Perspective

Automation 5.0: The Key to Systems Intelligence and Industry 5.0

By Ljubo Vlacic, *Life Senior Member, IEEE*, Hailong Huang, *Senior Member, IEEE*, Mariagrazia Dotoli, *Fellow, IEEE*, Yutong Wang, *Member, IEEE*, Petros A. Ioannou, *Life Fellow, IEEE*, Lili Fan, Xingxia Wang, *Student Member, IEEE*, Raffaele Carli, *Member, IEEE*, Chen Lv, *Senior Member, IEEE*, Lingxi Li, *Senior Member, IEEE*, Xiaoxiang Na, *Member, IEEE*, Qing-Long Han, *Fellow, IEEE*, Fei-Yue Wang, *Fellow, IEEE*

AUTOMATION has come a long way since the early days of mechanization, i.e., the process of working exclusively by hand or using animals to work with machinery. The rise of steam engines and water wheels represented the first generation of industry, which is now called Industry 1.0. Subsequently, Industry 2.0 witnessed the development of electric power and assembly lines. Later on, programmable logic controllers and Human Machine Interfaces (HMI) were the new productivity tools in Industry 3.0, which enabled precise and consistent production. In recent years, Industry 4.0 absorbed the latest technologies of Internet of Things (IoT), Artificial Intelligence (AI), and big data, making production processes integrated, interconnected, and smart. Nowadays, Industry 5.0 has been proposed, which emphasizes human-centric automation. Specifically, the new concept of automation in Industry 5.0, named Automation 5.0, is no longer about how to create machinery to replace humans. Instead, it aims to reach organic interactions and cooperation between humans and machines, meeting the goal of "6S" - Safety, Security, Sustainability, Sensitivity, Service, and Smartness [1]–[4] - and the overall objective of deploying automation for the better, human-friendly, and smarter industry.

In this perspective, we briefly address several crucial aspects of Automation 5.0, including human-centric automation, AI-empowered automation, parallel intelligence for automation, and knowledge automation. In addition, the potential trends of future development are discussed accordingly.

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L. Vlacic is with the Institute of Intelligent and Integrated Systems and the School of Engineering and Built Environment, Griffith University, Nathan, QLD 4111, Australia (e-mail: l.vlacic@griffith.edu.au).

H. Huang is with the Department of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University, Hong Kong, China (e-mail: hailong.huang@polyu.edu.hk).

M. Dotoli and R. Carli are with the Department of Electrical and Information Engineering, Polytechnic of Bari, 70126 Bari, Italy (e-mail: mariagrazia.dotoli@poliba.it; raffaele.carli@poliba.it).

Y. Wang is with the State Key Laboratory of Multimodal Artificial Intelligence Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, and also with the Qingdao Academy of Intelligent Industries, Qingdao 266114, China (e-mail: yutong.wang@ia.ac.cn).

P. Ioannou is with the Department of Electrical Engineering-Systems, University of Southern California, Los Angeles, CA 90007 USA (e-mail: ioannou@usc.edu).

L. Fan is with the School of Automation, Beijing Institute of Technology, Beijing 100081, China (e-mail: lilifan@bit.edu.cn)

X. Wang is with the State Key Laboratory of Multimodal Artificial Intelligence Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, the School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing 100049, and the Beijing Huairou Academy of Parallel Sensing, Beijing 101499, China (e-mail: wangxingxia2022@ia.ac.cn).

C. Lv is with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore (e-mail: lyuchen@ntu.edu.sg).

L. Li is with the Department of Electrical and Computer Engineering, Purdue School of Engineering and Technology, Indiana University-Purdue University Indianapolis, Indianapolis, IN 46202 USA (e-mail: ll7@iupui.edu).

X. Na is with the Department of Engineering, University of Cambridge, CB2 1TN Cambridge, U.K. (e-mail: xnhn2@eng.cam.ac.uk).

