Internet of Robotic Things: current technologies, applications, challenges and future directions

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***Abstract*—Nowadays, the Internet of Things (IoT) concept is gaining more and more notoriety bringing the number of connected devices to reach the order of billion units. Its smart technology is influencing the research and developments of advanced solutions in many areas. This paper focuses on the merger between the IoT and robotics named the Internet of Robotic Things (IoRT). Allowing robotic systems to communicate over the internet at a minimal cost is an important technological opportunity. Robots can use the cloud to improve the overall performance and for offloading demanding tasks. Since communicating to the cloud results in latency, data loss, and energy loss, finding efficient techniques is a concern that can be addressed with current machine learning methodologies. The aim of this paper is to provide a better understanding and awareness of the new concept of IoRT with its benefits and limitations, as well as guidelines and directions for future research and studies.**

***Index Terms*—Internet of Things (IoT), autonomous systems, network communication, Internet of Robotic Things (IoRT), cloud computing, machine learning.**

I. Introduction

Over the past decades till today, the Internet of Things is experiencing an exponential growth and attention. Its smart technology allows the creation of a network of real-world objects, namely ‘Things’, with the purpose of connecting everything through the ability of exchanging information over the Internet. This revolution is shaping all aspects of the human being life. The IoT concept is being adopted by more and more organizations in several different fields, like military, robotics, healthcare, nanotechnology or space, creating the Internet of X Things, where X is the relevant area. According to the analyst firm Gartner [1], every second 127 new IoT devices are connected to the web which will bring its overall number to reach 75 billion units by 2025. The global spending on the IoT should reach 1.29 trillion dollars during 2020 with a 93% of adoption of the IoT technology by the enterprises.

An area where the Internet of Things technology is finding fertile ground is the robotics. Robotics consists of a modern and fast-evolving technology that is bringing enormous changes in several aspects of human society over the past decades. It can be defined as the branch of engineering that involves the conception, design, manufacture and operation of robots [2]. Its application can range from the execution of repetitive and tedious jobs in a manufacturing line to helping and performing critical or dangerous tasks unaffordable by a human being, such as rescuing in disaster areas or extra-terrestrial operations. The robots initially used in these applications were just single machines with limitation given by the hardware components and the computational abilities. To resolve those issues, the robots are started to be connected through a wired or wireless communication network creating a networked robotic system [3]. However, they suffer from inherent resource constraints which leads to network latency, limited memory and low computational and learning capabilities. Today real-life scenarios demand fast and complex task executions which require sophisticated data analysis and high computational abilities. The solution to these limitations have been recently tried to be addressed in the novel form of Cloud Robotics which takes advantage of a cloud infrastructure to access resources on-demand and to support the operations. However, these systems are affected by new issues like interoperability, network latency, security, quality of service and standardization [4]. The Internet of Robotic Things perfectly fits in this scenario to overcome these constraints by combining together the IoT with robotics and leading to a more efficient, smart, adaptive and also cheaper robotic network solution.

This paper has the aim to provide a comprehensive description of the Internet of Robotic Things concept showing its general architecture, benefits and challenges as well as some practical use cases and guidelines in the hope of giving awareness on this subject and inspiring future research. The rest of the paper is organizes as follows. Section II gives an overview of the IoRT concept, while Section III explains in more details its architecture. Some practical use-case examples are discussed in Section IV. Section V introduces the topic of the regulations and human factor that involve the use of robots in the everyday life together with future directions and guidelines for the IoRT. Finally, the conclusions are addressed in Section VI.

II. Overview of the Internet of Robotic Things

~~The Internet of Robotic Things (IoRT)~~ is the merge between IoT and robotics. The term IoRT was coined by Dan Kara in a report of ABI Research [5] to denote intelligent devices that can monitor events, gather data from a variety of sources and sensors, and exploit both a local and a distributed intelligence to control objects

