Guest Editorial Special Section on Communication in Automation

AUTOMATION systems are composed of tightly integrated mechanical, electronic, and computer equipment being designed to reduce or even eliminate the need for human intervention in the realization of many different tasks. Also, the automation of systems and processes is often characterized by some interesting features, such as reduced exploration costs and intrinsically higher efficiency, safety, and quality.

Automation systems are nowadays ubiquitous, being found in process and manufacturing industries, telecommunications and transportation systems, machine control and buildings, to name just a few [1]. Many of these systems belong to the so-called cyber-physical system category, characterized by the existence of a tight coupling between the computational and physical elements, which typically form a feedback loop. For this class of systems, in addition to correctness, computations are subject to further strong requirements, which include aspects such as timeliness, predictability, security, and dependability [2], imposed by the physics laws that rule those processes.

The continuous and increasingly rapid evolution of information engineering technologies observed over the last decades has a deep impact on many aspects of modern societies. In what concerns specifically the automation domain, the availability of low-cost and resourceful computing devices revolutionized the way in which control and supervision applications are implemented. At a first stage, these systems moved from analog realizations to digital ones, which became prevalent over the last decades.

Further advancements enhanced even more the capabilities of computing systems, which became cheaper, smaller, and more powerful, and start integrating communication interfaces. These characteristics allowed a dramatic paradigm change on the design of automation systems, which moved from centralized architectures, where the processing and intelligence are essentially concentrated in a single computer element, to distributed architectures, where these functions are spread across the nodes that compose the distributed system. Distributed architectures gained popularity over the centralized ones because they present several advantages, such as allowing resource sharing, being more scalable, and providing higher levels of fault tolerance and dependability.

As discussed above, automation systems have to satisfy several requirements. Particularly, the use of distributed architectures implies that the communication infrastructure becomes a critical component, as it definitely conditions the ability of the whole system in satisfying the requirements imposed by the applications.

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Indeed, real-time communication networks have an enormous impact on the behavior of the systems that use them, due to the inherent characteristics, such as latency, transmission rate, message jitter and associated synchronization metrics, minimum and maximum message size, and packet drop rate. Thus, initially several special-purpose networks have been developed. They were generically called fieldbuses as they are particularly suited for supporting frequent exchanges of small amounts of data under time, priority, and dependability constraints at the field level of factory automation systems [3].

The quantity, complexity, and functionality of the nodes used in automation systems since their creation have increased steadily. As a side effect, the amount of data exchanged over the networks also increased, both for configuration and operational purposes. Eventually, the increase of the amount of data exceeded the limits that are achievable using traditional fieldbuses.

As a consequence, Ethernet emerged as a better candidate, given its large bandwidth, high availability, easy integration with Internet, and clear path for future expandability. Furthermore, in many application areas, Ethernet was already used at the management level. Thus, using Ethernet also at the lower levels facilitates system-wide vertical integration and may bring along a reduction of the maintenance efforts. However, Ethernet is a general-purpose data network that was not originally designed to satisfy the requirements of automation systems. In particular, the lack of predictability is regarded as a major issue that impairs the direct use of this technology on many automation systems. Consequently, several innovative protocols, commonly known as Real-Time Ethernet (RTE) protocols, have been developed [4].

Wireless technologies have been used in general-purpose telecommunication systems for some decades. However, their use in the automation domain was, for a long time, considered as questionable. Several reasons contributed to such widepread opinion. First, the quality of the wireless channels is highly variable when compared with the wired ones. Electromagnetic waves are subject to phenomena like reflexion and scattering, which may interfere at the receive location, originating packet error rates higher than those typically found on wired technologies. To complicate things further, these effects become worse in environments containing metallic surfaces, electric machinery, and moving objects, which is a common situation in industrial environments. In addition, wireless media are inherently open, which has several implications. On the one hand, the channel is subject to a varying number of users, impacting on the channel load and thus on the predictability. Moreover, the radio frequencies are shared among different technologies, which also impacts negatively on the communication link quality.

Despite the above-mentioned problems, however, wireless technologies are extremely appealing for the automation world. Indeed, in some scenarios, such as machinery with moving parts, cabling is a source of errors and unreliability, implying also elevated maintenance costs. In these cases, the use of wireless technologies can be extremely beneficial. Mobility, such as for example that typical of automated guided vehicles, turns the use of wireless technologies unavoidable. Moreover, wireless systems allow reducing the time and cost of the installation and commissioning of plants. Finally, new functions like localization and tracking of goods, natively belonging to wireless technologies, are key information pieces on the management of the production and transport supply chains, and thus are increasingly demanded for the management systems.