Q.-L. Han is with the School of Science, Computing and Engineering Technologies, Swinburne University of Technology, Melbourne VIC 3122, Australia (e-mail: qhan@swin.edu.au).

F.-Y. Wang is with the State Key Laboratory for Management and Control of Complex Systems, Chinese Academy of Sciences, Beijing 100190, the School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing 100049, the Dazhou Artificial Intelligence Institute, Dazhou, and the Faculty of Innovation Engineering, Macau University of Science and Technology, Macau 999078, China (e-mail: feiyue.wang@ia.ac.cn).

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Human-centric Automation

In Automation 5.0, the various industrial automation systems, for instance, an industrial robotic arm or an unmanned ground vehicle, need to fully collaborate with human beings. To this end, it is necessary to understand humans' intentions timely and correctly. Different from Industry 3.0, where automation systems simply accept commands of humans via HMIs, or Industry 4.0, where the commands are sent and actioned via IoT in a passive, non-interactive manner, Automation 5.0 requires industrial automation systems to interact with human operators in the factory actively [5], [6]. Hence, in this paradigm the new type of interaction goes beyond the traditional touch pads or tablets and includes active perception via either onboard force/torque sensors, visual sensors, microphones, or factory-mounted motion capture systems; see e.g., Fig. 1. While the industrial automation systems can process measurements directly in the former case, in the latter case, IoT technology is required to share the centrally captured information with particular segment(s) of automation systems. From a perspective of Decentralized Autonomous Organizations (DAO) [7]–[11], active perception via onboard sensors is the trend of future factories thanks to the scalability [12]–[16]. While using force/torque sensors and visual sensors for human intention estimation is still limited due to their low accuracy [17], the recent generative AI technology [18] allows for the linguistic interaction between humans and automation systems. For example, as noted in [18], ChatGPT is trained on a wide range of subjects, therefore its depth of understanding on specialized issues may not be as great as that of highly experienced specialists in a particular field. Although linguistic interactions are believed to be more accurate and efficient than conventional ways using force/torque and visual sensors, applying generative AI tools such as ChatGPT still requires customization. Therefore, ensuring accurate human intention estimation via conventional sensors and customizing generative AI tools with domain knowledge are two alternatives to achieve a timely and correct understanding of humans in Automation 5.0 for the industry.

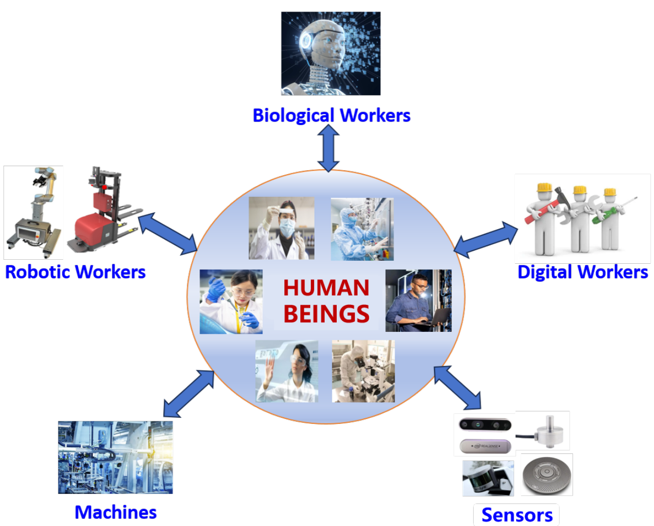

Fig. 1. Human-centric automation in Automation 5.0.

AI-empowered Automation

Conventional industrial robots are mainly pre-programmed and then repeat certain designed operations. Such robots definitely have high productivity but cannot meet the requirement of smartness and service under the umbrella of Automation 5.0, as they are unable to interact. AI has experienced a super-fast development stage, and quite a lot of technologies are now accessible. Such technologies can make a big difference to conventional industrial robots by enabling on-the-job learning. Indeed, on-the-job learning (interactive) robots refer to those who can get new information and grasp new knowledge during operation. The interactive ability enables robots to become cooperative, i.e., to assist their human partners in achieving new levels of efficiency and quality [19].

