Clock Synchronization in Future Industrial Networks: Applications, Challenges, and Directions

Rahul Nandkumar Gore, Elena Lisova, Johan Åkerberg, Mats Björkman
Mälardalen University, Västerås, Sweden
{Rahul.Nandkumar.Gore, Elena.Lisova, Johan.Akerberg, Mats.Bjorkman}@mdh.se

***Abstract*—Time synchronization is essential for the correct and consistent operation of automation systems. An inaccurate analysis being a consequence of improper synchronization, can affect automation functions, e.g., by producing false commands and warnings. Industrial systems are evolving from the rigid automation pyramid to a flexible and reconfigurable architecture due to market evolution. The new trends in Cyber-Physical-Systems (CPS), Industry 4.0, and Internet of Things (IoT) are enabling this evolution. Citing a need to understand the future synchronization requirements, this paper envisions the architecture, communication network, and applications of future automation systems. Built on this vision, the paper derives the future needs of synchronization and analyzes them with state-of-art synchronization means. Based on the analysis, we envision the future of synchronization systems for automation systems.**

***Keywords*—Time Synchronization, NTP, PTP, Cyber Physical Systems, Industrial Automation, Factory Automation, Industrial Networks, Cloud robotics, Drones, UAV, Smart Grid**

I. INTRODUCTION

To shorten product life cycles and time to market, the next generation of industrial automation systems must be built with high flexibility and a possibility of fast reconfiguration. The traditional paradigm of industrial automation is not satisfactorily suitable to keep pace with the evolving business scenarios. The concepts of CPS and IoT promise the integration of internet and operational traffic for next-level distributed automation [1]. The future industrial automation systems envision to use Service-Oriented-Architectures (SOAs) to deal with flexibility and reconfiguration issues [2]. The paradigm shift in the architecture of future industrial automation systems opens doors for the implementation of advanced and futuristic applications.

An essential aspect of implementing monitoring and control applications in industrial systems is to meet their synchronization requirements. Synchronization of devices, controllers, subsystems, and communication infrastructure with adequate accuracy and precision levels is required for efficient and accurate applications. While the proposed architecture of future automation systems enables the possibility of new applications, their success depends on the performance of synchronization mechanisms. Consequently, there is a need to develop future synchronization requirements for industrial automation systems based on predicted applications.

Currently, industrial networks use two types of synchronization: direct synchronization used by Global Positioning Systems (GPS), Inter-range instrumentation group time codes B (IRIG-B) [3], One Pulse Per Second (1PPS) and synchronization over a network used by Precision time Protocol (PTP), Network Time Protocol (NTP), Simple Network Time Protocol (SNTP). All the existing synchronization techniques have different specifications. It is paramount to confirm if the existing synchronization systems are sufficient to meet the synchronization needs of future industrial applications, as the emerging applications may need enhanced or improved synchronization mechanisms.

The scope of this paper is to unveil future synchronization needs and assess the readiness of state-of-practice synchronization mechanisms to support the future industrial automation evolution. The learnings from this work would dictate the architectures of future synchronization systems, which is planned as future work.

The contribution of the paper is as follows:
(1) There is no comprehensive literature that looks into the synchronization needs of future industrial automation systems. The available literature describes individual synchronization challenges, such as assessing the feasibility of using wireless networks for synchronization [4], improving fault tolerance [5], and achieving accurate synchronization in industrial networks [6]. In contrast, this paper brings out the future synchronization requirements in automation systems.
(2) We compare the future synchronization requirements with specifications of current synchronization techniques. This analysis is a basis for deciding whether the current synchronization means are sufficient for future industrial applications.
(3) The future synchronization for industrial automation systems can be envisioned based on the future synchronization requirements and state-of-the-art methods.

The paper is structured as follows. Section II envisions the future industrial automation systems, their architecture, and emerging applications. Section III lists the synchronization needs for future automation systems. Section IV discusses if current solutions can meet future synchronization requirements and indicates possible technology directions.

978-8-8872-3747-4

II. FUTURE INDUSTRIAL AUTOMATION SYSTEMS

Industrial automation systems have evolved from fully mechanical to electro-mechanical to electronic systems. In the last few years, there has been an extensive discussion about the evolution of industrial automation systems.