For these reasons, over the last years, the research community devoted a significant effort to tackle the issues above identified, resulting in the development of new technologies and protocols for enabling the use of wireless systems in automation applications [5]. Most of these protocols rely on unlicensed frequency bands, particularly the 2.45-GHz industrial, scientific, and medical band. Technologies like the IEEE 802.11 Wireless LAN, IEEE 802.15.1, and IEEE 802.15.4 are on the focus of the research currently carried out. The use of wireless technologies for automation is nowadays a reality, being available on the market equipment based on protocols such as WirelessHART, ISA-100.11a, KNX RF (mainly for building automation), IEEE 802.11, Zigbee, etc.

Nonetheless, despite all the efforts put in the development of these protocols, several issues still need to be addressed. The research community currently investigates topics such as deterministic MAC layers, development of realistic models, analytic frameworks, implementation of affordable security mechanisms, redundancy, improved synchronization, certification issues, and energy efficiency, among many others.

Currently, the border between the automation world and the general-purpose information systems is vanishing quickly. For instance, emerging concepts like the Internet of Things (IoT, a distributed computing paradigm that is based on the concept of pervasive communication between a huge variety of entities embedded with electronics, sensors and/or actuators and capable of communicating, i.e., the "things") rapidly extended to traditional fields of automation systems, giving rise to the so-called industrial Internet of Things (IIoT). A similar situation is happening with other emerging concepts and technologies, like big data and software-defined networks (SDN). Big data, SDN, and IoT/IIoT are cornerstones of the envisioned smart automation systems, which are described as a "type of information system-through sensors and actuators embedded in physical objects . . . [where] processes govern themselves, where smart products take corrective action to avoid damages and where individual parts are automatically replenished" ("The Internet of Things and the future of manufacturing," McKinsey & Company, June 2013 [6]).

The trend to integrate the information and communication technology (ICT) and automation worlds, materialized, for example, by concepts and initiatives like Industrial Internet, Industry 4.0, and Smart Cities [7], embodies several challenges in what concerns the communication technologies, architectures, and paradigms. [8]. From the automation world perspective, this integration should not jeopardize the satisfaction of determinism, timeliness, safety, reliability, and stability requirements. Also, security aspects should not be compromised by the frequent inherent openness of ICT systems [9].

The move to distributed architectures puts the communication technologies on the center of automation systems. Indeed, the communication infrastructure is intrinsically bounded to the satisfaction of the functional and nonfunctional properties that these systems must comply with.

All the aforementioned issues are at the core of this Special Section on "Communication in Automation," which collects extended versions of the best papers from the 11th IEEE World Conference on Factory Communication Systems 2015. The Special Section comprises seven papers that have been selected by their outstanding quality and relevance, covering some of the topics highlighted above.

The paper "Automatic Packing Mechanism for Simplification of the Scheduling in Profinet IRT" by R. Schlesinger, T. Sauter, and A. Springer proposes an improvement to the popular Profinet IRT RTE network. The current version of Profinet IRT uses a dynamic frame packing (DFP) mechanism, which makes it possible to achieve very short cycle times. DFP demonstrated to be very effective for linear topologies, whereas it does not provide substantial improvements for other configurations. Also, if the network structure is changed, then the scheduling has to be reelaborated. Thus, the authors propose an alternative technique, named automatic packing mechanism (APM), capable of overcoming the described limitations. Indeed, APM does not require a scheduling algorithm and, moreover, is able to provide good performance figures even for different topologies such as, for example, those based on star and tree configurations. Besides describing in detail the basic principles of APM, the paper shows the outcomes of some experimental sessions carried out on a network, in which APM was implemented by all the deployed stations. The obtained results confirm both the feasibility of the proposal and the expected performance [10].

The paper "RESTful Industrial Communication with OPC UA" by S. Grüner, J. Pfrommer, and F. Palm investigates the introduction of representational state transfer (REST) in the industrial communication scenario. REST is a software architecture that provides a uniform interface to services that can be used by different applications. After a general description of the advantages that could derive from the adoption of REST, the paper focuses on OPC UA, a widespread standard for interoperable high-layer industrial communication. In this context, the authors propose a RESTful implementation of OPC UA which requires only a few modifications to the original standard and, at the same time, can maintain backward compatibility. An accurate performance analysis has been carried out, based on the implementation of the proposed extension on an open-source OPC UA architecture that was installed on two embedded systems. The obtained results showed a dramatic performance improvement in terms of both service invocation time and throughput [11].

