Editorial
Special Section on Communication in Automation

COMMUNICATION systems have been an essential part of automation for more than 25 years. In fact, modern automation systems in all their diversity are unthinkable without an equally large diversity of communication systems, filling every application niche.

Historically, the need for communication in automation arose when the concept of computer integrated manufacturing (CIM) was introduced in the 1970s. It defined a hierarchical approach to structure the information flow required for factory and process automation. Clearly, a transparent, multilevel network was needed to achieve this goal [1]. Nevertheless, communication possibilities, let alone computer networks, were limited at that time. Ethernet had just emerged, and dedicated automation networks were not even considered. The evolution of CIM thus went along with the evolution of communication networks and partially also stimulated it.

The need for field-level networking was not clearly perceived and had just slowly become apparent [2]. The late 1980s and especially the 1990s saw the development of multiple fieldbus systems tailored to all kinds of application domains, which were proposed together with fierce struggles in the international standardization committees [3]. These dedicated communication networks were in sharp contrast to the already existing local area networks, the distinction relying mostly on the characteristics of the transported data. LANs had high data rates and carried large amounts of data in large packets. Timeliness was not a primary concern, and real-time behavior was not even required. Fieldbus systems, by contrast, were designed for low data rates. Since they mainly transported process data, the size of the data packets was small, and real-time capabilities were important. For some time, these distinction criteria between LANs and field-level networks were adequate and fairly described the situation. Recently, however, drawing the line according to data rates, packet sizes, and timing requirements is no longer applicable. In fact, the boundaries between LANs and fieldbus systems have faded. Today, it is quite common for field-level networks to support applications requiring the transmission of video or voice data, thus reaching the former LAN domain. Nevertheless, the investigation and assertion of real-time behavior has always been an essential topic in research on automation networks [4]–[9].

After two decades of development, fieldbus systems have found broad acceptance. In recent years, a significant amount of research work has been done to extend fieldbus networks, in order to include wireless segments and mobile nodes [10]. It was demonstrated that an integration of wireless communication channels in traditional fieldbus systems is possible without sacrificing real-time capabilities, albeit with substantial effort [11], [12].

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Another important topic of research has been the development of safety networks, which are intended to support distributed applications where reliability and safety issues are of major concern. In addition to the support of traditional process-control applications, recently, there is a trend to use specific fieldbus networks also to support safety-related functions, namely, to replace the traditional electromechanical protection systems [13], [14]. The most relevant approaches are based on the use of the black-channel concept developed for railway applications [15], where a safety-related middleware provides a set of safe and reliable services to the supported applications.

With such approaches, a broad and comprehensive coverage of the field level has been achieved, and not many changes are to be expected in the near future, as far as traditional fieldbus systems are concerned.

In a second wave of evolution, however, Ethernet has been penetrating the fieldbus domain for about six years [16], [17]. One of the main arguments for their introduction was the promising integration possibility in company LANs. Although marketing campaigns tried to draw a bright future with Ethernet solving all vertical integration problems, Ethernet on field-level remained disputed mostly due to the lack of real-time capabilities, even for the switched Ethernet solutions common in office LANs. As a response to these inefficiencies, much effort was and is still put in the development of Industrial Ethernet solutions. The target is to create a new generation of fieldbus systems that eventually will replace the traditional ones. Particular emphasis is put on the problems of determinism and real-time capabilities [18]–[21].

Ethernet is only one example for the impact standards from the office world have had on communication in automation. The evolution of the Internet had an even bigger influence on automation systems, in general, and on their underlying communication systems in particular [3]. Although the Internet consists of much more than the worldwide web, the sheer ubiquity of the WWW and its platform-independent software tools have coined the public perception. Hence, it is no wonder that these quasi-standards became attractive for the automation domain. First and foremost, web-based approaches (as well as other Internet-specific protocols) are being used as a means to remotely access automation systems and thus to integrate them into the higher levels of a company hierarchy dominated by office applications. This has finally revived the old CIM idea of vertical integration. Generally speaking, Internet technology seems to make possible what was bound to fail 20 years ago. Examples for this trend are not only the adoption of web standards for business and enterprise integration [22] but also the use of distributed software paradigms—which originated in the Internet—for resource and production planning [23]. This last example is particularly appealing because it bridges the traditional gap between the high-level, information-oriented enter-

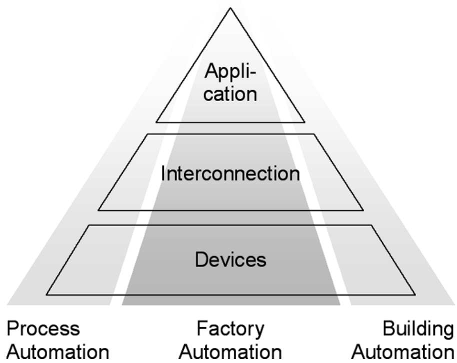

Fig. 1. Reduced functional automation hierarchy.

prise environment and the low-level, communication-oriented factory floor.