A. Vision

The vision of future industrial automation systems is characterized by miniaturization, fully automated operation, minimum/no operator interference, self-configuring, self-organizing and self-healing automation systems [2].

The reason for today's ample and centralized factories is the localized availability of skills, personnel, and technology. This has resulted in a long time to market due to the transport of raw material to the factory and manufactured products to market over long distances. The factory of the future will take advantage of the global availability of skills, technology. This means the factories do not need to transport raw material or products over longer distances. This would also result in compact, smaller manufacturing units that could be movable as well. Thus, future automation systems are well envisioned. The technology advances have ensured that the journey to future industrial automation systems has already begun [7].

B. Technology Enablers

Industrial automation can generate explosive growth with advancements in technologies related to new inflection points such as machine learning, artificial intelligence (AI), nanotech, wireless everything, blockchain, 3D printing technologies, and complex adaptive systems [8]. Industry 4.0 promises to facilitate the increased adoption of industrial networks in the future. The main technology trends that will enable this are as follows:

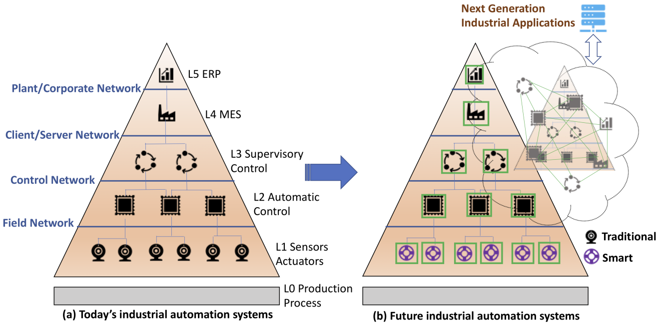
(1) TSN: TSN is a set of standards that defines mechanisms for the transmission of time-sensitive data over deterministic Ethernet networks. With TSN as underlying communication infrastructure, Open Platform Communication Unified Architecture (OPC UA) could become the unified approach to industrial communication that has been sought for the last few decades.

(2) Industrial wireless networks: The existing wireless solutions deployed in automation systems provide soft real-time performance; hence, they are used for less critical applications. There are continuous research efforts to improve the adoption of wireless networks in industrial automation functions.

(3) 5G Cellular networks: The capabilities of 5G extend beyond mobile broadband with increasing data rates, higher reliability, and very low latencies. As a step change from previous generations, 5G networks have put a strong focus on machine-type communication and IoT.

(4) Software-Defined Networking (SDN): SDN is the networking concept of segregating the control and forwarding plane of the network to enable centrally managed network for optimization, scalability, and robustness. SDN will ensure fast and dynamic reconfiguration of production lines, simultaneous handling of separate network infrastructures, with improved security and reliability.

C. Architecture

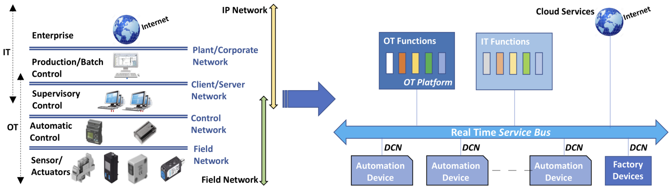


(a) Today's industrial automation systems

(b) Future industrial automation systems

Fig. 1. Envisioned industrial automation systems journey

The future industrial automation system will be fully equipped with actors, sensors and CPSs [9]. In the factory, robots, sensors, controllers, raw material, and databases will seamlessly talk to each other. The factory of the future will partly break the traditional automation pyramid. Through the usage of CPSs in smart factories, today's strictly separated automation hierarchy shown in Fig. 1(a) will be replaced by decentralized, self-organized, and networked services shown in Fig. 1(b). Data, functions, and services are available for each entity in the CPS and each entity can interact with a service. The different levels of future automation systems would be connected seamlessly, and the information would flow from top to down or reverse way. Thus the decisions can be made at a down level rather than at the topmost level. This results in an increase in flexibility and productivity compared to the traditional automation pyramid.