The paper "iPRP: Parallel Redundancy Protocol for IP Networks—Protocol Design and Operation" by M. Popovic,

M. Mohiuddin, D.-C. Tomozei, and J.-Y. Le Boudec describes iPRP, a reliable transport layer protocol, specifically conceived for time-critical applications. The proposed protocol overcomes the limitations of the existing solutions, which are mainly based on packet retransmission: a strategy that may introduce nontolerable delays. iPRP, actually, exploits a sort of "space diversity" technique, which is based on the transmission of replicated copies of time-critical messages over fail-independent paths. In the paper, the authors use a smart grid application as running example and describe in detail the behavior as well as the various components of the protocol. Then, they analyze the outcomes of an extensive set of measurements aimed at evaluating both the operation of iPRP and the elaboration overhead introduced by the protocol. The obtained results clearly indicate that packet losses are considerably reduced by the adoption of iPRP. Also, the CPU usage showed only limited increments (below 1%), confirming the soundness of the proposed protocol [12].

The paper "Scheduling for Source Relaying with Packet Aggregation in Industrial Wireless Networks" by S. Girs, A. Willig, E. Uhlemann, and M. Björkman is, again, concerned with timeless and reliability of real-time communication systems. In this case, however, the paper focuses specifically on the data link layer of industrial wireless networks and proposes a technique based on the adoption of both relaying and packet aggregation to improve performance. The analysis of the authors is based on a typical industrial wireless network that uses a time-division multiple access protocol. In this framework, the paper proposes some source-scheduling techniques as well as some decision schemes that allow a source station to select the packets to aggregate (to the one it is going to transmit) among those it overheard in the previous transmission slots. The behaviors of the proposed strategies have been assessed through simulations that evaluated some typical performance indicators such as, for example, the probability that the source packets are correctly delivered before their deadlines under different network conditions. The analysis clearly revealed that significant improvements can be achieved, especially if the source scheduling is adjusted in agreement with the estimated channel status. Also, the choice of adequate aggregation schemes definitely contributes to further considerable improvements [13].

The paper "Improved Holistic Analysis for Fork–Join Distributed Real–Time Tasks Supported by the FTT-SE Protocol" by R. Garibay-Martinez, G. Nelissen, L. L. Ferreira, P. Pedereiras, and L. M. Pinho focuses on the execution of distributed real-time tasks, a topic of considerable interest in modern factory communication systems. The authors consider a set of fork-join parallel/distributed tasks located on different nodes of a network, which makes use of the Flexible Time Triggered-Switched Ethernet protocol. In a first step, they theoretically evaluated the worst-case response time for parallel/distributed tasks that are transformed by a specific algorithm, namely the distributed stretch transformation. Then, the authors provided a detailed holistic analysis of the worst-case task response time that takes into consideration the presence of the network. The results of this theoretical analysis have been confirmed by the outcomes of a set of experiments that comprised both simulations and practical measurements. It is worth observing that such experiments have been carried out on a network prototype setup, in which all nodes used routines of a library developed by the authors that allow handling tasks in agreement with the distributed stretch transformation algorithm [14].

The paper "On the Use of IEEE 802.11n for Industrial Communications" by F. Tramarin, S. Vitturi, M. Luvisotto, and A. Zanella addresses the IEEE 802.11n wireless LAN (WLAN) and investigates its adoption for industrial communication. IEEE 802.11n, actually, introduces considerable enhancements with respect to the former WLAN versions, which can be fruitfully exploited also in the challenging industrial scenario. In the first part of the paper, the authors provide a description of the innovative IEEE 802.11n features along with a theoretical analysis aimed at assessing their performance in terms of both timeliness and reliability. Then, they present the results of an extensive experimental session. In particular, the opportunity of adopting multiple-input multiple-output configurations, that has been deeply investigated, showed that reliability can be consistently improved if space-time block coding is adopted. Indeed, with such a technique, the packet transmission success probability is considerably increased at the expense of only a minimal reduction of the network throughput for the typical industrial traffic. Finally, the paper provides a useful set of recommendations for the appropriate deployment of IEEE 802.11n WLANs in industrial communication systems [15].

The paper "Using Two Independent Channels with Gateway for FlexRay Static Segment Scheduling" by J. Dvořák and Z. Hanzálek describes a strategy to enhance the performance of Flexray networks. In practice, the authors propose both a more efficient schedule for the static segment and the use of the two FlexRay channels in an independent way. The proposal of the authors is implemented in two different steps. In the first one, electronics control units are assigned to channels, whereas in the second one, an adequate channel scheduling is devised. For both the steps, suitable algorithms are proposed that are able to find heuristic solutions. The algorithms have been implemented on practical devices (personal computers were used in this case), and some experimental analyses have been carried out in different application scenarios that used real as well as synthesized benchmark datasets. The obtained results are interesting, since they show that the strategy proposed by the authors can save about 30% of the bandwidth [16].

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