and determine the best action. More in general, the IoRT can be seen as a global infrastructure enabling advanced robotic services thanks to the interconnection of robotic things. The robotic things can exploit the advantages of modern communication and interoperable technologies based on the cloud through the IP protocol and its IPv6 version to take benefits regarding data processing, memory storage, computational overhead and security. This mitigates and/or resolves the previous robotics issues. Moreover, the Internet of Robotic Things goes beyond the networked and cloud robotic paradigms by taking advantage of the enabling IoT technologies. This has the aim to integrate heterogeneous intelligent devices empowering enormous flexibility in the design and implementation of a distributed architecture which provides computing resources both in the cloud and at the edge. The IoRT multidisciplinary nature follows the same IoT trend by providing advanced robotic capabilities which leads to the emergence of interdisciplinary solutions for various and different disciplines.
From a technological perspective, IoRT enhances the ordinary robot abilities which are usually classified in 3 groups: basic (perception, motion, manipulation); higher-level (decisional, autonomy, interaction cognitive); and system-level (configurability, adaptability, dependability). To achieve this, in addition to the IoT features, IoRT solutions are supported by other technologies such as: multi-radio access to link smart devices together, artificial intelligence to generate optimized solutions for complex problems, and cognitive technologies to allow operational efficiency.

To summarize, the Internet of Robotic thing is designed to be placed at the summit of the Cloud robotics and combines the IoT technology features with the autonomous and self-learning behavior of connected robotic things to generate advanced and smart solutions making an optimal use of distributed resources.

III. IoRT ARCHITECTURE

The architecture of an Internet of Robotic Things system can be described as being composed by 3 main layers: Physical, Network and Control, Service and Application (Figure 1) [6] [7]. Its composition recalls the typical structure of the OSI model but with a different perspective which takes into account also the robotic part of IoRT.

A. Physical

The physical layer consists of the lowest part of the IoRT architecture. It includes everything related to the hardware components, such as robots, sensors and actuators. The robots can be described as intelligent agents that can communicate between each other and have the ability to establish a more complex system in order to accomplish a specific objective thanks to a sequence of distributed actions. A robot can be represented for example with a vehicle, a drone, a home appliances, or a health care equipment. On the other hand, sensors refer to any kind of system that the agent can use to perceive a data from the surrounding environment, while an

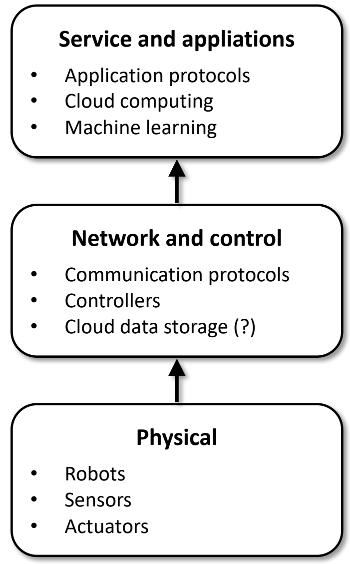

Fig. 1. Internet of Robotic Things architecture overview

actuators to any kind of tool used to perform an action. Both sensors and actuators can also be integrated inside a single robot system to enhance and optimize the performance. As in the standard OSI model, the purpose of the physical layer is to abstract all the technical information and to provide a set of services about its periphery to the network and control layer.

B. Network and Control

Robotic devices are able to send information to other robots or to the cloud using various methods. There are a few main protocols used for communication depending on the range between the sender and receiver and the power required to send data over that range. Using any protocol should allow data to be communicated over the Internet. Common short-range protocols are Wi-Fi, Bluetooth, and 6LoWPAN. Common long-range protocols are SigFox, LoRa, and NB-IoT. 6LoWPAN allows a Low Rate Wireless Personal Area Network (LR-WPAN) to use IPv6. This protocol is particularly used for the IoT for its ability to be low-energy and low-cost which is crucial for small, battery-powered robots or sensors. Protocols that were initially designed for wired networks, such as Precision Time Protocol (PTP), can be adapted for 6LoWPAN [8].

Many of the application areas for the IoRT, such as manufacturing, are high-stakes environments and therefore should have cyber-security measures to protect the network from malicious intent. One way to address the problem of malicious nodes in a network is trustworthiness management [9]. There may be subjective trustworthiness, where every node in a network computes their own trust of other nodes. In contrast, there may be objective trustworthiness, where the trustworthiness of a node lies in a distributed system that is shared among the nodes in the network. Subjective trustworthiness can slow a network down but can be more protected from malicious intent than an objective trustworthiness system.

Looking to the future, one area of research that may show promise in the IoRT is large intelligent surfaces (LIS) [10]. Walls can have a large number of antennas and act as a massive multi-input multi-output (MIMO) system. This technology could allow for more capabilities in a smart environment by making the infrastructure more active. Robots could receive data from large intelligent surfaces and could even interact with them in the case of a wall-climbing robot.