(a) Today's industrial network

(b) Future industrial network

Fig. 2. Envisioned industrial network transformation

Fig. 2 depicts the architecture of the existing communication hierarchy shown in Fig. 2(a) and envisioned Industrial CPS shown in Fig. 2(b), which is compliant to the automation "pyramid" view, but complement it with flat information driven modern system and enhance its integrability via modern software engineering practices [10]. The future communication architecture would comprise of the following major components:

(1) Operational Technology (OT) Platform: The new hardware and software-based platform would use open

source and virtualization technologies. The platform will be equipped with real-time capabilities.
(2) Service Bus: The real-time data services would be enabled by the service bus. The bus facilitates a set of data services that will tie the system together.
(3) Distributed Control Node (DCN): This highly distributed edge module can participate in a distributed control execution environment. In most cases, a DCN will regulate just a single control loop. Over time, existing control system functions may migrate either to the DCNs or the real-time operations platform.

The new architecture will adopt a rigorous software design framework and modern software engineering practices so that new applications, required by modern, fast-paced industrial environments, can be rapidly realized.

D. Driving Applications

The future synchronization requirements are driven by the future automation applications and the kind of synchronization they require for efficient operation. To get the insight into future synchronization needs, we considered the following representative applications from a list of applications widely highlighted by the community to be the future of the industrial automation [11].

1) Cloud Robotics: Cloud robotics leverages cloud technologies like distributed computing and cloud storage along with robotics. Such a robot is equipped with all the cloud offerings, e.g., storage, powerful computation, and communication resources, resulting in a moderately lightweight, intelligent, and inexpensive robot. With multiple robots, a robotic cloud system enables intensive and complicated tasks to be carried out efficiently and in a cooperative manner [12].

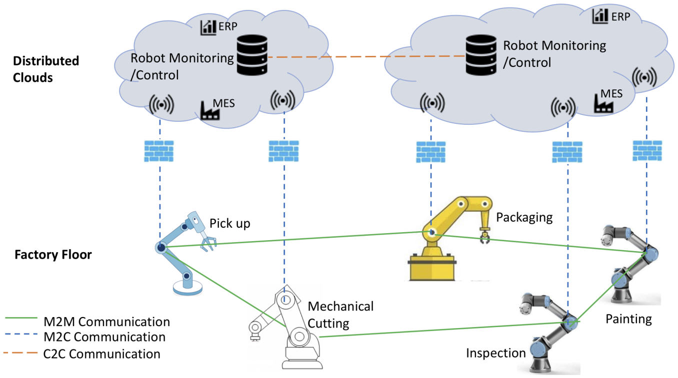


Fig. 3. Cloud control of factory robots

Fig. 3 shows a typical use case of factory robots controlled by cloud technology. Various robots used for pick-up, assembly, cutting, packaging, and painting coordinate with each other via machine-to-machine (M2M) communication and are connected to clouds via machine-to-cloud (M2C) communication. In the case of distributed clouds, inter-cloud communication takes place via cloud-to-cloud (C2C) communication. Synchronization among robots, between robots and factory subsystems such as actuators, cloud infrastructure, and distributed cloud systems, needs to be established to carry out the monitoring or controlling activity from the cloud. Traditional vendor-specific approaches for synchronization are complex and hybrid with the accuracy of hundreds of milliseconds. There is a need for a standard, more accurate synchronization means (up to microseconds) if we have to gain from robot and cloud technology integration.

2) Drones in Automation: Unmanned-Aerial-Vehicles or drones open up new opportunities in industries such as mining, oil, gas, and other large industrial facilities. Drones have a significant advantage in terms of precision, convenience, and cost over more traditional solutions such as satellites and helicopters. Drone-mounted sensors can be used to capture an impressive array of data, paving the way for digitalization. An automated drone system increases efficiency by eliminating the need for a drone operator while providing seamless access to periodically captured real-time data.

