"Towards Smart Systems, Their Sensing and Control in Industrial Electronics and Applications"

CARMEN ARACIL, GABOR SZIEBIG, PETER KORONDI, SEHOON OH, ZHICHAO TAN,
MICHAEL RUDERMAN, WANGLI HE, LEI DING, HAO LUO, SHEN YIN, ADEL HAGHANI

Introduction: Industrial Electronics has evolved profoundly in the last decades going hand in hand with Smart Systems. This huge improvement of the current industrial electronics systems comes from different areas, going from Control, Robotics, Sensors and Actuators, or the use of technologies as Mechatronics, and Micro and Nanotechnology. From the point of view of Control, different implementations can be regarded, for example by Data-Driven Control, Monitoring critical parameters, Motion Control of certain elements of the system, Network-based Control Systems, or the implementation of fault diagnosis and the fault-tolerant control systems. This article aims to present the evolution in the last years in this respect, and future challenges.

Control, Robotics and Mechatronics for future of Smart Systems

The last decade has been a major gamechanger in the field of Control, Robotics and Mechatronics. Technology development, hardware miniaturization and increase in computational power has led to a new industrial revolution, namely Industry 4.0 and its' equivalents in the different continents (Europe: Industry 4.0 [1], China: Made in China 2025 [2], USA: Advanced Manufacturing [3], Japan: Super Smart Society [4]). Industry 4.0 based solutions is the new standard, when someone would like to address automation challenges, control of smart systems or establishing relationship between humans and robots. Control systems are transitioning from offline to online and inclusion of Artificial Intelligence based control, where mechatronics systems are working in high risk applications (e.g. high payload human-robot collaboration) is expanding fast.

During the last decades, the industrial robot has clearly demonstrated its capability to be the core component in industrial automation, due to the fact that it provides an optimum of high working capacity and flexibility. By connecting the robot even closer to the human, in terms of direct collaboration or task sharing within the same working area, there is important potential for a strong synergy between the robots' and the humans' capability; thus, a very productive, user friendly, however, rapidly changeable system. Robots are no longer stand-alone systems in the factory floor and became a part of a complex mechatronics ecosystem.

The demand for industrial robots (market) is anticipated to be growing to 65 billion € by the year 2023. Within all areas of robotics, the demand for collaborative and more flexible systems is rising as well [5]. The level of desired collaboration and increased flexibility will only be reached if the systems are developed as whole e.g. perception, reasoning and physical manipulation. One of the main concerns in the realization of a human robot collaboration system is the safety of the human.

Within the next decade, there will be paradigm shift from traditional control methods, toward online, AI based control solutions. In this setup the mechatronics ecosystems will be more ubiquitous and more cooperative with humans [6], as shown in Fig. 1.

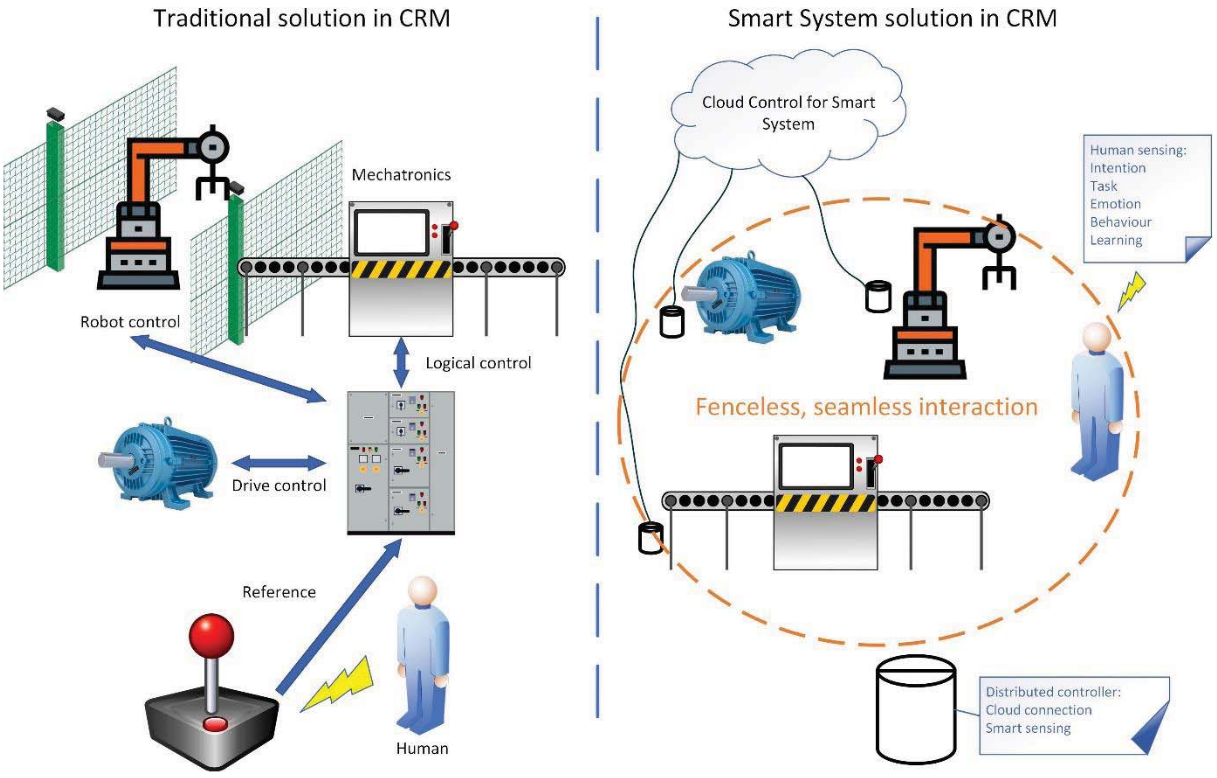

Fig. 1. Traditional approach vs. novel approach in Smart Systems for Control, Robotics and Mechatronics

The continued rise of industrial robots certainly seems to be an inevitability being driven by a variety of production demands, including the need for safer and more "simplified" robotic technologies to work in collaboration with humans, increased resource efficiency, and continued adaptation to the proliferation of automation and the Internet of Things (IoT) [7]. These smarter industrial robots draw on a much broader range of robotics technology such as improved and interactive human-machine interfaces, the ability to learn tasks without formal programming, and higher levels of dexterity and flexibility.