C. Services and Applications

At the application layer, there are several options for protocols. One example is CoAP (Constrained Application Protocol) which uses UDP at the transport layer. It is useful for resource-constrained devices on low-power, lossy networks. The security and applicability of using CoAP for IoT devices is questionable. A more widely used protocol is MQTT (Message Queue Telemetry Transport) which uses a publish/subscribe architecture. MQTT aims to be lightweight and reliable over unreliable networks. A commonly used communication architecture in the IoT is REST, or representational state transfer. It only relies on HTTP methods and its ubiquity is a strength. However, REST adds to the complexity of a robotic system and may be avoided.

Cloud robotics is used to keep robotic things operating at a low power and intelligence level while having a powerful data center to communicate with. Robots may send data to the cloud for mapping and localization, perception, and actuation purposes. The cloud can be accessed for more data that robots may need for training neural networks. The robot can also learn by taking models from the cloud without having to do extra computation. The cloud may provide more general knowledge while the robot learns its local environment. Cloud robotics also allows for human-robot interaction by having humans make decisions for robots or control robots over a network. Having multiple robots communicate over a network simultaneously can result in high latency and data loss. There may be much more data that robots need to send to the cloud or to other robots. For example, streaming LIDAR over WiFi can result in a network failure with multiple robots [11].

It is important for a robot that comes in contact with humans to be able to act and react with humans differently than other robots. To do this, a robot must express personality and connect with the emotions and storytelling of humans so that humans can understand what the robot is doing and for what reason. A robot whose behavior is influenced by a robot can be called a socially responsive robot [12]. A promising technique is when a human can teach a robot the movements of a behavior by showing an example. Reinforcement learning, a subset of machine learning, can be used for the robot to learn the actions and states that make up a behavior, such as dancing, without needing to understand the dynamics of systems. Promising application areas of socially responsive robots are in hospitals and in rehabilitation. A future area for the IoRT is in smart environments, or indoor areas with many types of sensors.

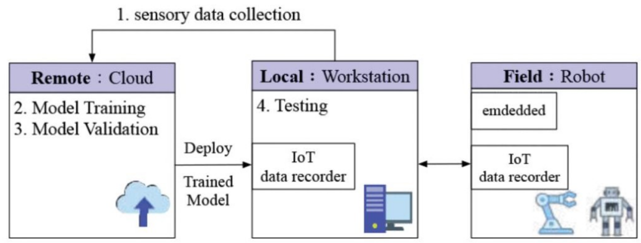

Fig. 2. IoRT in disaster response use case example.

IV. Application domains

IoRT has been widely used in many fields and the machine learning concept is undoubtedly one of the key links. In particular, robots combined with IoT can bring lots of benefits in doing repetitive tasks and in operating in disaster areas where it is unaffordable for a human being to work properly.

A. Disaster response

In [13] the authors exploit an IoRT architecture for a disaster response. A lot of major disasters happen on Earth every year, e.g. earthquakes, tsunamis or typhoons. When a calamity of this magnitude happens, the time is very precious. The most urgent task to achieve is to save as many people as possible in the shortest time. Robots can offer a lot of help in this kind of situations after they have received a deep learning training. In order to accomplish this, the first step is to use mobile robots to collect data from the local environment. A remote network elaborates these data to build an AI model which is evaluated by the internal system. The model is also distributed from the cloud to the local workstation for further performance testing. After it has reached a certain level of reliability, the model is ultimately deployed into the robots for the next level of learning process. The proposed architecture can be schematically represented in Figure 2! This solution can make the robots have enough experience on how to respond to disasters in one area. However, different places might have different environments. If the robot has information about the environment of one single type of place, it cannot be appointed to other places to carry out rescue missions. A solution to this issue is to consider the cloud to store different AI models for various environments. Once a disaster happens, the AI model of that environment can be directly deployed in the robots so that they are immediately able to successfully accomplish the rescue mission in that area.