In Automation 5.0, on-the-job training works well for both human workers and robots [20]. Innovative technologies like Augmented Reality (AR) and Virtual Reality (VR) provide a means of facilitating experiential learning for industrial training, either in a virtual or actual machine or factory [21]. For the training of human workers, a typical mode previously adopted by many companies is to ask the human workers to practice on the production lines. Undoubtedly, a small error by inexperienced human workers may result in a serious impact on normal production. In recent years, such training has been conducted using AR and VR technologies with semi-physical entities. For example, to assemble a certain product, the material is seen as a real entity but the assembly line can go into virtual. Then, the human workers' training process will not impact normal production. The training of robots, conducting it directly in a factory may also cause safety issues, especially at the very beginning stage of training. With the aforementioned technologies, both the robots and the environment can be digital; see e.g., Fig. 2. Specifically, the Digital Twin (DT) technology can now be adopted to create a virtual factory based on the sensing information of the corresponding real factory. Using the dynamic models of the robots, virtual robots could also be deployed in the virtual factory [22], [23]. Moreover, human-in-the-loop training can also be conducted by combining the DT and AR/VR technologies [24]. So, various functions of the robots could be trained and tested in the virtual environment, which will not cause any damage to the real environment or create safety issues for the human workers in the training stage. Therefore, it is more favourable to design advanced automation system by way of using AI technologies-based design tools instead of going through a costly and time-consuming design process if/when traditional technologies-based design tool is in use.

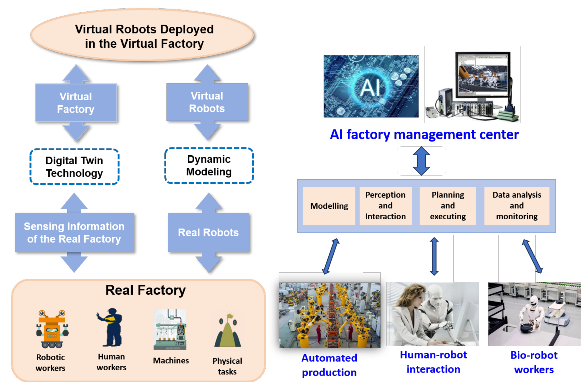

Fig. 2. Examples of AI-empowered automation.

Parallel Intelligence for Automation

Fei-Yue Wang and his research team started in 1999 to work on creating a theory for AI called Parallel Intelligence (PI) in Cyber-Social-Physical Space (CSP, later renamed to CPSS, Cyber-Physical-Social Systems) [25], [26] which become the foundation for their Industry 5.0 Initiative in 2014 [27]. The proposal of PI-based Control 5.0 [28] and subsequent Metacontrol to "transform" actual reality into virtual reality, achieving the Virtual-Real Duality (VRD) of control, lays the technical foundation for Automation 5.0. Wang proposed in his theory of parallel philosophy that Leibniz's ideas about Monad [29], coupled with Popper's theory of Three Worlds [30], are the philosophical forebears of PI and Industry 5.0. The philosophical basis for PI and related parallel industries comes from the philosophical conflict between idealism's "way of truth" and materialism's "way of opinion" as well as their contrary. The Three Worlds model refers to Being in the physical world, Becoming in the mental world, and Believing in the artificial world [31], [32]. Accordingly, traditional information technologies were invented to enrich the physical world, past information technologies flourished in the mental world, while contemporary cooperative information technologies are enabling the fulfilment of Automation 5.0 requirements, see e.g., Fig. 3. Wang made the effort to promote the idea that the future would be a parallel era of virtual-real interactions, noting that Industry 5.0 equals the first generation of PI, i.e., Parallel 1.0 [33], [34].

