Robotics 4.0 – Are we there yet?

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Abstract—**Robotics is one of the major megatrends unfolding this decade. Robots are capable of doing more and more as becoming detached from the assembly lines, and service robots are starting to have an impact on the whole society. This paper deals with establishing the overarching theme and context of the quite few exciting novel aspects of automated technologies: Industry 4.0 in the factories, robots on the roads, as self driving cars, and robots in the operating theaters, performing not only teleoperated surgeries but complex, delicate procedures. A robotics taxonomy should be developed clearly identifying the types and functions of such robots, assessing their key components and capabilities. Both the common sense and the standardized definitions of these robots should be agreed by the community of developers, manufacturers and users. Ensuring the safety of such hybrid control systems requires a good understanding of the technology from the user side and novel and efficient human–machine interfaces. This will lead to increased transparency and trust towards these systems, which shall have a positive effect on the robot development procedures, increasing safety.**

Index Terms—**Robotics 4.0, autonomous systems, internet of robotic things, internet of skills, cloud robotics**

I. INTRODUCTION

Robotics and Artificial Intelligence (AI) are often cited as the dominating, transformational technology trends of our times. While both have been around for several decades, the more recent advances in mechatronics, controllers and machine learning jointly opened new, very successful application domains, as illustrated in Fig. 1. While a robot traditionally consists already of hardware and software components, the importance of machine intelligence and decision making means that AI is addressed more than just the cognitive controller block of a robot, on the contrary, robots many times are just denoted as the embodiment of AI algorithms [1]. Arguably, AI can have numerous application domains apart from robotics, e.g., Deep Learning (DL) in image processing [2], but in this paper, we only focus on the physical application of robotics, and the AI supporting it directly.

Robotics has changed from being just part of a particular industry domain, and service robotics is now growing at an unprecedented pace, steamed by the rise of consumer robotics (Fig. 2). This means that robotics is joining the megatrends in human history (such as internet, mobile communication, 3D printing), profoundly shaping the entire society, and may help to resolve some of the Grand challenges we face[1].

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[1] https://www.un.org/en/sections/issues-depth/global-issues-overview/

Fig. 1. Robotics is becoming mainstream due to the recent advances in safety and applicability, yet the domain is often over-hyped, and therefore general communication should reflect the true technological advancements of the field. Image credit: Haidegger [3].

II. THE CORE OF ROBOTICS

It has been a long professional debate to unambiguously define a robot, its components. The traditional *ISO 8373 - Robots and robotic devices – Vocabulary* standard under the International Organization for Standardization (ISO) Technical Committee (TC) 299 has revised its official definition numerous times in the past years to incorporate all new domains and forms of robots, while excluding household appliances and simple machines. The key distinguishing factors are autonomy, mobility and task oriented behavior. The current official definition of a robot being ''*programmed actuated mechanism with a degree of autonomy, moving within its environment, to perform intended tasks*", wherein autonomy is defined as *"ability to perform intended tasks based on current state and sensing, without human intervention"*. The standard also distinguishes core application areas of robotics, such as industrial and service domains (Fig. 3).

To support the relevant R&D initiatives, the first IEEE standard came out in 2015, the *1872-2015 – IEEE Standard Ontologies for Robotics and Automation*, which is now followed by many other standards within the same family. The IEEE 1872 defines a robot in a broader sense: *"An agentive device (Agent and Device in SUMO) in a broad sense, purposed to act in the physical world in order to accomplish*
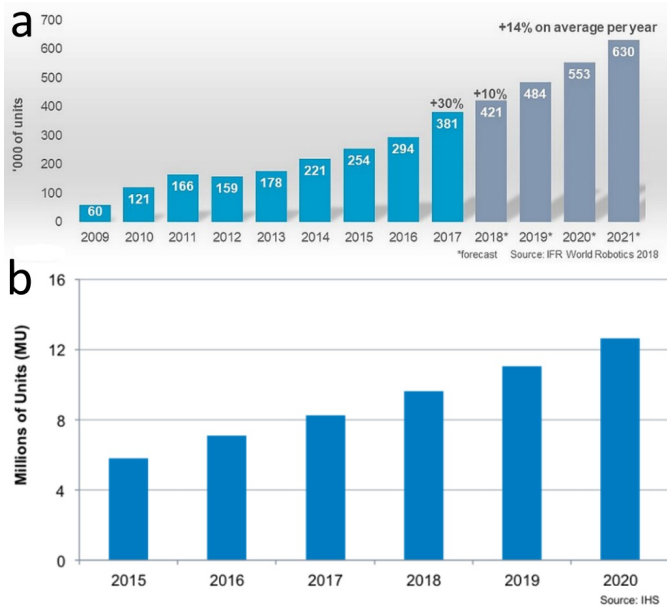
Fig. 2. The number of robot sales is massively increasing globally. a) The number of industrial robot units sold annually. b) Service robot deployment has increased dramatically in the past years.