For example, in the event of an earthquake, the robots might be able to detect the victim's position thanks to their sensors and help on removing reinforced concrete that might have collapsed. Additionally, If a victim is trapped under the ruins and is not able to get out momentarily, the robots can be responsible for transporting food and water to help the victim maintain the nutrition they need. The overall success rate

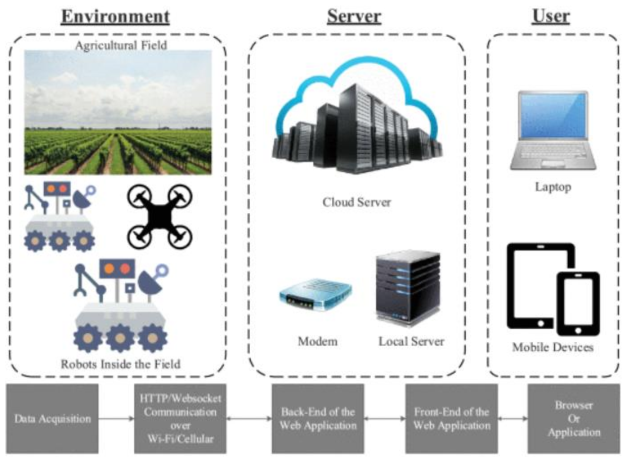

Fig. 3. Conceptual design of the agriculture system.

of rescue operations and the survival rate of victims can be greatly improved thanks to the use of these robots.

B. Precision agriculture

Authors in [14] provide an IoRT application in the field of precision agriculture. In figure 3, there is a sketch of an agricultural IoRT system. The mobile robots in the environment first collect data using on board sensors. The data contain information about temperature, humidity, pressure, light measurement and etc. The server can retrieve these data from the mobile robots using cellular communication or Wi-Fi so that it can process them. After that, the data will be deployed to web applications and the user is able to visualize them it through a website interface. This solution brings the advantages of the IoRT into full play. The mobile robots are able to collect data on-demand instead of the human. These processed data can be used to develop appropriate agricultural plans during climate changes or hazard situations. This will result in a saving of time and resources as well as an increasing of the productivity. However, static robots or devices are also needed in this system to measure weather conditions or provide alarm device in case of hazards. An appropriate website design is a key point to give information easily and to visualize data in a more apprehensive way to the user. Further work can also focus on the subsequent application of the processed data. For example, the users could assign further instructions to mobile robots through web applications after the data acquired have been collected and analyzed.

C. Medical services

Another field where IoRT can bring benefits is the medical one. In [15] authors have developed an application comprising a massage robot. The robot exploits an IoT architecture with sensors to collect data real-time combined and combine them with a smart control system to apply the proper pressures of the desired massage technique. The robot is a mixture of data-mining and brain-based networks. This use case perfectly represents the current trend of the technology showing how the IoRT is fitting in the medical health area. This opens the doors for a huge variety of future development research.

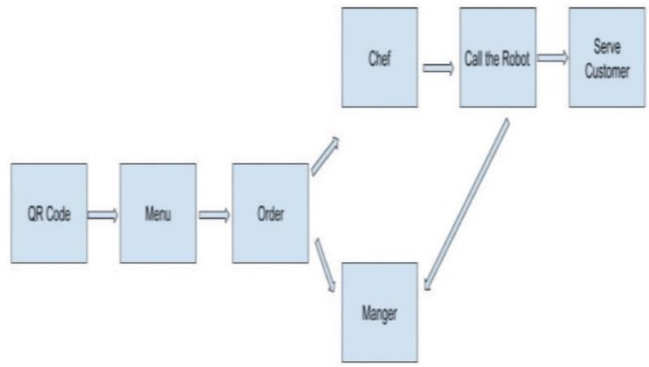

Fig. 4. Main blocks of the waiter robot system.

D. Waiter robots

The revolution in the use of IoRT is shaping all aspects in the people daily's life. In [16] a robot acting as a restaurant waiter is proposed. Figure 4 shows the main blocks of the system. The information about table number and menu are stored in a QR code. The orders are managed by a website and are received by both the cuisine and the manager together with the table number. As soon as the orders are ready, the chef exploits the robot to deliver them to the customers. The whole system is automatic and the information are stored in the cloud. The solution is simple and feasible. However, some key problems still need to be addressed. For example, the robot lacks some emergency measure and it may have issues if the walking route is blocked. Another significant factor is that the waiter robot cannot speak with customers, which may leave a bad impression at the end. Nevertheless, this IoRT solution has the potential to significantly increase the employer profit by reducing the personnel expenses and to provide a faster service to the customers.

In short, the IoRT applications are being largely considered in the academic field and some solutions have been already used to develop a commercial product. With the imminent introduction of 5G and, in the future, of 6G, the IoRT technology has the potential to increase its performance and to continue to be considered a valuable field of research.