More related to the actual communication systems, Internet technology is today the basis for device description languages that simplify and unify device and system configuration. At the same time, more and more field devices are equipped with embedded web servers that allow easy remote access via the Internet protocol suite [24]. As a supporting measure, many fieldbus systems have already included in their most recent versions a possibility of tunneling IP traffic over the fieldbus protocol. As a consequence, the traditional multilevel automation hierarchy is dramatically reduced, and the formerly stringent barriers between the levels diminish. In a very abstract functional way, there is a tendency to move ahead into the direction of a flat hierarchy made up of devices, interconnection, and automation applications (see Fig. 1). It is also important to recognize that this trend is not restricted to manufacturing or factory automation but can also be found in other areas like process or building automation, where specific boundary conditions may be different, but the basic tendencies, i.e., the creation of seamless and transparent integration of information management, are identical.

As a result, what are the major open issues in automation-related communication? Even though fieldbus systems have reached a mature status, applications have become more demanding, which in turn creates new problems. On the network level, real-time properties and extensions remain an area of interest, even for well-known fieldbus systems. Also, the trend at this lower level is the continuously increasing reliability and availability requirements, as they are the core for higher quality and productivity of the supported automation systems.

Apart from such low-level aspects, other problems are lurking on the system and application level. One issue is the increasing complexity of automation systems. With the advent of building automation, the usual number of data points has grown, and installations with several thousand network nodes are the rule. Not only does this pose a challenge for the communication itself, but also the planning and management of such networks is no longer straightforward and requires the application of proper modeling and performance estimation tools. The overwhelming variety of communication systems also necessitated very cumbersome endeavors to unify interfaces and functionalities, at least at the higher level. The definition of the so-called profiles in all kinds of application areas tries to solve this problem [25]. On the other hand, complexity also grows within applications that become increasingly distributed. Concepts like holonic systems or agent-based automation try to increase the flexibility of automation systems throughout the life cycle [23], which in turn requires flexibility from the communication networks. Features like auto-configuration or service brokerage are known from the computer science world and typically demand IP-based means of communication [24], [26].

The last issue currently receiving attention is the security problem that became obvious with the rising degree of interconnection between automation systems. Security had never been given much attention in the fieldbus world, which traditionally consisted of standalone installations [27]. In recent years, however, the connection of automation systems and networks to the "outside world" became feasible and (for flexibility and cost reasons) also reasonable. Security becomes an obvious requirement in such a setup, and solutions tailored to the specific boundary conditions in automation are being investigated on the communication network level [28] as well as for the network interconnections and—on a higher level—the applications [29].

This special section on communication in automation presents, without attempting to give a comprehensive overview, a few aspects of relevant research work being done in this large field. The six papers considered in this special section cover a large range of topics, from the lowest to the highest level of the automation hierarchy. They address real-time communication in both FTDMA and CAN networks, fault-tolerant communication in CAN networks, as well as the modeling and analysis of large building automation networks, QoS (Quality of Service)-oriented communication scheduling, and the use of web services for the vertical integration of enterprise systems.

Initially developed for the automotive sector, the Controller Area Network (CAN) is nowadays widespread in distributed embedded systems used at the lowest level of the automation hierarchy, where fault-tolerant and reliable communication using proven-by-use fieldbus systems is an important research issue. The paper "An active star topology for improving fault confinement in CAN networks," by M. Barranco *et al.*, presents a new active star topology for CAN networks, called CANcentrate [30]. It is intended to solve some of the dependability problems of CAN networks that are caused by the CAN bus topology. By means of a hub-based approach, the CANcentrate system is able to reduce the number of components whose failure can cause a severe failure of communication, to a unique single point of failure, i.e., the hub. This represents an important step to improve the dependability of CAN networks, as it is easier to improve the dependability for the single hub than for the many components that may cause a severe failure of communication in a bus topology. The CANcentrate star topology has been implemented and tested and can be used with any CAN-based protocol.