Not only robotics has benefited from the industrial revolution. Mechatronics has become an even more dominant engineering field [8]. IoT based solutions present a novel approach in case of mechatronics: inexpensive, off-the-shelf controllers, connected to internet provides excellent platform for seamless hardware – software control [9].

Sensors and Actuator technology for Smart Human Robot Interaction

Delving in the interaction robot/human it includes not only information interchange, but also physical interactions. When it comes to this smart physical interaction between humans and robots, there are still challenging problems to be addressed by many researchers. The most significant aspect of the physical human-robot interaction is that it contains conflicting purposes; the robot/mechatronic system is required to perform desired motions to achieve the assigned tasks while it needs to behave flexibly changing its motion plan according to human's (unknown) involvement [10].

This aspect is significantly different from what was required for robots in the past; the robots were supposed to be operated by themselves, and peoples were not allowed to stay near the robots. What was required from the robots was the precision and high speed, not safety nor flexibility.

The most cutting-edge examples of this human-robot interaction can be found in the assistive robots and collaborative robots. Through the research to successfully develop these robots, it has been found what kinds of technologies are required and which aspects should be intensively investigated. Fig. 2 elaborates on the details of the required technology for the safe and high-performance human-robot interaction.

Fig. 2. Various sensor and actuator technologies for safe human robot interface.

The key technology to address these issues is significantly related to sensors and actuator technology; breakthroughs in sensors and actuators fields are awaited for the robots to interact with humans in a smart, flexible and satisfying way. Actuators need to be redesigned or properly analyzed and selected. The high force output of robots usually takes advantage of reduction gears. However, this reduction gear diminishes the back-drivability of the robot, which means the actuator cannot sense or respond with respect to the external force. Several approaches are developed to address this issue; elasticity is employed to add the ability to react more flexibly [11], and novel transmission mechanisms are developed which are able to maintain high back-drivability while it can still transmit/amplify the force from the actuator [12].

Sensor technology is also investigated to improve safety: researchers come up with new designs of force sensors, which can overcome the limited range of sensitivity and the complicated mechanism [13]. Moreover, observers are developed to overcome the limitations of conventional sensors. The problems of force sensors such as noise, bias, and latency of the sensors are now to be fixed by these approaches [14]. Not only observer design, but also controller design, is a very significant technology for the advanced human-robot interaction. Since the interaction force measurement and feedback cause the non- collocated system problem, which restricts hi-gain controllers [15]. In other words, the control performance is limited in this interaction force control. On top of this issue, the stability issue appears differently from the conventional position/velocity control; the interaction with stiff environments should be taken into consideration when analyzing stability. Passivity has been widely utilized as a criterion to analyze and guarantee interaction stability [16]. The control performance is largely limited when passivity is considered necessary. Novel control design approaches to be researched to develop controllers to achieve high performance while it maintains interaction stability [17].

These technologies related to sensors and actuators will not only contribute to the hardware aspect of advanced human-robot interaction, but it will also play an important role for Artificial Intelligence (AI) technology to be applied to human-robot interaction, by collecting necessary data and provide motions as the result of AI technology.

Micro-Nano Technology for Sensor Systems

In the coming technology wave of IoT and artificial intelligence (AI), sensor systems are becoming more and more critical in industrial applications since they are the access to getting knowledge of real-world and delivering information to computer engine for further processing. The sensor performance is often a bottle neck of the whole system, thus the design for high performance low power sensors becomes a challenging task for researchers in different fields including MEMSs, readout circuits and digital processing, etc.

As the definition of sensor system indicates in Fig. 3, it commonly consists of the sensing element, which converts physical information to electrical signal such as voltage, current or charge. After that, the mixed signal circuit chain converts the analog electrical signal further into digital word; this step involves amplification, filtering and analog-to-digital conversion.

The output of analog-to-digital converter (ADC) then can be used for digital correction and calibration, and is ready to be reported to back-end micro-controller [18]. The analog/mixed signal processing chain which is usually referred as "readout chain" often consumes most of the power consumption of the sensor system, and constrains the accuracy of the system.