Fig. 3. Basic categories of robots according to the ISO 8373 [5].

one or more tasks. In some cases, the actions of a robot might be subordinated to actions of other agents (Agent in SUMO), such as software agents (bots) or humans. A robot is composed of suitable mechanical and electronic parts. Robots might form social groups, where they interact to achieve a common goal. A robot (or a group of robots) can form robotic systems together with special environments geared to facilitate their work."

Certain application domains could also rely on definition standards, e.g., for medical robots [4]; the ISO/IEC TC 62/SC 62D joint committee started to work on the minimum requirements to provide for a practical degree of safety for surgical robots in 2015. The result of the work, the *IEC 80601-2-77: Particular requirements for the basic safety and essential performance of robotically assisted surgical equipment* and the *IEC/CD 80601-2-78: Particular requirements for the basic safety and essential performance of medical robots for rehabilitation, compensation or alleviation of disease, injury or disability* are to be published in 2019.

In 2018, the IEEE Engineering in Medicine and Biology (EMB) (co-sponsored by the IEEE Robotics and Automation Society (RAS)) started a new working group: *IEEE P2730 Standard for Classification, Terminologies, and Definitions of Medical Robots*, with the scope to specify the category, naming and definition of medical robots [5].

Nevertheless, the numerous additional elements and components of a complete robotic system are still under getting proper definitions, including the tools and concepts of *Human–Robot Interfaces (HRI)* and interactions. There still may exist a gap (and sometimes overlap) between the definitions, thus the *IEEE Robotics and Automation Society (RAS)* initiated a Standards Strategy meeting series in conjunction with its flagship conferences, where all the leading Standard Develop-
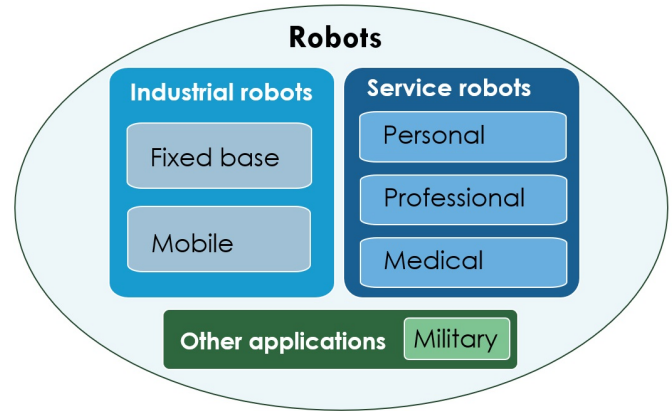
ing Organizations' representative gather to work on the open issues.

These official definitions all remain very conservative, as the aim of standards is generally to codify an already widely accepted consensus. Certain areas are excluded on purpose, such as military and toys. Nevertheless, these still generate a lot of public attention, and sometimes, the borderline is very fine [6]. Given the fast pace of technology development, new terms and "buzzwords" emerge. These are reviewed and put into the bigger context of robotic R&D in the following Section.

III. CUTTING EDGE ROBOTICS

Understanding the fact that robotics means much more today than mechatronics, the term *Cyber-Physical System* (CPS) is often used, defined as "*a mechanism that is operated, controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users*"[2], emphasizing the importance of the user and the interface (HRI).