Sharing technology and solutions with the automotive sector has been one of the driving forces for the development of industrial communication solutions, at least for the lowest levels of the communication hierarchy. Common requirements on timeliness, reliability, and availability were one of the enabling factors for such successful interactions. Among the most recent developments from the automotive communication domain, two communication protocols, Byteflight and FlexRay, have been conceived to support high data rates, deterministic behavior, and a high degree of flexibility. Due to the size of the automotive market, low-cost communication products based on these protocols are expected to be available in the near future. Therefore, it is of utmost importance to analyze their underlying concepts, in order to assess their interest and potential to support industrial applications. The paper "On the properties of the flexible time division multiple access technique," by G. Cena and A. Valenzano, analyzes the main features of the Flexible Time Division Multiple Access medium access technique used in both Byteflight and FlexRay networks (in FlexRay only for the dynamic segment) [31]. The detailed analysis shows that there is a significant tradeoff between communication efficiency and flexibility, that is, higher flexibility is achieved at the cost of lower performance.

Next-generation automation systems require the use of communication protocols with both high operational flexibility and increased dependability levels. Such requirements are, however, in conflict, as the traditional approaches to provide dependability in communication systems consider static table-based traffic scheduling. Such static concepts are not able to adequately support the dynamic communication requirements of an increasing number of applications. The support of dependable communication has been recently addressed in the scope of the FTT-CAN protocol [32]. The paper "Combining operational flexibility and dependability in FTT-CAN," by J. Ferreira *et al.*, gathers and reviews the main mechanisms that were recently developed to provide FTT-CAN with an adequate level of dependability while preserving its high level of operational flexibility [33].

In the domain of building automation, networks with tens of thousands of elements, like sensors, controllers, or actuators, are common. Even though the individual message streams typically have weak real-time requirements, their huge number may lead to timing-related failures or to communication bottlenecks. In addition, the use of CSMA-based access schemes, where time bounds cannot be guaranteed, can cause instable control cycles, discomfort, and malfunction. The paper "Automated modeling and analysis of CSMA-type access schemes for building automation networks," by J. Ploennigs *et al.*, proposes an automated modeling approach to deal with large building automation networks, gathering information that is mostly already available from the design tool and therefore facilitating dimensioning of the system and performance prediction before implementation [34]. The process of automated performance analysis relies on a network model providing the structural details for the analysis and a traffic model that supplies the parameterization details. It allows the implementation of an efficient and reliable design process, where bottlenecks can be identified at an early stage, and the utilization and latency of the network can be easily computed.

The design of hard real-time systems is often hindered by the consideration of worst-case conditions that seldom occur. As a consequence, there is the need to allocate a large amount of computing resources that are hardly ever used at run time. Conversely, for soft real-time systems requiring only statistic timing guarantees, it can be suitable to have a system design based on average-case conditions. However, for IP-based communication systems that are often found in the automation world, providing only statistic deadline guarantees can be unacceptable. For this type of applications, a more precise specification on how the deadline misses are distributed in time is necessary. If the supported applications are able to tolerate a specified percentage of non-consecutive deadline misses, such behavior can be modeled using the (m,k)-firm paradigm. The paper "Providing real-time applications with graceful degradation of QoS and fault tolerance according to the (m,k)-firm model," by J. Li *et al.*, addresses a question that has received growing interest during the last years, namely, the flexibility to combine QoS adaptation with minimum QoS guarantees [35]. The target of the presented work is the provision of dynamic QoS management and fault-tolerance to the supported applications.

Finally, on the highest level of the automation hierarchy, flexibility and interoperability are key issues. Internet technology provides the unifying framework for the horizontal and vertical integration of diverse systems and applications both inside a plant and between plants or even different enterprises. The paper "Vertical integration of enterprise industrial systems utilizing web services," by A. Kalogeras *et al.*, addresses the need for uniform interfaces and proposes web services as an easily available and platform-independent middleware technology to solve the problem [36]. Flexibility is achieved by a modular structure that decouples the enterprise workflows from the actual web services and links them dynamically with an ontology describing the business logic.

A special section like the present one requires the support of many people, and we would thus like to thank all of them: the authors for their contributions and revisions; the reviewers for their careful and thorough review work, which contributed significantly to the quality of the papers that finally made their way into this section; and last but not least, the editors of the transactions for guiding the evolution of this issue from the first idea until its publication.