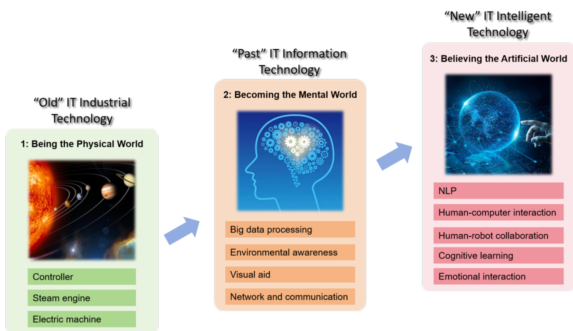

Fig. 3. Believing the Artificial World.

While PI is a promising field, it also presents difficulties and ethical questions. Effectively coordinating and integrating several intelligent entities can be difficult, since these may each have unique objectives, prejudices, and constraints. With proper design and engineering, these entities can ensure smooth communication and prevent conflicts. Transparency and fairness are two typical ethical concerns in PI. When AI and human labor are integrated, i.e., co-operate, it becomes unclear who is ultimately accountable for the choices taken and the outcomes resulted. Establishing transparent accountability structures and making sure that judgments by both cooperative entities are justifiable and explicable is essential.

Knowledge Automation

Although the focus of Automation 5.0 is not to replace human workers with machines, freeing humans from physical and mental work is an important goal of automation systems. With the aforementioned technologies, machines shall become more capable than ever before, i.e., a cooperative. However, the wisdom of humans, especially the abilities of creative thinking and logical analysis, is still not available in the current automation systems.

Knowledge Automation [35], [36] is a novel approach to distributing intelligence throughout an organization. A popular instance is self-service. In banks, hospitals, airports, and supermarkets, lots of manpower can be saved thanks to self-service machines. the purpose of quickly serving their customers and reducing manpower costs. Phone services share the same idea. However, this initial stage of self-service is limited. Although updates can be made after launching, the users may not easily find their needs via the self-services especially when they are new to the users.

In the last decade, a significant milestone of Knowledge Automation was AlphaGo, a type of Algorithmic Intelligence, suggesting that any efficient method for solving difficult decision-making issues can be applied using an AlphaGo-like method [37]. Another milestone in terms of Linguistic Intelligence is that of the so-called Large Language Models (LLMs) [38], and a typical model is ChatGPT. Language models are computational models that can comprehend and produce human language. Language models are transformational enough to forecast the probability of words occurring in a certain order and generate new text based on input. However, language models also have to deal with issues including overfitting, difficult-to-capture complicated linguistic context, and uncommon or unseen words. LLMs are sophisticated language models with large parameter sizes and outstanding learning capabilities that can intake information from the end user, understand the information and context, and generate answers accordingly [39], [40]. Different from the aforementioned initial stage of self-services, LLMs are nowadays able to solve users' queries directly without asking users to dig into the service themselves. Moreover, LLMs-supported new generation of self-services can take the users' knowledge and also learn from the users' input to further develop the cores of the LLMs (see Fig. 4). Such exciting features have attracted the attention of both academia and industry. The latest milestone in the direction of Imaginative Intelligence [41] is Sora, which can generate realistic and imaginative scenes from test instructions [42]. Powered by Sora, the next milestone is expected to be scenarios engineering [43]–[46], which aims to achieve more trustworthy AI through Intelligence & Index (I&I), Calibration & Certification (C&C), and Verification & Validation (V&V).

Nevertheless, the development of Knowledge Automation via tools like AlphaGo, LLMs, and Sora is still facing various issues [47]. The one that comes first is the trustworthiness. In particular, whether the results of these tools comply with regulations, values, and social standards is a key obstacle preventing their usage in various critical scenarios such as healthcare and education. To this end, a systematic evaluation tool is needed.