V. Challenges and future directions

As a novel area, Internet of Robotic Things is growing rapidly with a promising future. However, it is still facing many challenges, such as lack of regulations, computation and communication problem, and security issues. One task of the future directions of IoRT is to overcome those challenges.

A. Regulations

Until 2019, there was no regulatory framework specifically on IoRT, but only some regulations on relevant technologies may have been applied [17]. For example, in European Union, robots can be regulated as general product under some safety regulations Directive 2001/95/EC. Depending on their use, such as industrial robots or medical devices robots, they may also be subject to specific legislation like Machinery Directive 2006/42/EC or Regulation 2017/745. However, since all those regulations are only for general products or robots, they cannot reflect and regulate the unique and specific needs in the area on IoRT which combines robots and IoT technologies together. One main negative impact is that due to the wide diversity and heterogeneity of IoT and robotics devices, it is usually difficult to integrate, configure, and coordinate the IoRT technologies from different manufacturers based on different standards or regulations [7].

The current situation can be improved by issuing new mandatory regulations by states or voluntary standards by the industry, although this may create some other challenges like how to clarify liability [17]. However, as the usage of IoRT technologies becomes more popular, this will be eventually solved through the collaboration of policymakers, companies, and consumers.

B. Computation and Communication

Because of the dual cyber–physical nature of IoRT, the computation will be mainly conducted on the remote cloud using the wireless network. However, this may bring the following problems:

- Latency on real-time applications, such as mobile robots in a factory, has a considerable impact on the operating efficiency.
- Massive data streaming, such as visual information from a military robot, either requires a significant bandwidth and a super powerful computing cloud, or less powerful local computing capability but on a huge amount of robots.
- Unstable communication in complex environment where IoRT system are commonly facing may significantly reduce the system performance.

To address those issues, some possible solutions are using new computing frameworks and new communication technologies:

- Edge computing, a distributed computing paradigm that brings computation and data storage closer to the location where it is needed, to improve response times and save bandwidth [19].
- Fog computing, an architecture that uses edge devices to carry out a substantial amount of computation, storage, and communication locally and routed over the internet backbone. Some computing strategies may also help to solve this problem, such as the IoRT can take decide whether it is more advantageous to execute the tasks within the IoRT or not [19].
- Terahertz communication, the next generation in wireless communications able to unlock significantly wider bandwidth and higher communication speed at more than 100 Gbit/s.

C. Security Issues

Security is a crucial issue in this area. Many application domains of IoRT have a high demand on the safety and stability among their operations. Security is also a challenging problem, since it is related not only on the security of the Internet of Things but also on the security of the robots. As we discussed above, there are massive amounts of data in the IoRT systems that need to be transmitted between the robots and the cloud as well as between robot and robot. This generates more chances for security failures from leaking sensitive date to cyber-attack. Some typical problems may include [6] [20]:

- Insecure communication between cloud and robot, or robot and robot may cause sensitive data to be exposed or hacked. The less the communication is secured, the easier a hacker breaks in, especially for those professional hacker sponsored by competitors or even foreign governments.
- Authentication failure may allow hackers or unauthorized persons to easily obtain the access to the system, hijacking the parts or even the whole system, and/or sabotaging the robots.
- Robot failures when facing unexpected incidents may worsen the incidents and even cause secondary accidents.

Those cyber-physical security issues can be overcome by the following aspects. For the part of data transmission, using centralized authentication and authorization processes to stream information [21], such as data fragments, distributed responsibility, monitored operator control, and granular authorization, can highly improve the security. Quantum communication is the other possible once and for all solution. For the part of robot, safety redundancy and system backups can help to guarantee the robustness of the system.

As one of the nine key technologies that form the foundation for Industry 4.0 [40] (shown in Figure 5), IoRT is an important area in the future research and studies. The current research are pointing in the right direction to overcome the above challenges in the following years.