Certain terms are often used, but do not refer to one particular technology, rather a set of technology components—linked to applications. The best example is *Networked Robotics*, which has been a classical term for functionally collaborating robots over a network. Naturally, this domain includes telerobotics and remote controlled robots [7]. Networked robotics has seen many paraphrasing, with overlapping meanings (Fig. 4). A collection of most commonly used robotics terms referring to the integration of some ICT technologies in certain application scenarios that evolved over time:

- **Networked robotics**: *"multiple robots operating together coordinating and cooperating by networked communication to accomplish a specified task"* [8]; remained the most general term for this domain.
- **Swarm robotics**: *"an approach to the coordination of multiple robots as a system which consist of large numbers of mostly simple physical robots"* [9]; mostly refers to the application of large number of low capability robots.

[2]https://www.inderscience.com/jhome.php

- **Collaborative robot** (co-bot): *"a robot intended to physically interact with humans in a shared workspace"* [10]; most often used for industrial manipulators able to operate safely in a shared human–robot environment.
- **Cloud robotics**: *"robots connected to modern cloud-computing infrastructure for access to distributed computing resources [. . .], the ability to share training and labeling data for robot learning"* [11]. Most typically, the control and the learning capabilities of the robot are driven through the cloud application.
- **Fog robotics**: *"robot systems that efficiently distribute computation and memory between edge, gateway, and cloud devices to address privacy and security (in analogy with Fog Computing)"*; where the key distinguishing factor is that fog is closer to end-users, bringing cloud capabilities down to the ground.[3]
- **Dew robotics**: *"analogous with dew computing; where the tasks are extremely distributed over a large number of devices, which are heterogeneous, ad-hoc programmable and self-adaptive. It makes possible to realize highly distributed applications without the use of central nodes."* The emphasize here is on the architecture and on the use of the resources available on the ground [12].
- **Cognitive robotics**: *"endowing a robot with intelligent behavior by providing it with a processing architecture that will allow it to learn and reason about how to behave in response to complex goals in a complex world"* [13]. The term expresses the decision making, reasoning and knowledge gathering and sharing capabilities of a robot. It has been often used by the European Commission to describe new generation robots.
- **Smart robot**: *"an embodied AI system that can learn from its environment and its experience and build on its capabilities based on that knowledge"* [14], which definition is much in line with a cognitive robot.
- **Ubiquitous robotics**: *"integrating robotic technologies with technologies from the fields of ubiquitous and pervasive computing, sensor networks, and ambient intelligence"* [15]; referring to the extended capabilities that cloud robotics offers, being deployed across various domains.
- **Internet of Robotic Things (IORT)**: *"sensor and data analytics technologies from the IoT are used to give robots a wider situational awareness that leads to better task execution"* [16]; a generalist term that covers all of the above.

IV. ROBOT GENERATIONS

In the past five years, Industry 4.0 has become a driving keyword in the field of automation. "4.0" refers to *"the fourth industrial revolution, the trend of automation and data exchange in manufacturing technologies that includes CPS, Internet of Things (IoT), cloud computing and cognitive computing"* [17]. Analogously, several other fields started

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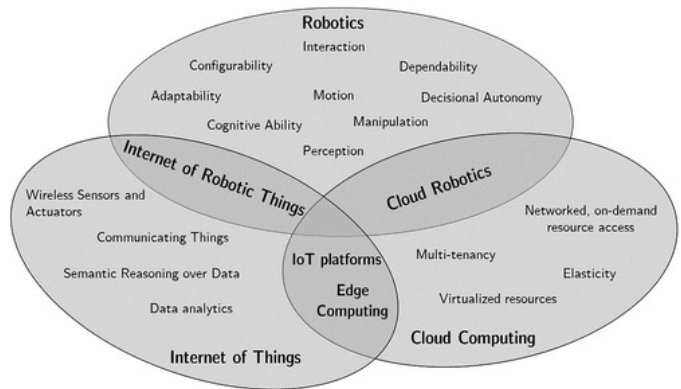[3]https://goldberg.berkeley.edu/fog-robotics

Fig. 4. Most common terms around the Internet of Robotic Things concept [16].

to claim their 4.0 revolution—including robotics. While it is important to recognize the contribution robots make to industrial automation (already at Industry 3.0 level), the stage of 4.0 comes not only from the application of networked robots, but means a change in application paradigm, and being a combination of smart approaches, including agile production management, re-configurable production lines and value-oriented manufacturing.

As for the generations of robotics itself, "pre-historical" 0.0 generation could refer to simple mechatronic structures without any degree of autonomy.