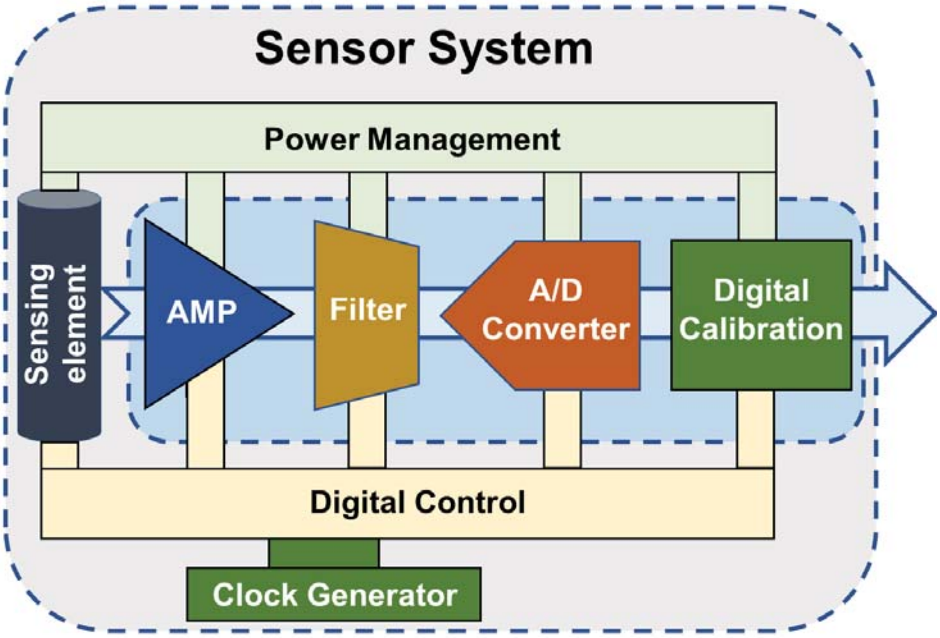

Fig. 3. Sensor system diagram

Development of sensing element such as MEMS (Micro-Electro-Mechanical Systems) and nano-technology drives the sensing element into highly integrated fashion. The miniaturization makes the sensing element integrated with its readout circuit. Fully integrated sensor becomes one of the major driving forces of the technology trend such as IoT. Such rapid development of IoT technology creates not only a strong market pull, but also tremendous driving forces for the innovative MEMS sensors. The main development trends of the MEMS sensor include following aspects: firstly, the MEMS sensor performance in terms of accuracy, robustness and power consumption is constantly being improved, which enables the large scale deployment of sensor nodes [19]; secondly, the integration level of MEMS sensors with circuits and other sensors is continuously increasing, greatly enhancing the functionalities of sensor modules [20],

[21]; thirdly, the microfabrication processes are being developed in a unprecedented speed, leading to the increase in the sensors functionality and reduction in size and cost [22]; fourthly, new data processing hardware and algorithms are constantly emerging, making it possible for the MEMS sensor to output complex measurement results [23]; fifthly, with new generation of data transmission technologies (such as 5G), large quantity of sensor nodes can be connected efficiently without the limitation of geographical factors and data quantity [24]. The ever-growing functionality, robustness, reliability in combination with the reduced size, cost and power consumption make it possible for the MEMS sensors to be deployed in various segments of the IoT applications, such as automotive, healthcare, industry, environmental monitoring, food industry, and smart homes. In addition to the enhancement in the performance, there are also increasing demand for the fabrication of MEMS devices. The fabrication of MEMS is always one of the most critical factor for the development of new devices, with following known challenges: high cost of equipment and processes, time-consuming and long development cycles, as well as highly customized process integration needs. Neverthelss, the options for fabricating the MEMS devices are also increasing, such as fabricating MEMS with CMOS processes and thus integrate them with the circuit, fabricating MEMS devices with foundry process, or developing prototypes by using a Multi-User MEMS Processes (MUMPs) to reduce cost.

Regarging readout chain, power consumption and performance are two important parameters, especially in the application such as IoT, since energy available for sensing comes from wireless transforming or energy harvesting, so the power consumption becomes a decisive factor. Thus, readout circuit design shifts from performance driving into power driving; how to decrease readout circuit power consumption while maintaining performance becomes a challenging task [25]. In the future emerging applications, the key factor for the sensor design will be system approach, co-design of sensing element and readout circuit. This approach delivers the performance which satisfies application need while drives the power consumption as low as possible.

Motion Control in smart systems and applications

In nowadays smart systems and applications, the motion control is even more present and challenging as before. Through versatile interaction with environment and number of other interfacing and/or networked systems, the motion control technologies move from the lumped and predefined concepts and paradigms, to more adjustable and distributed structures of the control loops and motion control objects.

Let us recall that the motion control encompasses a wide band of industrial and other applications. Starting from nano-scale, the motion control is crucial for nano- and micro-positioning. On the other side of the motion-scale are quite heavy manipulators and machines which have to operate robustly often within open-air, off-road, or harsh environments [26]. Another challenging field for the motion control technologies which are operating under harsh outdoor conditions are the positioning and heading control of ships and offshore rigs. Here, the non-collocated sensing and actuating in the control loops, equally as unavailable measurement of relative motion in the time-varying and uncertain reference coordinates, are since long the most crucial and safety-critical aspects of the motion control to be designed. Also in the ground vehicles, and particularly electric vehicles of today and tomorrow, the motion control technologies play an increasingly important role. This is especially in view of semi-automatic and driver-assisting control functions and distributed actuators in the powertrain and chassis components, like for instance in-wheel-motors see e.g. Thinking back about more ”classical” applications of the motion control, like in robotics and mechatronics, always more flexible and safe interaction with human beings and other environmental subjects are required in a regular operation [27]. Here, apart from the corresponding force and motion reaction, the issues of detection, isolation and identification of robot collisions in real-time, or even in preventive manner, are the most essential [28]. The motion stiffness, recognized as a prime factor for flexible motion control in the former works [29], is a physically reasonable way of specifying an ideal motion control, ideal force control, and impedance control as a large spectrum between both.

