelligent automation: State-of-the-art review. *IEEE Transactions on Industrial Informatics*, 7(4):768 – 781. Cited by: 325.