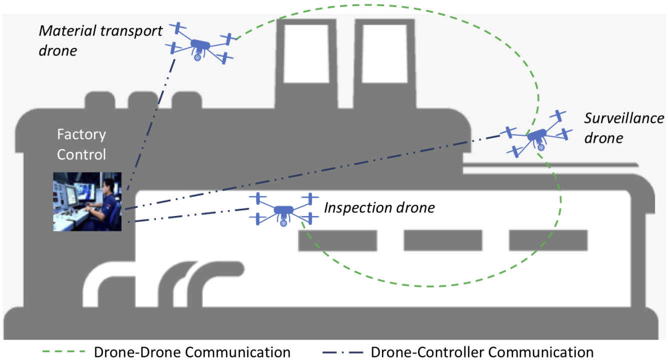


Fig. 4. Drones in automation

Fig. 4 demonstrates the use of drones in factory automation systems for collecting data from various subsystems of a factory. The data can be used to carry out functions such as inventory management, aerial monitoring, and periodic maintenance of equipment. From a synchronization perspective, drones need to be synchronized with each other and with the subsystems they are monitoring, and the controllers. Drones communicate with each other, and factory subsystems over wireless networks. This calls for robust synchronization over a wireless network with accuracy up to microseconds for the effective utilization of the drone technology in factory automation.

3) Smart Grid Wide Area Monitoring Protection and Control: A smart grid is an autonomous and supervisory control system for power network that ensures bidirectional, seamless information and power flow from all nodes of power network to end-users. A smart grid has established itself as an answer to reliability and stability issues in today's power grid. Carrying out monitoring, protecting the grid on a real-time basis, and responding to contingencies are critical. Understanding the health of the grid and continuous monitoring of it to prevent damage is an integral part of a smart grid journey.

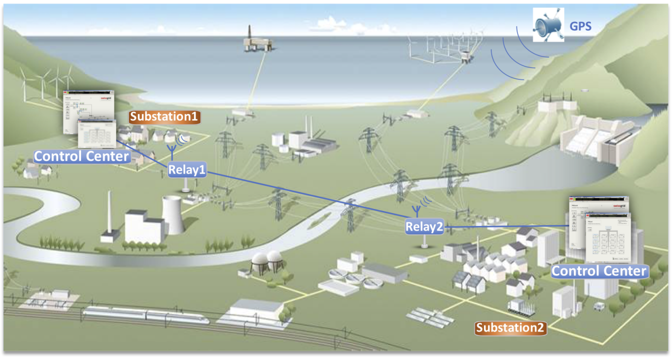


Fig. 5. Wide area control application in a smart grid

Fig. 5 shows the typical use case of the smart grid, i.e., monitoring and controlling a power-line between two substations that are hundreds of kilometers apart. The power-lines need to be monitored for any faults such as a tree falling on the power-line. Moreover, localization of faults is important for a maintenance crew to go to the correct place and fix it. For fault localization, the sub-station Intelligent-Electronic-Device (IED) at one end, utilizes the voltage and current samples obtained from the other end substation. The accuracy of a fault localization algorithm depends on how closely the IEDs at different sub-stations are synchronized. Thus, clock synchronization with accuracy up to microseconds is essential to correlate power quality and high sampling frequency measure, and generally coordinate any distributed actions.

III. SYNCHRONIZATION IN FUTURE INDUSTRIAL AUTOMATION SYSTEMS

Based on the examples of applications that are most likely to be implemented in future automation systems, we identified the parts of future network architecture required for these applications to be realized, as shown in Table 1. The synchronization requirements were derived for each of these applications. The synchronization methods to achieve synchronization needs were also identified.

The mapping of applications with a future industrial automation architecture and communication network has allowed us to come up with the following synchronization requirements.

1) Relative synchronization: Synchronization in typical industrial plants is based on the principle of relative synchronization. All entities in a plant such as field devices, controllers, IEDs and other operator-facing computers are synchronized to each other [13]. The centralized timing system chooses one device as a master, and most of the devices receive timing information from the master. The slave devices listen to the master device and synchronize their clocks to the master device. Improving the accuracy of existing relative synchronization methods to integrate legacy industrial devices to TSN network is an immediate need from the industry and research community [14].