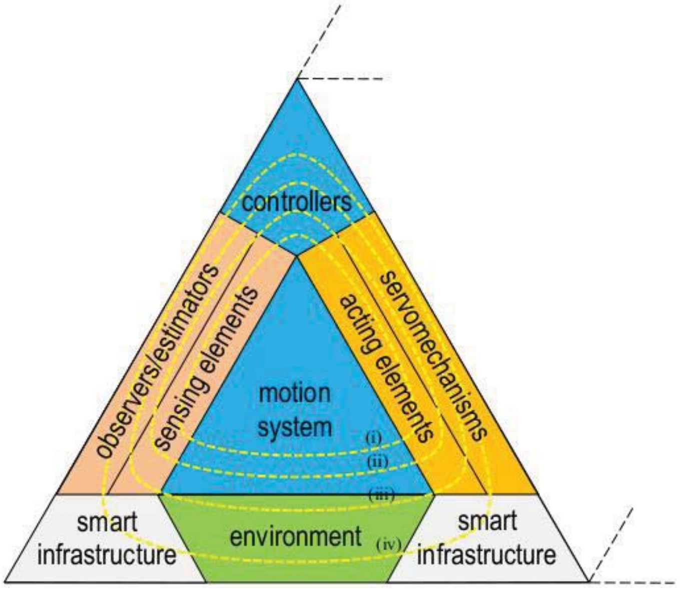

Fig. 4. Triangle-type topology of motion control system setting with infrastructural and environmental interfacing

The motion control systems in smart applications can incorporate multiple controllers, servomechanisms, sensing and acting elements, observers and estimators, and structural and functional interfaces at the same time. A generic arrangement and interaction of the above elements can be thought of as schematically represented in Fig. 4. Here a triangle-type arrangement around a core motion system allows such setting to interface with other (also triangle-shaped) subsystems, while these can also be tilted or rotated. That way allows one to analyze and design different topologies within a global system under consideration. The denoted smart-infrastructures, which are bounded on environment, enclose all the specified connections and interactions of a natural and artificial kind, like signals, commands, protocols, structures, hardware and software components and networks.

Despite a large number of the well-established techniques and methods of control and systems theory are available for an advanced motion control, the application-specific challenges and smart system concepts continue to reveal significant issues for both the researches and practicing engineers. Several general approaches appear promising for further elaboration in scope of the motion control studies. For instance a specifically-controlled supplying and dissipating of energy, in other words optimal energy shaping see e.g. [30], arises as a natural way for the motion control design. A rather disturbing dissipation of energy due to kinetic friction remains further among the most relevant issues of the motion control, see e.g. [31], [32], even though the principle phenomena and effects of friction have been analyzed and described in the nineties see [33]. In order to deal with large uncertainties and perturbations coming from smart systems paradigms, the motion controllers have to be designed in a particularly robust manner, thus calling also for variable structure and switching strategies, like for example sliding-modes see e.g. [34].

The control loop synthesis self, despite shown up more than one degrees-of-freedom as robust and efficient already in nineties, remains also a promising field of research for the motion control applications. By and large, more closing a gap to the control theory remains further topical for efficiently bringing the motion control technologies into the future smart systems and industrial applications.

Network-based Control Systems and Applications

With the rapid development of advanced technologies such as communication networks, intelligent sensing and monitoring, intelligent computing, and so on, a smart system is more involved in a large-scale network, providing vital services to sustain the modern technological society. The ever-increasing need for real time, reliable and low-cost network-based control systems is becoming more and more universal, especially in medical, industrial and social fields.

A networked control system (NCS) is spatially distributed, where information exchange between sensors, actuators, and controllers is achieved through a shared band-limited digital communication network [35], as depicted in Fig. 5. It is well acknowledged that such networked configuration has some remarkable advantages of information sharing, energy-saving, and flexibility, thus significantly accommodating the current trend for nowadays Industry 4.0 with wide applications to smart grids, autonomous cars, intelligent traffic systems, manufacturing systems, and unmanned aerial vehicles. However, the usage of communication networks always suffers from various network-induced constraints such as communication delays, packet dropouts, and quantization effects, etc., which may degrade the system performance or even destroy the stable operation. Therefore, it poses new and fundamental issues on how to carry on reliable control design and implementation under various network -induced constraints. Surveys on recent advances in addressing this issue well can be referred to in [36], [37] and reference therein.

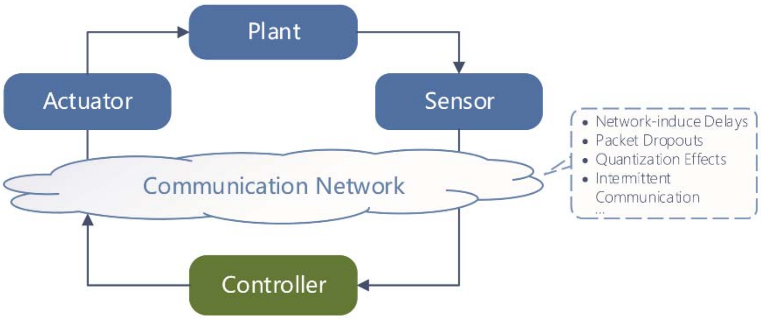

Fig. 5. The configuration of traditional NCSs

In the era of smart systems, since breakthroughs in sensor, actuator, and data transmission technology, versatile intelligent terminals are deployed and connected. The widespread utilization of intelligent terminals and IoT makes it possible, and facilitate to realize versatile interactions with the environment, human, other interfacing and/or networked systems. NCSs have been experiencing a huge configuration transformation from a decentralized framework to a distributed one, as shown in Fig. 6. Therefore, it becomes even more challenging for networked control than before. One of the key challenges focuses on efficiently achieving coordinated control of networked systems while maintaining the quality performance of individual subsystems. In order to confront this challenge, distributed cooperative control provides a promising way for controller design [38]. A prominent characteristic of distributed strategies is that the coordinated functioning is realized by transmitting/receiving information to/from other controllers within a certain neighboring area. That is, each controller only needs to access, and share necessary information of system states or output measurements with local neighboring controllers. The distributed configuration of NCSs can show outstanding advantages in improving scalability, robustness and efficiency, thereby contributing to various applications such as blockchain technology, autonomous cars, smart grids, and so on. Recently, great efforts from researchers have been made on how to design distributed control protocols incorporating network-induced constraints by using only local measurement outputs. Several methods such as distributed sampled-data control, distributed impulsive control, distributed event-triggered control, and distributed strategies based on data quantization, can be referred to in [39] [40]. Some open challenge problems are listed as follows.