- **Robotics 1.0**: pre-programed and teleoperated systems formulate the two major early control paradigms in robotics, that already lead to wide adaption e.g., along assembly lines or in nuclear facilities. Traditionally, tele-operation solved all the cognitive problems (involving the human in the control loop), even in most challenging domains, such as space robotics and medicine [18].
- **Robotics 2.0**: means sensor-driven robotics, which powers collaborative robots. Primarily, integrated force/torque sensing was a key enabling technology here [19], which eventually led to an officially recognized new robot category even in standards term (*ISO/TS 15066:2016 Robots and robotic devices Collaborative robots, and also the ISO 13482:2014 Robots and robotic devices Safety requirements for personal care robots*). Most of the current service robots falls under this category, which requires close human–robot interaction [20].
- **Robotics 3.0**: may be distinguished from the above in terms of the system's autonomous capabilities. Given a higher degree of autonomy [21], these robots can present complex behaviors and complete safety-critical tasks in the proximity of humans. It may be referred to as "human-centered robotics", and fits very well to the concept of CPS. Self-driving cars at higher Level of Autonomy (LoA) 3+ belong here [22], along with advanced surgical robots [21]. Particular application of cloud robotics, fog robotics also fall here [11].
- **Robotics 4.0**: will mean the next revolutionary jump in

the technology integration, the synergies of all of the above. Most probably, it will start off with the trends identified under IORT [16], and will largely rely on the high level automation of cognitive knowledge e.g., via Data Science[4] and ontologies [23].

V. Enabling factors of Robotics 4.0

In the followings some "gamechanger" aspects of a new era in robotics is discussed in more details.

A. Advanced networked robotics

Cloud robotics—as the ultimate form of networked robot—was first mentioned almost 10 years ago [24], and applied solutions are only now appearing for this domain. A single isolated robot has limited resources in terms of computing power (CPU) and memory. Furthermore, in the case of mobile robots, energy storage is the most limiting factor that implies a trade-off between mobility, manipulation performance and computing power available on-board. Obviously, physical actuators cannot be displaced from the robot, thus, the rest of the robot's functions are to be delegated into the cloud. Industrial and retail sectors rise high demand against robots requiring advanced cognitive capabilities, that are hardly manageable using onboard resources exclusively, while also providing a fair battery last.

We can define *Cloudsourcing* in robotics as the software architecture strategy, which introduces distributed control by delegating the execution of certain tasks into external and virtualized computing resources.

The most extreme implementation of cloudsourcing is when only the sensing, low-level actuation (servo) and communication functions remain onboard, for which we propose the name *"Zombiebotics"*. In such an extreme case, every higher-level cognitive task is performed remotely that implements remote controlled robots governed by software running on networked virtualized resources.

Leading cloud technologies like OpenStack [25] and Docker [26] that empower many services of the major providers (AWS, Google, Microsoft, IBM, etc.) form a solid basis for robotic applications. Each layer of generic cloud services have a clear analogy in networked robotics:

- **Software as a Service (SaaS)** layer manifests the robot functions that are in direct connection with the robot that relies on the remote services. Robots consumes remote services through APIs (e.g., RESTful, GraphQL) that are interfaces between the robot and the service backend that implements the task logic. Without a claim to completeness, the highest affinity tasks to cloudsourcing are computer vision, speech processing and other Natural Language Processing (NLP) tasks, Simultaneous localization and mapping (SLAM), path planning, grasp planning, etc.
- **Platform as a Service (PaaS)** concept includes the cloud-based utilization of fundamental services, such

as databases, various runtime environments and more specific frameworks for e.g., machine learning. The PaaS hides the hardware-related details from the service consumer, and provides auto-scaling, monitoring and other high-level management features. For roboticists, popular platforms like NodeJS or Python application engines are available. More robotics-specific platforms are also on the way, e.g., Microsoft is about to provide ROS (Robot Operating System) as a service along with IoT data hub service in Azure[5].

- **Infrastructure as a Service (IaaS)** layer provides the bare computing resources in terms of CPU, GPU, memory and disk capacity. At this level, there is no robotics-specific characteristics of the cloud services. In some cases however, availability of GPU or TPU (Tenzor Processing Units) are required especially in computer vision and neural network-based applications. Cloud providers offer virtualized and bare metal servers too.