2) Absolute synchronization: For most of today's applications, a relative synchronization approach is sufficient. However, the emerging applications, such as remote monitoring and controlling, require external devices to be connected to plant devices. External devices also need to collect data from plant devices and make decisions based on that data. Such applications require plant devices to be aware of the absolute time in order to support remote operations. The most popular way of achieving absolute synchronization is to use GPS as a time master. However, the identified failure modes and cost associated with installation and maintenance of GPS, makes it an essential area for further investigations to find alternatives to GPS [15].

3) Synchronization over an IP network: Network synchronization deals with the distribution of time and frequency over a network of clocks, including clocks spread over a wide area. Ethernet transport has become standard due to lower operation costs and the convergence of fixed and mobile services. The network evolution toward IP packet switching has led to increased interest in time synchronization using packet-based methods. Most industrial applications use IP networks for their system function. The packet delay variance, losses over IP network, and network dynamics affect the timing accuracy. Security is also a major point of concern for communication over IP networks. All these challenges make a case for precise and secured synchronization over IP network for industrial applications.

4) Synchronization over wireless networks: Wireless networks are an increasingly important medium for distributed control systems. As wireless applications grow more diverse and sophisticated, synchronization among wireless nodes has emerged as a common requirement of many applications. For example, synchronization is essential in sensor networks, which collect data from a physical environment and then tag it with the time of its occurrence. Synchronization is also needed in high-level applications to timestamp and order events and signals, and for security purposes. The wireless media presents a unique set of challenges such as network dynamics and energy consumption. The enhanced version IEEE 802.15.4e (the basis of Zigbee, ISA100.11a, WirelessHART, MiWi, 6LoWPAN protocols) has introduced five different MAC behavior modes suit to industrial applications. The research directions, such as new stack development at Physical and MAC layers, and full-duplex modes promise to improve wireless networks' performance and their adoption to industrial use cases [8].

5) Synchronization in a distributed cloud network: Cloud integration with IoT has facilitated convenient and

TABLE I. FUTURE SYNCHRONIZATION REQUIREMENTS

Future applications	Enabling network architecture	Synchronization requirements	Synchronization need
Cloud robotics	-A real-time, flat communication network within a plant -Connectivity to a cloud network	-Synchronization within a plant -Synchronization of plant with a cloud network -Synchronized distributed cloud networks -Security of synchronization in a plant, plant to cloud and inter-cloud network -Synchronization scalable to growing network -Easy troubleshooting of synchronization	-Absolute synchronization -Relative synchronization -Synchronization over IP network -Inter-cloud network synchronization -Scalable synchronized systems -Highly secured synchronization means -Monitored synchronization mechanism
Drones in automation	-A real-time, flat communication network within a plant -Robust drone to drone communication network -Robust plant connectivity to drones network	-The accurately synchronized drone network -Synchronization of a plant with drone network -Security of synchronization mechanisms in a plant to drone and inter-drone network -Synchronization scalable to growing network -Easy troubleshooting of synchronization	-Relative synchronization -Synchronization over a wireless network -Scalable synchronized systems -Highly secured synchronization mechanism -Monitored synchronization mechanism
Smart grid wide area monitoring protection and control	-A real-time, flat communication network within a substation -Connectivity to remote substations -Available data communication	-Accurately synchronized substation network -Synchronization over IP network -Security of synchronization mechanisms intra and inter substation networks -Fault-tolerant synchronization for substation -Synchronization scalable to growing network -Easy troubleshooting of synchronization	-Absolute synchronization -Relative synchronization -Synchronization over IP network -Scalable synchronized systems -Secured synchronization means -Available synchronization mechanism -Monitored synchronization mechanism

straightforward approaches for dealing with big data generated by sensors. The distributed clouds employ a geographically distributed cloud execution platform that utilizes different parts to execute different monitoring or controlling functions. The different cloud parts are connected using a network, however, managed as one entity for applications and cloud-users. Synchronization of the IoT devices hosted by a plant is required so that the data collected by these devices is consistent. A distributed cloud system analyzes the data. To get accurate results from collected data, the cloud system needs to be synchronized with plant devices. Since a distributed cloud system uses computation devices from different geographical sites, these computation systems need to be synchronized. Thus, there has to be a common notion of time among plant network devices, cloud nodes, and internally within distributed cloud components for the integrated distributed cloud and IoT solution to work efficiently.