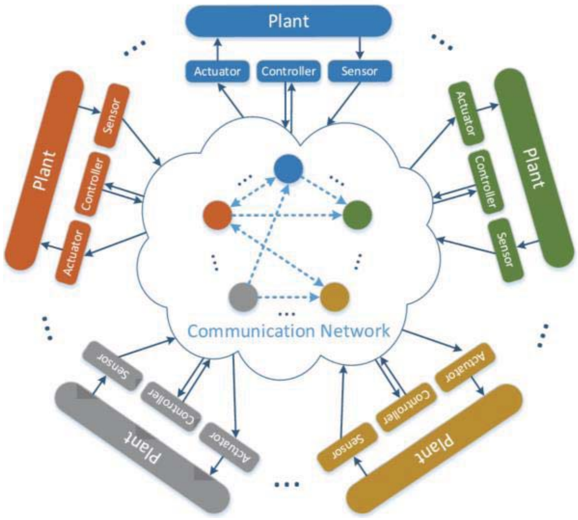

Fig. 6. The configuration of distributed NCSs

In distributed NCSs, another important issue to be addressed carefully is to make efficient use of computational and communication resources. A promising solution to this issue is to adopt an event-triggered control strategy in which the data is only transmitted as needed to maintain the desired performance criteria. This can be realized by well-designed events and triggering rules. Extensive research efforts have been devoted to the design of distributed event-triggering strategy (DETS). Moreover, it is revealed that dynamic DETS can exceed the static one in terms of the consumption of communication resources [40].

Numerous applications of NCSs are safety-critical. While the distributed configuration offers merits of information sharing, scalability, and flexibility, the open network setting gives rise to some security issues suffering from cyber-attacks. Therefore, there is a strong need to develop novel analysis and synthesis tools for distributed NCSs to ensure safe and secure operations against cyber attacks. Some resilient distributed control strategies, such as resilient event-triggered control [41] and resilient impulsive control [42], have received increasing interests recently, whereas remaining in an infant stage and worthy of further study.

Despite a large number of analysis methods and synthesis tools have been well-established for NCSs, there remain many open and challenging issues for future smart systems and industrial applications, such as developing fully distributed resilient control strategies against malicious attacks, designing novel flexible distributed event-triggering schemes, exploring impacts of network structure and constraints on coordinated behaviors in uncertain environments, and so on.

Performance-Oriented Fault Diagnosis and Fault-Tolerant Control: An Integrated Data-Driven Realization

To meet the ever-growing requirements on higher product quality and economic benefit, industrial systems are nowadays designed with higher complexity. Towards this endeavor, advanced intelligent sub-systems and devices are now increasingly being used to enhance the safety and the reliability of the overall process while improving the overall control performance. The most important modules to be designed are the fault diagnosis (FD) and the fault-tolerant control (FTC) systems [43][44][45], the aims of which are to accurately assess the status and the performance of the industrial system and timely provide feasible control actions once an abnormality is detected. The developments seen in the past 30 years in computer science and data networking technologies have enabled the collection of a vast amount of system information that can be effectively shared among the sub-systems towards overall superior control performance. This inspires many studies on data-driven (or model-free) process monitoring and control methodologies, which have become a popular trend both in academic and industrial arenas. Of the developed data-driven process monitoring and control techniques, most of the studies focus on FD and FTC using multivariate analysis [46], subspace-aided methods [47] and signal-based methods [48]. In order to analyze the effects of the system uncertainties and possible changes (component aging, faults, hardware replacement, etc.) on the closed-loop stability, studies on the data-driven performance-oriented FD and FTC methodologies have been presented recently.