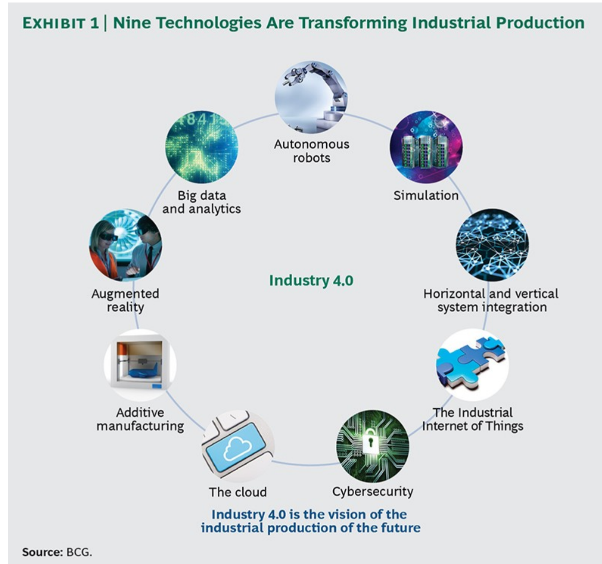

Fig. 5. Nine key technology in Industry 4.0 [40]

VI. Conclusion

The Internet of Robotics Things is an emerging area aiming at integrating robotics technologies into IoT scenarios. Internet of Robotic Things enables robotic systems to communicate with each other, connecting to the cloud and sharing data and knowledge to accomplish sophisticated tasks. For providing a better understanding of IoRT and its future, in this paper, we have reviewed the relevant concepts, technologies, applications, current challenges, and future direction. We discussed the three main layer, physical layer, network and control, and service and applications, in current IoRT architecture. Several typical application domains of IoRT were demonstrated, including disaster response, precision agriculture, and medical services. Some key challenges, such as lack of regulations, computation and communication problem, and security issues are needed to be solved through further research and studies.

References

[1] https://www.gartner.com/, November 2020.

[2] J. L. Fuller, *Robotics*. USA: Prentice Hall PTR, 2nd ed., 1998.

[3] N. Mohamed, J. Al-Jaroodi, and I. Jawhar, "A review of middleware for networked robots," *The International Journal of Computer Science and Network Security*, vol. 9, January 2009.

[4] B. Kehoe, S. Patil, P. Abbeel, and K. Goldberg, "A survey of research on cloud robotics and automation," *IEEE Transactions on Automation Science and Engineering*, April 2015.

[5] "The internet of roboic things," *ABI Research*, p. 20, 2014.

[6] I. Afanasyev *et al.*, "Towards the internet of robotic things: Analysis, architecture, components and challenges," pp. 3–8, October 2019.

[7] L. Romeo, A. Petitti, R. Marani, and A. Milella, "Internet of robotic things in smart domains: Applications and challenges," *Sensors*, vol. 20, pp. 33–55, June 2020.

[8] F. M. Anwar and M. B. Srivastava, "Precision time protocol over lr-wpan and 6lowpan," in *2017 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS)*, pp. 1–6, August 2017.

[9] S. Chinchali *et al.*, "Network offloading policies for cloud robotics: a learning-based approach," February 2019.

[10] S. Hu, F. Rusek, and O. Edfors, "Beyond massive mimo: The potential of data transmission with large intelligent surfaces," *IEEE Transactions on Signal Processing*, vol. 66, pp. 2746–2758, March 2018.

[11] K. Dautenhahn and I. Werry, "Issues of robot-human interaction dynamics in the rehabilitation of children with autism," May 2000.

[12] M. Nitti, R. Girau, and L. Atzori, "Trustworthiness management in the social internet of things," *Knowledge and Data Engineering, IEEE Transactions on*, vol. 26, pp. 1253–1266, May 2014.

[13] M. F. R. Lee and T. W. Chien, "Artificial intelligence and internet of things for robotic disaster response," in *2020 International Conference on Advanced Robotics and Intelligent Systems (ARIS)*, August 2020.

[14] H. Durmuş and E. Gunes, "Integration of the mobile robot and internet of things to collect data from the agricultural fields," in *8th International Conference on Agro-Geoinformatics*, pp. 1–5, July 2019.

[15] W. Si, G. Srivastava, Y. Zhang, and L. Jiang, "Green internet of things application of a medical massage robot with system interruption," *IEEE Access*, September 2019.

[16] T. M. N. U. Akhund *et al.*, "Iot waiter bot: A low cost iot based multi functioned robot for restaurants," in *8th International Conference on Reliability, Infocom Technologies and Optimization*, pp. 1174–1178, October 2020.

[17] E. Fosch Villaronga and C. Millard, "Cloud robotics law and regulation cloud robotics law and regulation. challenges in the governance of complex and dynamic cyber-physical ecosystems," *Robotics and Autonomous Systems*, vol. 119, pp. 77–91, December 2018.

[18] X. Liu, "Research toward iot and robotics in intelligent manufacturing: A survey," *International Journal of Materials, Mechanics and Manufacturing*, vol. 7, pp. 128–132, June 2019.