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REFERENCES

[1] J. P. Thomesse, "Fieldbuses and interoperability," *Control Eng. Practice*, vol. 7, pp. 81–94, 1999.
[2] M. Mariton, "Local area networks and future process control systems," *IEEE Control Syst. Mag.*, vol. 6, no. 2, p. 27, 1986.
[3] T. Sauter, "Fieldbus Systems: History and Evolution," in *The Industrial Communication Technology Handbook*, R. Zurawski, Ed.. Boca Raton, FL: CRC, 2005, pp. 7-1–7-39.
[4] L. Pinho and F. Vasques, "Reliable real-time communication in CAN networks," *IEEE Trans. Comput.*, vol. 52, no. 12, pp. 1594–1607, Dec. 2003.
[5] S. Cavalieri, "Meeting real-time constraints in CAN," *IEEE Trans. Ind. Informat.*, vol. 1, no. 2, pp. 124–135, May 2005.

[6] T. Nolte, M. Nolin, and H. A. Hansson, "Real-time server-based communication with CAN," *IEEE Trans. Industrial Informat.*, vol. 1, no. 3, pp. 192–201, Aug. 2005.

[7] L. Almeida, E. Tovar, J. Fonseca, and F. Vasques, "Schedulability analysis of real-time traffic in WorldFIP networks: An integrated approach," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1165–1174, Oct. 2002.

[8] E. Tovar, F. Vasques, and A. Burns, "Communication response time in P-NET networks: Worst-case analysis considering the actual token utilisation," *J. Real-Time Syst.*, vol. 22, pp. 229–249, 2002.

[9] E. Tovar and F. Vasques, "Real-time fieldbus communications using Profibus networks," *IEEE Trans. Ind. Electron.*, vol. 46, no. 6, pp. 1241–1251, Dec. 1999.

[10] J.-D. Decotignie, "Wireless fieldbusses—A survey of issues and solutions," in *Proc. 15th IFAC World Congress Automatic Control*, Barcelona, Spain, Jul. 21–26, 2002.

[11] M. Alves, E. Tovar, and F. Vasques, "On the adaptation of broadcast transactions in token-passing fieldbus networks with heterogeneous transmission media," in *Proc. IFAC Int. Conf. Fieldbus Systems Applications (FeT'01)*, Nancy, France, Nov. 15–16, 2001, pp. 278–284.

[12] M. Alves, E. Tovar, F. Vasques, G. Hammer, and K. Rother, "Real-time communications over hybrid wired/wireless PROFIBUS-based networks," in *Proc. 13th Euromicro Conf. Real-Time Systems (ECRTS'02)*, Vienna, Austria, Jun. 2002, pp. 142–151.

[13] R. Piggin, "A fieldbus for machine safety," *IEE Rev.*, vol. 46, no. 4, pp. 33–37, Jul. 2000.

[14] R. Piggin, Safety Networking—New Technology Enables Greater Flexibility, ISA InTech, May 2004.

[15] IEC 62280-1: Railway Applications—Communications, Signalling and Processing Systems—Part I: Safety Related Communication in Closed Transmission Systems, 2002, Ed. 1.0 b.

[16] M. Felser and T. Sauter, "Standardization of industrial ethernet—The next battlefield?," in *Proc. IEEE Int. Workshop Factory Communication Systems (WFCS)*, Wien, Austria, Sept. 22–24, 2004, pp. 413–421.

[17] L. Lo Bello and O. Mirabella, "Design issues for ethernet in automation," in *Proc. 8th Int. Conf. Emerging Technologies Factory Automation*, Antibes, France, Oct. 15–18, 2001, vol. 1, pp. 213–221.

[18] L. LoBello, G. A. Kaczynski, and O. Mirabella, "Improving the real-time behavior of ethernet networks using traffic smoothing," *IEEE Trans. Ind. Informat.*, vol. 1, no. 3, pp. 151–161, Aug. 2005.

[19] P. Pedreiras, P. Gai, L. Almeida, and G. C. Buttazzo, "FTT-ethernet: A flexible real-time communication protocol that supports dynamic QoS management on ethernet-based systems," *IEEE Trans. Ind. Informat.*, vol. 1, no. 3, pp. 162–172, Aug. 2005.

[20] T. Skeie, S. Johannessen, and O. Holmeide, "Timeliness of real-time IP communication in switched industrial ethernet networks," *IEEE Trans. Ind. Informat.*, vol. 2, no. 1, pp. 25–39, Feb. 2006.