Concluding Remarks

Automation 5.0 is a key enabling technology for Industry 5.0. We discussed several important aspects of Automation 5.0 in this perspective. Industry 5.0 emphasizes human-centric automation, and the current technologies for actively and precisely understanding the intention of biological workers are still under development. AI technologies have empowered various automation systems, and on-the-job learning supported by AI technologies is expected to enable safe, low-cost, and time-efficient tools. Another essential component of Automation 5.0 is PI, which enables several agents to work on the same issue simultaneously and cooperatively, thereby, increasing

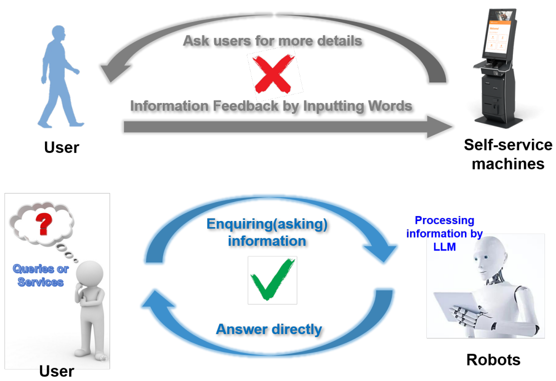

Fig. 4. Difference between the initial stage of self-services and LLMs-supported self-services.

efficiency. However, the transparency and fairness of PI are two typical ethical concerns. It is crucial to set up open accountability and ensure that decisions are reasonable and understandable. Knowledge automation is also a key aspect of Automation 5.0. Recent technologies such as LLMs have created lots of possibilities. However, their trustworthiness is still under concern, and much work is needed to comprehensively evaluate LLMs to ensure their outcomes align with regulations, ethical values, and social standards. More importantly, while multiple specific directions are well under development, it is still necessary to consider the overall design from the perspectives of the organization level, coordination level, and execution level [48], which serves as a systematic guidance for the further development of Automation 5.0 and the guarantor of integrated systems.

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About the Author

Ljubo Vlacic (Life Senior Member, IEEE) Bio of Ljubo Vlacic can be found at https://ieeexplore.ieee.org/author/37284636100.
Hailong Huang (Senior Member, IEEE) Bio of Hailong Huang can be found at https://ieeexplore.ieee.org/author/37085839743.
Mariagrazia Dotoli (Fellow, IEEE) Bio of Mariagrazia Dotoli can be found at https://ieeexplore.ieee.org/author/37300909600.
Yutong Wang (Member, IEEE) Bio of Yutong Wang can be found at https://ieeexplore.ieee.org/author/37088758926.
Petros A. Ioannou (Life Fellow, IEEE) Bio of Petros A. Ioannou can be found at https://ieeexplore.ieee.org/author/37281518200.
Lili Fan Bio of Lili Fan can be found at https://ieeexplore.ieee.org/author/37089635745.
Xingxia Wang (Student Member, IEEE) Bio of Xingxia Wang can be found at https://ieeexplore.ieee.org/author/37089629764.
Raffaele Carli (Member, IEEE) Bio of Raffaele Carli can be found at https://ieeexplore.ieee.org/author/37085348833.
Chen Lv (Senior Member, IEEE) Bio of Chen Lv can be found at https://ieeexplore.ieee.org/author/37086095836.
Lingxi Li (Senior Member, IEEE) Bio of Lingxi Li can be found at https://ieeexplore.ieee.org/author/37293042500.
Xiaoxiang Na (Member, IEEE) Bio of Xiaoxiang Na can be found at https://ieeexplore.ieee.org/author/37085545267.
Qing-Long Han (Fellow, IEEE) Bio of Qing-Long Han can be found at https://ieeexplore.ieee.org/author/37274962400.
Fei-Yue Wang (Fellow, IEEE) Bio of Fei-Yue Wang can be found at https://ieeexplore.ieee.org/author/37277656000.