[19] P. P. Ray, "Internet of robotic things: Concept, technologies, and challenges," *IEEE Access*, vol. 4, pp. 9489–9500, January 2017.

[20] N. Dragoni, A. Giaretta, and M. Mazzara, "The internet of hackable things," in *Proceedings of 5th International Conference in Software Engineering for Defence Applications*, pp. 129–140, Springer International Publishing, 2018.

[21] A. Wegner, J. Graham, and E. Ribble, *Cybersecurity for Industry 4.0: Analysis for Design and Manufacturing*, ch. A New Approach to Cyberphysical Security in Industry 4.0, pp. 59–72. Springer International Publishing, 2017.

[22] 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, February 2018.

[23] R. Batth, A. Nayyar, and A. Nagpal, "Internet of robotic things: Driving intelligent robotics of future - concept, architecture, applications and technologies," in *2018 4th International Conference on Computing Sciences (ICCS)*, pp. 151–160, August 2018.

[24] O. Vermesan *et al.*, "Internet of robotic things intelligent connectivity and platforms," *Frontiers in Robotics and AI*, vol. 7, p. 104, 09 2020.

[25] C. Razafimandimby, V. Loscri, and A. M. Vegni, "A neural network and iot based scheme for performance assessment in internet of robotic things," in *IEEE First International Conference on Internet-of-Things Design and Implementation (IoTDI)*, pp. 241–246, April 2016.

[26] P. Simoens *et al.*, "Internet of robotic things: Context-aware and personalized interventions of assistive social robots (short paper)," in *5th IEEE International Conference on Cloud Networking (Cloudnet)*, pp. 204–207, October 2016.

[27] C. Mahieu *et al.*, "Semantics-based platform for context-aware and personalized robot interaction in the internet of robotic things," *Journal of Systems and Software*, vol. 149, November 2018.

[28] S. Loke, "Are we ready for the internet of robotic things in public spaces?," pp. 891–900, Association for Computing Machinery, 10 2018.

[29] O. Saha and R. Dasgupta, "A comprehensive survey of recent trends in cloud robotics architectures and applications," *Robotics*, vol. 7, 08 2018.

[30] O. Vermesan *et al.*, "Internet of robotic things – converging sensing/actuating, hyperconnectivity, artificial intelligence and iot platforms," in *Cognitive Hyperconnected Digital Transformation, Internet of Things Intelligence Evolution*, pp. 97–155, June 2017.

[31] S. Sabah, N. Qarabash, and H. Obaid, "The road to the internet of things: a survey," in *9th Annual Information Technology, Electromechanical Engineering and Microelectronics Conference (IEMECON)*, pp. 290–296, March 2019.

[32] I. Ud Din *et al.*, "The internet of things: A review of enabled technologies and future challenges," *IEEE Access*, December 2018.

[33] G.-Z. Yang *et al.*, "Combating covid-19—the role of robotics in managing public health and infectious diseases," *Science Robotics*, vol. 5, March 2020.

[34] K. Borner *et al.*, "Mapping the co-evolution of artificial intelligence, robotics, and the internet of things over 20 years (1998-2017)," 06 2020.

[35] A. Patel *et al.*, "Significance of robotics in manufacturing, energy, goods and transport sector in internet of things (iot) paradigm," in *Fourth International Conference on Computing Communication Control and Automation (ICCUBEA)*, pp. 1–4, August 2018.

[36] A. Kamilaris and N. Botteghi, "The penetration of internet of things in robotics: Towards a web of robotic things," January 2020.

[37] M. Kumari, A. Kumar, and R. Singhal, "Design and analysis of iot-based intelligent robot for real-time monitoring and control," in *International Conference on Power Electronics IoT Applications in Renewable Energy and its Control (PARC)*, pp. 549–552, February 2020.

[38] M. Kanwar and A. Loganathan, "Iot based fire fighting robot," in *7th International Conference on Reliability, Infocom Technologies and Optimization (ICRITO)*, pp. 718–723, August 2018.

[39] S. Gvk, D. Sai, T. Adhisaya, P. Aswini, B. Jyotsna, and D. Debabrata, "Robotic extension to iot testbed for indoor environment supervision," in *Third International conference on I-SMAC*, pp. 29–35, December 2019.

[40] M. Rüßmann *et al.*, "Industry 4.0: The future of productivity and growth in manufacturing industries," April 2015.