Benefits of cloudsourcing for networked robots includes:

- Energy efficiency;
- Weight and size reduction;
- Practically unlimited memory and computing power;
- Increased intelligence;
- Multiple alternative solutions of each tasks (competition).

Cloudsourcing introduces vulnerabilities as well, especially in the cybersecurity domain [27], [28]. Different application areas have their own security standards, which may or may not allow for introducing external resources. Large-scale public clouds, on-premises private cloud environments are the two extremes that should be considered in the architecture design.

Boosting effect of client-side technologies is similarly relevant. Community-driven and open source software components can be easily integrated into robot software of any complexity, that reduces product development time by multiple factors.

All the above derives to **Robotics as a Service (RaaS)**, defined as a virtual model (sometimes only referring to a business model), which is the combination of AI solutions, cloud computing and shared services as described [29].

B. Superfast Internet

In robot system architecture, location of task execution is a critical decision. Battery size, CPU performance, storage and memory are the main aspects that must be considered. Besides these well defined characteristics, the allowable time-delay in a given task execution is the most critical. Advances of wired and wireless communication seriously influences the architectural decisions.

Rich sensory representations, e.g., RGB-D and point cloud requires very high bandwidth. New generation of vision sensors often require USB 3.0+ (e.g., Intel RealSense [30]) or 10 Gigabit Ethernet (e.g., PhotoNeo MotionCam) connection, that shows the increasing demands. 5G mobile communication is aimed at providing near optimal circumstances that would

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[4]https://towardsdatascience.com/data-science-trends-for-2019-11b2397bd16b

[5]https://ms-iot.github.io/ROSOnWindows/

satisfy the requirements of stiff force-based interactions [31]. This is a critical condition which constraints the implementation of the Tactile Internet concept, which is defined as "*an internet network that combines ultra low latency with extremely high availability, reliability and security*" [32].

Currently, in lack of robust and reliable long-range client–server connection, safety-critical tasks and other real-time functions must be running on-board in short loop including all sensing, control and actuation component within the given robotic device.

In spite of the difficulties with superfast and reliable data connection, a large set of less critical task can be cloudsourced using existing technologies. These functions are for example vision and audio-based HRI, longer-range robot navigation or grasp planning[6].

On-board vs. cloudsourced spectrum spreads from the conventional industrial approach that puts everything on-board, to the entirely cloud-based robots, where the physical device is only responsible for sensing and actuation. Virtual assistants, like Amazon's Alexa or the Google Home devices are precursors of the zombiebotics era. The above examples currently lack locomotion capabilities, but it is easy to imagine the next level of development, where the digital assistant technology and Internet of skills move into mechanically capable humanoids.

C. Machine Learning for hard problems

Among various machine learning approaches, deep neural networks gained special attention in the robotics community. A general review on the frequently used DL methods can be found in [33], while other surveys have a sharper focus: Robot control through reinforcement learning [34], [35], robotic manipulation and grasping [35], [36], mobile robot navigation [36] and transfer learning for robotics [36], [37], to mention a few. These outstanding surveys show the complex landscape of robotics-related DL applications.

One popular direction is the so-called end-to-end technique that addresses the perception and control tasks via a single DL model [38]–[40]. In these methods, solutions for perception and actuation are not clearly separable. In robotics, these models are usually used for motion control (e.g., object manipulation) based on complex sensory input (e.g., vision) to perform a given task.

Common characteristics of any robot-application (excluding HRI) is that the operation is manifested in motion and manipulation in order to perform a useful task. From this viewpoint, different types of robots i.e., robotic arms and mobile robots can be considered uniformly. Even though the tasks of robotic manipulation and mobile robotics differ significantly, the solutions introduced in current literature utilize similar methodologies and both can be divided into motion planning, and motion control parts.

Apart from DL, the hierarchical temporal memory model should be mentioned, that is also utilized in certain object recognition and navigation-related problems [41], [42].

[6]https://ai.googleblog.com/2019/02/long-range-robotic-navigation-via.html

Despite the spectacular results of DL-based experiments, one must be cautious regarding the scalability of the end-to-end approach. Often, the results are only valid for a very specific problem and for a given robot, that was used through the training. A balanced combination of analytical methods (e.g., for kinematics, dynamics and control) and machine learning shall outperform end-to-end learning in terms of generalization and flexibility.