6) Secured synchronization mechanisms: In synchronization systems, the devices, as well as the synch related communication messages, are prone to security incidents [16]. The current NTP V4 implemented Autokey Authentication Protocol (RFC 5906) based on public key infrastructure for security. However, several NTP security reports revealed flaws in the implementations of the autokey scheme. The standardization body is working on Network Time Security (NTS) using Transport Layer Security and Authenticated Encryption to address them. In case of PTP, the most recent version IEEE 1588 V2.1 (draft) covers security in PTP by providing a multi-pronged approach - PTP Integrated Security Mechanisms (Prong A), External Transport Security Mechanisms (Prong B), Architecture Guidance (Prong C) and Monitoring and Management Guidance (Prong D). It depends upon how practitioners implement the new security standards and whether these measures are good enough to protect industrial systems against cyber-attacks. The advanced applications and growing device networks are creating complex operational environments for synchronization systems. There is a need to address security challenges thoroughly and systematically.

7) Synchronization monitoring mechanisms: Time synchronization has been a significant component in the imposition of hard real-time requirements on cyber-physical and distributed industrial systems. Guarantees of determinism and correctness are invalidated if an attacker compromises a synchronous network malfunction. This can lead to serious ramifications, especially in industrial automation, military, and automotive industries. Therefore, ensuring that time transfer is adequately secured is a high priority item for most system architectures. Monitoring systems for timing infrastructure enables detection of a component failure, non-conformance, or poorly performing implementations as well as some types of attacks, e.g., delay attacks. Monitoring mechanisms thus are an essential component of securing timing properties [16]. Existing mechanisms allow a comprehensive view of the distribution of time throughout a network, but they do not scale to large networks. There is a need for highly efficient and scalable monitoring systems for industrial timing systems.

8) Available synchronization mechanisms: Safety-relevant and safety-critical industrial systems such as protection function in substation automation, require the synchronization systems to be highly available or having higher fault tolerance. In the case of PTP, different profiles improve the degree of fault tolerance through redundancy mechanisms. IEEE 1588 V2 came up with an alternate master clock to reduce the detection and switchover time. The IEEE Std 802.1AS–2011 profile reduced the master failover time by sending the synchronization frames separately from data frames. The IEEE Std 802.1AS–rev profile, which is part of the TSN standards, aims at supporting multiple active grandmaster clocks. Each master clock will send the synchronization messages separately, and network path failures between master and slave clocks will be taken care of. Thus for safety-critical systems, IEEE Std 802.1AS–rev is a promising synchronization solution.

IV. DISCUSSION

1) Can current synchronization solutions support future automation evolution?: While GPS can be an ultimate solution for all synchronization needs with an accuracy of tens of nanoseconds, the major problem with GPS is the unavailability of its signal due to radio jamming, tunnels, building structures, and higher installation/maintenance cost [15]. The next best network synchronization mechanism is PTP with an accuracy of microsecond level order; however, it requires hardware support in devices for precise timestamping. Moreover, PTP cannot easily be retrofitted on the internet, making it a non-obvious choice towards the cloud visions of factories. NTP is the most economical and easy to use network synchronization mechanism. However it lags in a synchronization accuracy (millisecond level) as it relies on software-based timestamping. Thus, there is no single solution for future synchronization needs.

2) Yet another synchronization protocol?: There are several synchronization protocols and standards, as mentioned in previous sections, available in the industrial automation domain. Coming up with another synchronization protocol for future automation systems makes it difficult from an interoperability point of view.

3) Future synchronization technology directions?: The future synchronization solution could be based on the existing mechanism and technical extensions that meet all the future needs. Based on the present analysis, a fully software-based synchronization system with performance comparable to hardware-based synchronization systems can be envisioned as a future solution for industrial automation systems. A software synchronization system with limited hardware support could be a step towards this vision in the immediate future.