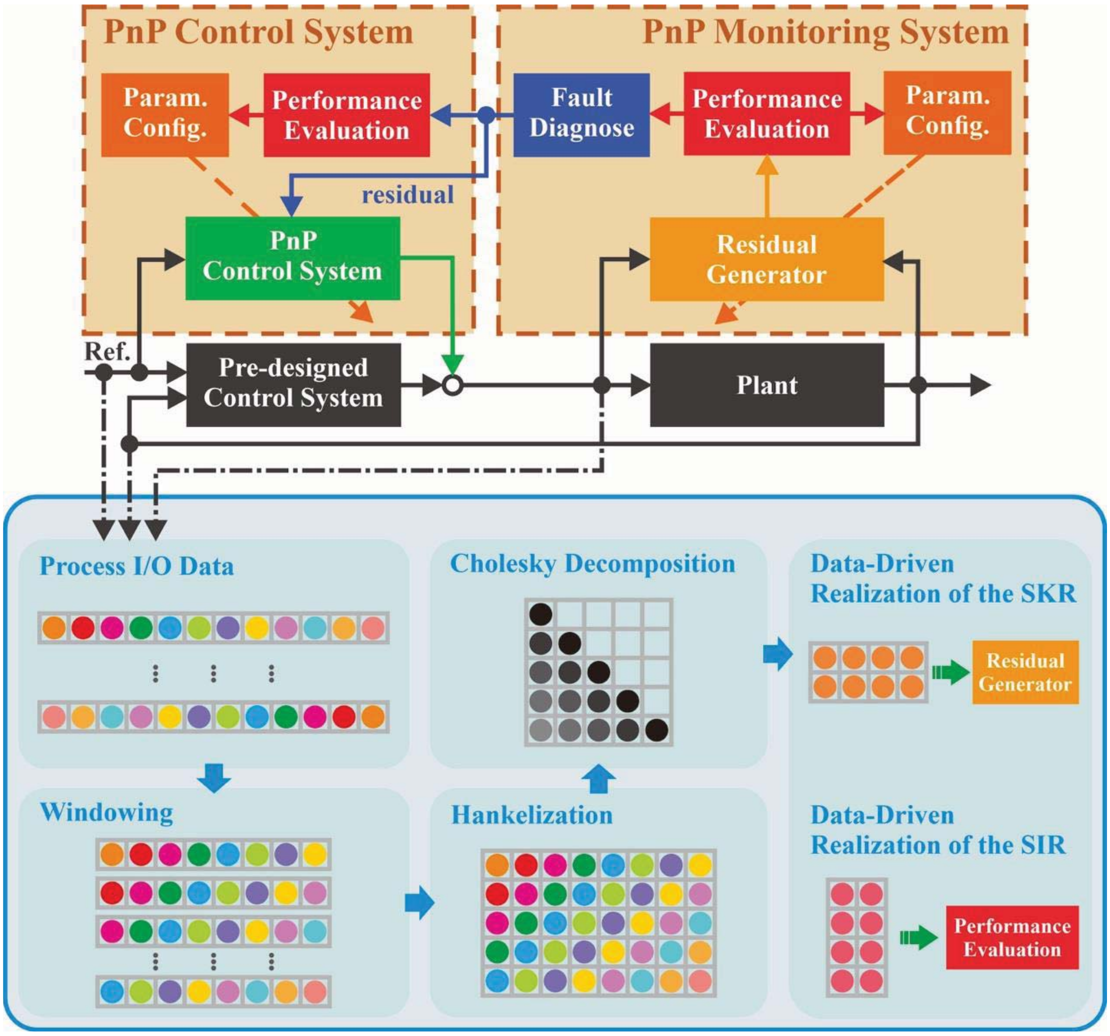

Fig. 7. The PnP-PMCA and its integrated data-driven realization

More specifically, seeking to bridge the gap between model-based and data-driven techniques and to develop a data-driven performance-oriented FD and FTC framework in an integrated manner, a so-called plug-and-play process monitoring and control architecture (PnP-PMCA) [49] is proposed, as shown in Fig. 7. Comparing with conventional FTC strategies, this architecture parameterizes all possible stabilizing feedback controllers and feed-forward controllers based on a pre-designed feedback control structure. In general, this architecture not only avoids the modification of the pre-designed control system and realizes the FD and FTC in a PnP manner, but also provides architectural design reliability and flexibility for the industrial application of advanced monitoring and control methodologies. Secondly, in the process monitoring and control architecture, the data-driven realization of the stability margin is carried out analytically [50], in which the closed-loop identification of the stable image representation (SIR) and stable kernel representation (SKR) of the plant plays an essential role. To meet real industrial practice, robust closed-loop identification approach is introduced to reliably obtain the plant dynamic by analyzing the mappings among the closed-loop process data. Based on the identified data-driven realizations of SIR and SKR, the closed-loop stability margin can be estimated, and recursive/iterative approaches can be adopted for the purpose of online estimation. This enables the developments of advanced performance-oriented FD and FTC methodologies to timely monitor/evaluate the effects of the system changes/faults on the closed-loop stability (a quantification about how severe does a system change/fault effect the whole closed-loop), and furthermore, to reliably guide the proper configurations of the feedback control system to achieve optimal/maximal uncertainty/fault-tolerant ability. The future focus includes the distributed PnP-PMCA, and the corresponding data-driven distributed monitoring and control objectives for large-scale industrial processes with unknown disturbances and model uncertainties.

Conclusions

Robotics and Mechatronics have played a crucial role in industrial automation, and the consequent increment of production efficiency. However, the collaboration between robots and humans taking into account the safety of the human is one of the key aspects to be deepened. Regarding this issue, the Sensor and Actuators and Motion control technologies have much to contribute. Breakthroughs in these areas are awaited for the machines to interact with humans in a smart, flexible, and satisfying way. Some of the promising approaches for the future related to these areas are novel transmission mechanisms, or elasticity from the side of the actuator, and optimal energy shaping for the side of motion control. Moreover, focusing on the sensor module, the development of modern Micro-Electro-Mechanical Systems and nano-technology drives to a high level of integration with its readout circuit leading to the increment in the sensor's functionality and its reduction in size and cost. This enhances the overall performance and robustness of the ever-growing functionality system.

Another relevant demand of the sector is the adaptation to the Internet of Things. The incorporation of data transmission technology is fundamental in this respect. Network control systems have been experiencing a huge configuration transformation from a decentralized framework to a distributed one with the benefits of information sharing, scalability, and flexibility. On the other hand, the need to develop tools to ensure the systems against cyber-attacks has arisen. Another relevant key point regarding reliability, safety, and real-time response is the efficient use of computational and communication resources and the incorporation of fault diagnosis and fault-tolerant control systems. This is a way for assuring the improvement of the overall control performance despite the increment of the complexity of designs based on advanced intelligent sub-systems, where possible changes (component aging, faults, hardware replacement, etc.) may occur. Accordingly, the future tendency is to include the distributed plug-and-play process monitoring and to develop control architecture for large-scale industrial processes to deal with large uncertainties and perturbations. Likewise, it has to be highlighted that motion controllers have to be designed in a particularly robust manner about this issue.

All these implementations have risen an increment of the efficiency, versatility, economic benefit, of high-quality products, in charge of covering new requirements of industrial society.

References

[1] M. Hankel, B. Rexroth. Industrie 4.0: The reference architectural model industrie 4.0 (rami 4.0). ZVEI: Die Elektroindustrie, 2015.

[2] C. C. Kuo, J.Z. Shyu, K. Ding. Industrial revitalization via industry 4.0 – a comparative policy analysis among China, Germany and the USA. Global Transitions 1, 3 – 14, 2019. DOI https://doi.org/10.1016/j.glt.2018.12.001.

[3] A. Anderson. Report to the President on Ensuring American Leadership in Advanced

Manufacturing. Executive office of the President, 2011.