[21] R. Moraes and F. Vasques, "Probabilistic timing analysis of the h-BEB collision resolution algorithm," in *Proc. 6th IFAC Int. Conf. Fieldbus Systems Applications (FeT'2005)*, Puebla, México, Nov. 14–15, 2005.

[22] T. Sauter, "Integration aspects in automation—a technology survey," in *Proc. 10th IEEE Int. Conf. Emerging Technologies Factory Automation (ETFA)*, Catania, Sep. 19.-22., 2005, vol. 2, pp. 255–263.

[23] J. Peschke, A. Lüder, A. Klostermeyer, A. Bratoukhine, and T. Sauter, "Distributed automation: PABADIS vs. HMS," *IEEE Trans. Ind. Informat.*, vol. 1, no. 1, pp. 31–38, Feb. 2005.

[24] F. Jammes and H. Smit, "Service-oriented paradigms in industrial automation," *IEEE Trans. Ind. Informat.*, vol. 1, no. 1, pp. 62–70, Feb. 2005.

[25] F. Benzi, G. S. Buja, and M. Felser, "Communication architectures for electrical drives," *IEEE Trans. Ind. Informat.*, vol. 1, no. 1, pp. 47–53, Feb. 2005.

[26] J. L. M. Lastra and M. Delamer, "Semantic web services in factory automation: Fundamental insights and research roadmap," *IEEE Trans. Ind. Informat.*, vol. 2, no. 1, pp. 1–11, Feb. 2006.

[27] A. Treytl, T. Sauter, and C. Schwaiger, "Security measures for industrial fieldbus systems—state of the art and solutions for IP-based approaches," in *Proc. IEEE Int. Workshop Factory Communication Systems (WFCS)*, Wien, Austria, Sep. 22-24, 2004, pp. 201–209.

[28] M. Long and C.-H. Wu, "Energy-efficient and intrusion-resilient authentication for ubiquitous access to factory floor information," *IEEE Trans. Ind. Informat.*, vol. 2, no. 1, pp. 40–47, Feb. 2006.

[29] Y. Xu, R. Song, L. Korba, L. Wang, W. Shen, and S. Lang, "Distributed device networks with security constraints," *IEEE Trans. Ind. Informat.*, vol. 1, no. 4, pp. 217–225, Nov. 2005.

[30] M. Barranco, J. Proenza, G. Rodríguez-Navas, and L. Almeida, "An active star topology for improving fault confinement in CAN networks," *IEEE Trans. Ind. Informat.*, vol. 2, no. 2, pp. 78–85, May 2006.

[31] G. Cena and A. Valenzano, "On the properties of the flexible time division multiple access technique," *IEEE Trans. Ind. Informat.*, vol. 2, no. 2, pp. 86–94, May 2006.

[32] L. Almeida, P. Pedreiras, and J. Fonseca, "The FTT-CAN protocol: Why and how," *IEEE Trans. Ind. Electron.*, vol. 49, no. 6, pp. 1189–1201, Dec. 2002.

[33] J. Ferreira, L. Almeida, J. Fonseca, P. Pedreiras, G. Rodríguez-Navas, J. Rigo, and J. Proenza, "Combining operational flexibility and dependability in FTT-CAN," *IEEE Trans. Ind. Informat.*, vol. 2, no. 2, pp. 95–102, May 2006.

[34] J. Ploennigs, P. Bucholz, M. Neugebauer, and K. Kabitzsch, "Automated modeling and analysis of CSMA-type access schemes for building automation networks," *IEEE Trans. Ind. Informat.*, vol. 2, no. 2, pp. 103–111, May 2006.

[35] J. Li, Y. Song, and F. Simonot-Lion, "Providing real-time applications with graceful degradation of QoS and fault-tolerance according to the (m, k)-firm model," *IEEE Trans. Ind. Informat.*, vol. 2, no. 2, pp. 112–119, May 2006.

[36] A. Kalogeras, J. Gialellis, C. Alexacos, M. Georgoudakis, and S. Koubias, "Vertical integration of enterprise industrial systems utilizing web services," *IEEE Trans. Ind. Informat.*, vol. 2, no. 2, pp. 120–128, May 2006.

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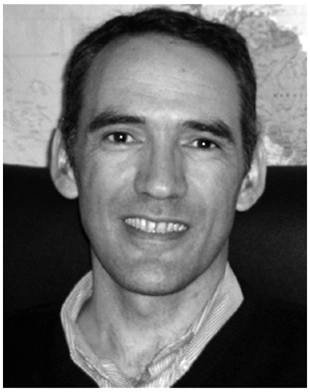

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