V. CONCLUSION AND FUTURE WORK

The industrial automation systems are transitioning to more flexible, reconfigurable, and software-centric service architectures enabled by CPS and Industrial IoT trends, paving ways for advanced applications. Following a methodical approach, we identified eight synchronization requirements of future industrial automation systems by envisioning the future automation architecture, communication network, and applications. The state-of-practice synchronization solutions do not meet all the requirements of future synchronization systems. NTP is a fitting solution to many future synchronization requirements and fares reasonably well compared to GPS and PTP. However, it lags massively on the accuracy and precision requirement. Improving the performance of software-based synchronization to match to hardware-based solutions is the future direction. The findings of this paper act as a stepping stone for building the architecture of future synchronization systems to enable the evolution of future automation systems, which is planned as future work.

ACKNOWLEDGMENTS

This work has been financed by the Future Industrial Networks project, grant number 2018-02196, within the Strategic innovation program for Process industrial IT and Automation, PiiA, a joint program by Vinnova, Formas and Energimyndigheten.

REFERENCES

[1] M. Wollschlaeger, T. Sauter and J. Jasperneite, ”The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0,” in IEEE Industrial Electronics Magazine, vol. 11, no. 1, pp. 17-27, March 2017.

[2] O. Carlsson, J. Delsing, F. Arrigucci, A.W. Colombo, T. Bangemann and P. Nappey, “Migration of industrial process control systems to service-oriented architectures”. *International Journal of Computer Integrated Manufacturing*, vol. 31, n. 2, pp. 175-198, 2018.

[3] IRIG Serial Time Code Formats, Standard 200-16, Aug. 2016.

[4] A. Mahmood, R. Exel and T. Sauter, ”Delay and Jitter Characterization for Software-Based Clock Synchronization Over WLAN Using PTP,” in *IEEE Transactions on Industrial Informatics*, May 2014

[5] I. Álvarez, A. Ballesteros, M. Barranco, D. Gessner, S. Djerasevic, J. Proenza, “Fault Tolerance in Highly Reliable Ethernet-Based Industrial Systems,” in *Proceedings of the IEEE*, June 2019

[6] F. Girela-López, J. López-Jiménez, M. Jiménez-López, R. Rodríguez, E. Ros, J. Díaz, “IEEE 1588 High Accuracy Default Profile: Applications and Challenges,” in *IEEE Access*, vol. 8, pp. 45211-45220, 2020.

[7] J. Pinto, *Automation Unplugged: Pinto’s Perspectives, Pointers, Prognostications*, ISA Publishers, 2004

[8] S. Vitturi, C. Zunino, T. Sauter, “Industrial communication systems and their future challenges: Next-generation Ethernet IIoT and 5G”, *Proc. IEEE*, vol. 107, no. 6, pp. 944-961, Jun. 2019.

[9] P. Leitao, S. Karnouskos, L. Ribeiro, J. Lee, T. Strasser, A. W. Colombo, “Smart Agents in Industrial Cyber-Physical Systems”, *Proc. IEEE*, 2016.

[10] H. Forbes, “ExxonMobils Quest for the Future of Process Automation,” *ARC Advisory Group*, Tech. Rep., April 2016.

[11] E. Oztemel, S. Gursev, “Literature review of Industry 4.0 and related technologies”, *Journal of Intelligent Manufacturing*, pp. 1-56, Jul. 2018.

[12] A. Hussnain, B. R. Ferrer, J. L. M. Lastra, “An application of Cloud Robotics for enhancing the Flexibility of Robotic Cells at Factory Shop Floors”, *IECON 2018*, pp. 2963-2970, 2018

[13] R. Zurawski, *The Industrial Communication Technology Handbook*, Second Edition, CRC Press, 2017.

[14] R. Gore; E. Lisova; J. Akerberg; M. Bjorkman, “In Sync with Today’s Industrial System Clocks”, *12th International Conference on Communication Systems Networks (COMSNETS)*, India, 2020

[15] S. Achanta, S. T. Watt, E. Sagen, “Mitigating GPS Vulnerabilities”, *Proceedings of the 17th Annual Power and Energy Automation Conference*, March 2015.

[16] E. Lisova, “Monitoring for Securing Clock Synchronization”, Ph.D. thesis, Mälardalen University, April 2018