D. Internet of Skills (IoS) for robots

The above discussed technical advances are necessary conditions of new generation robotics (Robotics 3.0+). Through these factors, the fundamental paradigms of high-level robot control are not only changing in terms of the geographical locations of the physical resources, but shifting to a next level. The cognitive robot capabilities forms a dynamically evolving networked ecosystem. In this newly forming cyber-physical control world [43], robot skills are going to be services consumed through the Internet, that are continuously evolving by the collected experience of millions of robots.

A similar transformation has already happened recently with the non-physical Internet, where the separated WWW servers (providing static HTML content) transformed into complex cross-dependent networks of servers and services. We refer to this ecosystem as Internet of Skills [31]. Technically, there exists no more barrier to implement IoS for the most demanded functions, and actually we can see such services in each large cloud providers for NLP and image processing.

VI. DISCUSSION AND FUTURE PROSPECTS

Arguably, it is hard to predict the advent of a new robotics era, yet there are several contributing factors that should be observed. Evolutionists and revolutionists will always argue, but the constellation of a set of powerful technologies can indeed lead to a new generation of robotics, the same way Industry 4.0 was forged due to the integration of robotics, big data, rapid prototyping, AR/VR, IoT, simulation and cloud computing.

Networked robotics capabilities will efinitely a key role. Moving beyond the traditional ISO definitions, walls between the narrow mechatronics meaning of robotics and the neighboring ICT technologies has completely disappeared. Latest robot generations either in industrial or service domain are depending on computing and telecommunications solutions that are extensively used in general purpose IT. The conventionally very conservative robotics community became open to exploit the synergies of fields like computer science, AI and the cognitive mechatronics.

Besides the pure technological aspects, we also witness a paradigm shift in the human compatibility of robotics. Following the concepts Cognitive Info-communications [44], robot builders are optimizing the cognitive couplings between humans and robots beyond the traditional HRI. As a result, robots evolve from complete isolation to interconnected, human-centric CPSs.

The next generation of robots will surely be able to provide services at every segment of the human life, therefore they will change our lives dramatically. By now, technically every major country has a protocol or script how to approach the Robotics and AI domain, however, hardly anyone is prepared for the sudden changes that are imminent. To better understand the role of robotics in the society, the IEEE RAS initiated a Delphi study, which shall conclude in 2019, focusing on robotic governance [45]. Leading professional organizations and industry players have a major responsibility in bounding the technology that will shape our future.

REFERENCES

[1] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*. Berlin, Heidelberg: Springer–Verlag, 2007.

[2] A. I. Károly, R. Fullér, and P. Galambos, "Unsupervised Clustering for Deep Learning: A tutorial survey," *Acta Polytechnica Hungarica*, vol. 15, no. 8, pp. 29–53, 2018.

[3] P. Barattini, F. Vicentini, G. Singh Virk, and T. Haidegger, *Human-Robot Interaction: Safety, Standardization, and Benchmarking*. Boca Raton, FL: CRC Press, 2019.

[4] M. Hoeckelmann, I. J. Rudas, P. Fiorini, F. Kirchner, and T. Haidegger, "Current capabilities and development potential in surgical robotics," *International Journal of Advanced Robotic Systems*, vol. 12, no. 5, p. 61, 2015.

[5] T. Jacobs, J. Veneman, G. S. Virk, and T. Haidegger, "The flourishing landscape of robot standardization [industrial activities]," *IEEE Robotics & Automation Magazine*, vol. 25, no. 1, pp. 8–15, 2018.

[6] A. Takacs, G. Eigner, L. Kovács, I. J. Rudas, and T. Haidegger, "Teacher's kit: Development, usability, and communities of modular robotic kits for classroom education," *IEEE Robotics & Automation Magazine*, vol. 23, no. 2, pp. 30–39, 2016.

[7] L. Márton, Z. Szántó, T. Haidegger, P. Galambos, and J. Kövecses, "Internet-based bilateral teleoperation using a revised time-domain passivity controller," *Acta Polytechnica Hungarica*, 2017.

[8] V. Kumar, D. Rus, and G. S. Sukhatme, "Networked robots," *Springer Handbook of Robotics*, pp. 943–958, 2008.