[4] M. Fukuyama. Society 5.0: Aiming for a new human-centered society. Japan Spotlight pp. 47–50, 2018.

[5] Paxton, C., Hundt, A., Jonathan, F., Guerin, K. and Hager, G.D., 2017, May. CoSTAR: Instructing collaborative robots with behavior trees and vision. In 2017 IEEE international conference on robotics and automation (ICRA) (pp. 564-571). IEEE.

[6] Evjemo, L.D., Gjerstad, T., Grøtli, E.I. et al. Trends in Smart Manufacturing: Role of Humans and Industrial Robots in Smart Factories. Curr Robot Rep 1, 35–41 (2020). https://doi.org/10.1007/s43154-020-00006-5

[7] B. Shu, G. Sziebig and S. Pieskä, "Human-Robot Collaboration: Task Sharing Through Virtual Reality," IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, 2018, pp. 6040-6044, doi: 10.1109/IECON.2018.8591102.

[8] Pang, C., Lee, C. and Suh, K.Y., 2013. Recent advances in flexible sensors for wearable and implantable devices. Journal of Applied Polymer Science, 130(3), pp.1429-1441.

[9] Stankovski, S., Ostojić, G. and Zhang, X., 2016. Influence of Industrial Internet of Things on Mechatronics. Journal of Mechatronics, Automation and Identification Technology, 1(1), pp.1-6.

[10] S. Haddadin, A. De Luca, and A. Albu-Schaffer, “Robot collisions: A survey on detection, isolation, and identification,” IEEE Transactions on Robotics, vol. 33, no. 6, pp. 1292–1312, 2017.

[11] B. Vanderborght, A. Albu-Schaeffer, A. Bicchi, E. Burdet, D. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh, M. Garabini, M. Grebenstein, G. Grioli, S. Haddadin, H. Hoppner, A. Jafari, M. Laffranchi, D. Lefeber, F. Petit, S. Stramigioli, N. Tsagarakis, M. V. Damme], R. V. Ham], L. Visser, and S. Wolf, “Variable impedance actuators: A review,” Robotics and Autonomous Systems, vol. 61, DOI https://doi.org/10.1016/j.robot.2013.06.009, no. 12, pp. 1601 – 1614, 2013.

[12] H. Matsuki, K. Nagano, and Y. Fujimoto, “Bilateral drive gear - a highly backdrivable reduction gearbox for robotic actuators,” IEEE/ASME Transactions on Mechatronics, vol. 24, DOI 10.1109/TMECH.2019.2946403, no. 6, pp. 2661–2673, Dec. 2019.

[13] D. Okumura, S. Sakaino, and T. Tsuji, “High dynamic range sensing by a multistage six-axis force sensor with stopper mechanism,” in 2018 IEEE International Conference on Robotics and Automation (ICRA), pp. 4065–4070, 2018.

[14] J. Lee, C. Lee, N. Tsagarakis, and S. Oh, “Residual-based external torque estimation in series elastic actuators over a wide stiffness range: Frequency domain approach,” IEEE Robotics and Automation Letters, vol. 3, DOI 10.1109/LRA.2018.2800128, no. 3, pp. 1442–1449, Jul. 2018.

[15] S. Eppinger and W. Seering, “Understanding bandwidth limitations in robot force control,” in Proceedings. 1987 IEEE International Conference on Robotics and Automation, vol. 4, pp. 904–909, Mar. 1987.

[16] C. Ott, A. Albu-Schaffer, A. Kugi, and G. Hirzinger, “On the passivity-based impedance control of flexible joint robots,” IEEE Transactions on Robotics, vol. 24, no. 2, pp. 416–429, Apr. 2008.

[17] K. Haninger and M. Tomizuka, “Robust passivity and passivity relaxation for

impedance control of flexible-joint robots with inner-loop torque control,” IEEE/ASME Transactions on Mechatronics, vol. 23, no. 6, pp. 2671–2680, 2018.

[18] G. Meijer, Smart Sensor System. Wiley Publisher, 2014.

[19] J. Lu, H. Okada, T. Itoh, T. Harada and R. Maeda, "Toward the World Smallest Wireless Sensor Nodes With Ultralow Power Consumption," in IEEE Sensors Journal, vol. 14, no. 6, pp. 2035-2041, June 2014.

[20] M. Ahmed, W. Xu, S. Mohamad, M. Duan, Y. Lee and A. Bermak, "Integrated CMOS-MEMS Flow Sensor With High Sensitivity and Large Flow Range," in IEEE Sensors Journal, vol. 17, no. 8, pp. 2318-2319, 15 April15, 2017.

[21] Y. Du, D. Wu, Z. Song, M. Liu, S. Yang and Z. Wang, "3-D Integration of MEMS and CMOS Using Electroless Plated Nickel Through-MEMS-Vias," in Journal of Microelectromechanical Systems, vol. 25, no. 4, pp. 770-779, Aug. 2016.

[22] Y. Li, "Challenges and Issues of Using Polymers as Structural Materials in MEMS: A Review," in Journal of Microelectromechanical Systems, vol. 27, no. 4, pp. 581-598, Aug. 2018.

[23] H. Kamata, M. Kimishima, T. Sawada, Y. Suga, H. Takeda, K. Yamashita, et al., "MEMS Gyro Array Employing Array Signal Processing for Interference and Outlier Suppression," in 2020 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL), 2020, pp. 1-4.

[24] B. O. Annaidh, P. Fitzgerald, H. Berney, R. Lakshmanan, N. Coburn, S. Geary, et al., "Devices and Sensors Applicable to 5G System Implementations," in 2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G), 2018, pp. 1-3.

[25] K. Makinwa, A. Baschirotto and P. Harpe, Low-Power Analog Techniques, Sensors for Mobile Devices, and Energy Efficient Amplifiers. Springer, 2019.