[9] Y. Tan and Z.-y. Zheng, "Research advance in swarm robotics," *Defence Technology*, vol. 9, no. 1, pp. 18–39, 2013.

[10] M. B. Popović, *Biomechanics and robotics*. Pan Stanford, 2013.

[11] S. Jordan, T. Haidegger, L. Kovács, I. Felde, and I. Rudas, "The rising prospects of cloud robotic applications," in *2013 IEEE 9th International Conference on Computational Cybernetics (ICCC)*. IEEE, 2013, pp. 327–332.

[12] A. Botta, L. Gallo, and G. Ventre, "Cloud, fog, and dew robotics: architectures for next generation applications," *preprint http://wpage.unina.it/a.botta/pub/dewRobotics.pdf*, 2019.

[13] Y. Liu, Z. Tian, Y. Liu, J. Li, F. Fu, and J. Bian, "Cognitive modeling for robotic assembly/maintenance task in space exploration," in *International Conference on Applied Human Factors and Ergonomics*. Springer, 2017, pp. 143–153.

[14] R. Murphy, R. Murphy, M. I. of Technology (Cambridge), and R. Arkin, *Introduction to AI Robotics*, ser. A Bradford book. MIT Press, 2000.

[15] J.-H. Kim, K.-H. Lee, Y.-D. Kim, N. S. Kuppuswamy, and J. Jo, "Ubiquitous robot: A new paradigm for integrated services," in *Proceedings 2007 IEEE international conference on robotics and automation*, 2007, pp. 2853–2858.

[16] P. Simoens, M. Dragone, and A. Saffiotti, "The internet of robotic things: A review of concept, added value and applications," *International Journal of Advanced Robotic Systems*, vol. 15, no. 1, p. 1729881418759424, 2018.

[17] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios," in *2016 49th Hawaii International Conference on System Sciences (HICSS)*, 2016, pp. 3928–3937.

[18] A. Takács, D. Á. Nagy, I. Rudas, and T. Haidegger, "Origins of surgical robotics: From space to the operating room," *Acta Polytechnica Hungarica*, vol. 13, no. 1, pp. 13–30, 2016.

[19] O. Khatib, "A unified approach for motion and force control of robot manipulators: The operational space formulation," *IEEE Journal of Robotics and Automation*, vol. RA-3, no. 1, pp. 43–53, 1987.

[20] M. Zinn, O. Khatib, B. Roth, and J. K. Salisbury, "Playing it safe [human-friendly robots]," *IEEE Robot. Automat. Mag.*, vol. 11, no. 2, pp. 12–21, 2004.

[21] T. Haidegger, "Autonomy for surgical robots: Concepts and paradigms," *IEEE Trans. on Medical Robotics and Bionics*, vol. 1, no. 2, pp. 1–15, 2019.

[22] A. Takacs, I. Rudas, D. Bosl, and T. Haidegger, "Highly automated vehicles and self-driving cars [industry tutorial]," *IEEE Robotics & Automation Magazine*, vol. 25, no. 4, pp. 106–112, 2018.

[23] D. Á. Nagy, T. D. Nagy, R. Elek, I. J. Rudas, and T. Haidegger, "Ontology-based surgical subtask automation, automating blunt dissection," *Journal of Medical Robotics Research*, p. 1841005.

[24] J. Kuffner, "Robots with their heads in the clouds," *Discovery News*, 2011.

[25] O. Sefraoui, M. Aissaoui, and M. Eleuldj, "OpenStack: Toward an Open-source Solution for Cloud Computing," *International Journal of Computer Applications*, vol. 55, pp. 38–42, Oct. 2012.

[26] C. Anderson, "Docker [Software engineering]," *IEEE Software*, vol. 32, no. 3, pp. 102–c3, May 2015.

[27] V. DiLuoffo, W. R. Michalson, and B. Sunar, "Robot Operating System 2: The need for a holistic security approach to robotic architectures," *International Journal of Advanced Robotic Systems*, vol. 15, no. 3, pp. 1–15, May 2018.