[26] N. Niksefat and N. Sepehri, “Designing robust force control of hydraulic actuators despite system and environmental uncertainties,” IEEE Control Systems Magazine, vol. 21, no. 2, pp. 66–77, 2001.

[27] R. J. Anderson and M. W. Spong, “Hybrid impedance control of robotic manipulators,” IEEE Journal on Robotics and Automation, vol. 4, no. 5, pp. 549–556, 1988.

[28] S. Haddadin, A. De Luca, and A. Albu-Sch¨affer, “Robot collisions: A survey on detection, isolation, and identification,” IEEE Transactions on Robotics, vol. 33, no. 6, pp. 1292–1312, 2017.

[29] K. Ohnishi, N. Matsui, and Y. Hori, “Estimation, identification, and sensorless control in motion control system,” Proc. IEEE, vol. 82, no. 8, pp. 1253–1265, 1994.

[30] R. Ortega, A. J. Van Der Schaft, I. Mareels, and B. Maschke, “Putting energy back in control,” IEEE Control Systems Magazine, vol. 21, no. 2, pp. 18–33, 2001.

[31] M. Ruderman, M. Iwasaki, and W.-H. Chen, “Motion-control techniques of today and tomorrow: A review and discussion of the challenges of controlled motion,” IEEE Industrial Electronics Magazine, vol. 14, no. 1, pp. 41–55.

[32] M. Ruderman and M. Iwasaki, “Observer of nonlinear friction dynamics for motion control,” IEEE Transactions on Industrial Electronics, vol. 62, no. 9, pp. 5941–5949, 2015.

[33] B. Armstrong-H´elouvry, P. Dupont, and C. C. De Wit, “A survey of models, analysis tools and compensation methods for the control of machines with friction,” Automatica, vol. 30, no. 7, pp. 1083–1138, 1994.

[34] Y. Shtessel, C. Edwards, L. Fridman, and A. Levant, Sliding mode control and observation. Springer, 2014.

[35] X. Zhang, Q.-L. Han, X. Ge, L. Ding, D. Yue and C. Peng, ``Networked control systems: a survey of trends and techniques," IEEE/CAA Journal of Automatica Sinica, vol. 7, no. 1, pp. 1--17, Jan. 2020.

[36] J. Hespanha, P. Naghshtabrizi, and Y. Xu, ``A survey of recent results in networked control systems," Proc. IEEE, vol. 95, no. 1, pp. 138--162, Jan. 2007.

[37] R. Gupta and M. Chow, ``Networked control system: Overview and research trends," IEEE Trans. Ind. Electron., vol. 57, no. 7, pp. 2527--535, Jul. 2010.

[38] Y. Cao, W. Yu, W. Ren and G. Chen. ``An overview of recent progress in the study of distributed multi-agent coordination," IEEE Trans. Ind. Infor., vol. 9, no. 1, pp. 427--438, Feb. 2013.

[39] W. He, T. Luo, Y. Tang, W. Du, Y.-C. Tian, F. Qian, ``Secure communication based on quantized synchronization of chaotic neural networks under an event-triggered strategy," IEEE Trans. Neural Networks and Learning Systems, 2019, DOI: 10.1109/TNNLS.2019.2943548, to be published.

[40] W. He, B. Xu, Q.-L. Han, and F. Qian, ``Adaptive consensus control of linear multi-agent systems with dynamic event-triggered strategies," IEEE Trans. Cybernetics, vol. 50, no. 7, pp. 2996–3008, Jul. 2020.

[41] W. Xu, D.W.C. Ho, J. Zhong, and B. Chen, "Event/self-triggered control for leader-following consensus over unreliable network with DoS attacks," *IEEE Trans. Neural Networks and Learning Systems*, vol. 30, no. 10, pp. 3137--3149, 2019.

[42] W. He, F. Qian, Q.-L. Han, G. Chen, ``Almost sure stability of nonlinear systems under random and impulsive sequential attacks," *IEEE Trans. Automatic Control*, 2020, DOI: 10.1109/TAC.2020.2972220, to be published.

[43] L. Chiang, E. Russell and R. Braatz, Fault Detection and Diagnosis in Industrial Systems. London: Springer, 2001.

[44] I. Hwang, S. Kim, Y. Kim and C.E. Seah, “A survey of fault detection, isolation, and reconfiguration methods,” IEEE Transactions on Control Systems Technology, vol. 18, no. 3, pp. 636–653, 2010.

[45] S.X. Ding, Model-based Fault Diagnosis Techniques - Design Schemes Algorithms and Tools, 2nd Ed., Springer, 2013.

[46] S. Qin, “Statistical process monitoring: basics and beyond,” Journal of Chemometrics, vol. 17, pp. 480–502, 2003.

[47] B. Huang and R. Kadali, Dynamic Modeling, Predictive Control and Performance Monitoring: A Data-Driven Subspace Approach. London: Springer, 2008.

[48] Z. Gao, C. Cecati and S. X. Ding, "A Survey of Fault Diagnosis and Fault-Tolerant Techniques—Part I: Fault Diagnosis With Model-Based and Signal-Based Approaches," IEEE Transactions on Industrial Electronics, vol. 62, no. 6, pp. 3757-3767, 2015.

[49] H. Luo, S. Yin, T. Liu and A. Q. Khan, "A Data-Driven Realization of the Control-Performance-Oriented Process Monitoring System," IEEE Transactions on Industrial Electronics, vol. 67, no. 1, pp. 521-530, 2020.

[50] H. Luo, X. Yang, M. Krueger, S. Ding, and K. Peng, “A plug-and-play monitoring and control architecture for disturbance compensation in rolling mills,” IEEE/ASME Transactions on Mechatronics, vol. 23, no. 1, pp. 200–210, 2018.