[28] N. DeMarinis, S. Tellex, V. Kemerlis, G. Konidaris, and R. Fonseca, "Scanning the Internet for ROS: A View of Security in Robotics Research," *arXiv:1808.03322 [cs]*, Jul. 2018, arXiv: 1808.03322. [Online]. Available: http://arxiv.org/abs/1808.03322

[29] O. Vermesan, A. Bröring, E. Tragos, M. Serrano, D. Bacciu, S. Chessa, C. Gallicchio, A. Micheli, M. Dragone, A. Saffiotti *et al.*, "Internet of robotic things: converging sensing/actuating, hypoconnectivity, artificial intelligence and iot platforms," 2017.

[30] L. Keselman, J. Iselin Woodfill, A. Grunnet-Jepsen, and A. Bhowmik, "Intel realsense stereoscopic depth cameras," in *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR) Workshops*, July 2017.

[31] M. Dohler, T. Mahmoodi, M. A. Lema, M. Condoluci, F. Sardis, K. Antonakoglou, and H. Aghvami, "Internet of skills, where robotics meets AI, 5g and the Tactile Internet," in *2017 European Conference on Networks and Communications (EuCNC)*, Jun. 2017, pp. 1–5.

[32] G. P. Fettweis, "The Tactile Internet: Applications and Challenges," *IEEE Vehicular Technology Magazine*, vol. 9, no. 1, pp. 64–70, Mar. 2014.

[33] H. A. Pierson and M. S. Gashler, "Deep learning in robotics: A review of recent research," *CoRR*, vol. abs/1707.07217, 2017. [Online]. Available: http://arxiv.org/abs/1707.07217

[34] J. Kober, J. A. Bagnell, and J. Peters, "Reinforcement learning in robotics: A survey," *The International Journal of Robotics Research*, vol. 32, no. 11, pp. 1238–1274, Sep. 2013.

[35] S. Amarjyoti, "Deep reinforcement learning for robotic manipulation - the state of the art," *CoRR*, vol. abs/1701.08878, 2017. [Online]. Available: http://arxiv.org/abs/1701.08878

[36] L. Tai and M. Liu, "Deep-learning in mobile robotics - from perception to control systems: A survey on why and why not," *CoRR*, vol. abs/1612.07139, 2016. [Online]. Available: http://arxiv.org/abs/1612.07139

[37] B. D. Argall, S. Chernova, M. Veloso, and B. Browning, "A survey of robot learning from demonstration," *Robotics and autonomous systems*, vol. 57, no. 5, pp. 469–483, 2009.

[38] S. Levine, P. Pastor, A. Krizhevsky, and D. Quillen, "Learning hand-eye coordination for robotic grasping with deep learning and large-scale data collection," *CoRR*, vol. abs/1603.02199, 2016. [Online]. Available: http://arxiv.org/abs/1603.02199

[39] M. Bojarski, D. D. Testa, D. Dworakowski, B. Firner, B. Flepp, P. Goyal, L. D. Jackel, M. Monfort, U. Muller, J. Zhang, X. Zhang, J. Zhao, and K. Zieba, "End to end learning for self-driving cars," *CoRR*, vol. abs/1604.07316, 2016. [Online]. Available: http://arxiv.org/abs/1604.07316

[40] S. Levine, C. Finn, T. Darrell, and P. Abbeel, "End-to-end training of deep visuomotor policies," *The Journal of Machine Learning Research*, vol. 17, no. 1, pp. 1334–1373, 2016.

[41] X. Zhang, J. Zhang, and J. Zhong, "Toward navigation ability for autonomous mobile robots with learning from demonstration paradigm: A view of hierarchical temporal memory," *International Journal of Advanced Robotic Systems*, vol. 15, no. 3, pp. 1–14, May 2018.

[42] ——, "Skill Learning for Intelligent Robot by Perception-Action Integration: A View from Hierarchical Temporal Memory," 2017.

[43] P. Galambos, I. J. Rudas, L. Zhang, and S.-F. Su, "Cyber-physical control," *Complexity*, vol. 2018, 2018.

[44] P. Baranyi, A. Csapo, and G. Sallai, *Cognitive Infocommunications (CogInfoCom)*. Springer, 2015.

[45] D. Boesl and M. Bode, "Signaling sustainable robotics a concept to implement the idea of robotic governance," in *IEEE International Conference on Intelligent Engineering Systems (INES)*, 2019, pp. 1–6.