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A literature survey of the robotic technologies during the COVID-19 pandemic

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ABSTRACT

Since the late 2019, the COVID-19 pandemic has been spread all around the world. The pandemic is a critical challenge to the health and safety of the general public, the medical staff and the medical systems worldwide. It has been globally proposed to utilise robots during the pandemic, to improve the treatment of patients and leverage the load of the medical system. However, there is still a lack of detailed and systematic review of the robotic research for the pandemic, from the technologies’ perspective. Thus a thorough literature survey is conducted in this research and more than 280 publications have been reviewed, with the focus on robotics during the pandemic. The main contribution of this literature survey is to answer two research questions, i.e. 1) what the main research contributions are to combat the pandemic from the robotic technologies’ perspective, and 2) what the promising supporting technologies are needed during and after the pandemic to help and guide future robotics research. The current achievements of robotic technologies are reviewed and discussed in different categories, followed by the identification of the representative work’s technology readiness level. The future research trends and essential technologies are then highlighted, including artificial intelligence, 5 G, big data, wireless sensor network, and human-robot collaboration.

1. Introduction

Since the late 2019, the COVID-19 disease has been spread worldwide. It leads to critical challenges to almost all countries in the world. Until November 2020, there have been 57,639,631 confirmed COVID-19 cases with 1,373,294 deaths globally, according to the statistics of the World Health Organisation (WHO) [1]. Different approaches and technologies are suggested to support the treatment and control of the pandemic, including robots.

In the past, some researchers briefly summarised the robotic applications during a pandemic [2–5]. Khan et al. [6] classified the robot utilisations in healthcare in different categories, including receptionist, nurse, ambulance, telemedicine, serving, cleaning, spraying/disinfection, surgical, radiologist, rehabilitation, food, and outdoor delivery robots. Zeng et al. [7] reviewed the robot applications based on the desired locations, i.e. robots in hospitals, communities, airports, transportations, recreations, hotels, restaurants, attractions and scenic areas. Those reviews have provided an overview of the robotic achievements so far. However, there is still a lack of detailed analysis from the robotic technology’s perspective. Therefore, it is necessary to discuss the key robotic technologies combating the pandemic and to identify future research trends. Thus in this research, a literature survey is conducted, aiming to systematically analyse the research achievements so far.

2. Methodology

The methodology of the literature survey is based on six stages as described underneath.

Formulating the research questions: as mentioned, the main objective of this literature survey is to analyse valuable robotics research during the pandemic and identify future research trends. The reported work aims to answer two Research Questions (RQs) underneath:

RQ1: What are the main research contributions to combat the pandemic from the robotic technologies’ perspective?

RQ2: What are the promising supporting technologies needed during and after the pandemic to help and guide future robotics research?

Searching the extant literature: the next step is searching the literature and making decisions on the suitability of the materials to be included in the review. In the proposed work, there are two main stages. At Stage 1, the exhaustive coverage is established to be as comprehensive as possible. The main objective of this literature survey is to analyse valuable robotics research during the pandemic and identify future research trends. The reported work aims to answer two Research Questions (RQs) underneath:

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RQ2: What are the promising supporting technologies needed during and after the pandemic to help and guide future robotics research?

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possible to ensure that all relevant studies are included. Discussions are established based on the all-inclusive knowledge base to identify the mainstream of robotics research relevant to infectious diseases. Stage 2 consists of presenting the materials that are representative in the given field. The searching criteria are narrowed down from infectious diseases to robotic technologies in the pandemic scenario specifically.

Screening for inclusion: at this phase, the collected materials are screened to guarantee the applicability. The output of the searching at stage 2 is processed based on predetermined rules, e.g. including robotic technology and excluding work focusing on medical research.

Assessing the quality of primary studies: in addition to screening the literature for inclusion, the quality of the selected references is also assessed, based on the scientific value in the research design, methods, and reported results.

Extracting information: then the applicable information from the primary study is gathered and extracted, which is the most relevant to the problems of interest. The extracted information depends on the initial research questions mentioned above. Important information is gathered about what, how, when, who and where.

Analysing and synthesising data: as a final step, the included studies are summarised, aggregated, organised and compared in a meaningful way. Different types of robotics research are first categorised based on the nature of the technology, and then thoroughly reviewed and discussed. Eventually, future research trends are also identified based on the results of the analysis.

3. Robots in infectious diseases

In the past years, automated devices and robots have significantly changed the industry and daily life. There is also a big interest in using robots in the scenario of infectious disease and epidemic. The intention is reasonable because the robots offer the opportunity of delivering the job in the contagious or dangerous area, while not getting people infected or affected.

Until November 2020, which is the cut-off date of the data collection in this research, there have been 3520 documents published with the relevance of robots used in infectious disease. The yearly publication statistics of the topic can be found in Fig. 1. In the 20th century, there are only a few predictions regarding medical applications using a robot. In the year 2000, surgical robots were approved in the US. Since then there has been a clearly increased and continuous interest in using robots in the contagious scenarios. In 2019 and 2020, the total publications in this area were boosted by the COVID-19 pandemic. Researchers worldwide are seeking solutions together to protect humans by utilising different types of robot devices. In fact, the publications in this area are increasing rapidly while this review research is conducted.

The connections among the keywords of the 3520 papers are visualised in Fig. 2. Each coloured circle refers to one keyword of the publications. The size of a circle represents the occurrences of the keyword. The more times the keyword is identified in the publications, the bigger the circle is. The lines connecting different keywords refer to the links between them. The thicker a line is, the stronger the connection they have.

In the infectious scenario, the most important application is robotic surgery, including minimally invasive surgery based on robots. Automated laparoscopy and laparoscopic surgery are performed by the robot for higher protection and fewer complications. Certain diseases are mentioned due to the special nature, including prostate cancer, endometrial cancer, rectal cancer, and related surgeries like prostatectomy and hysterectomy. To recap, there has been a big and continuous interest in utilising robots in the medical scenarios since 2020, especially in surgical applications. However, the pandemic breakout in 2020 inspired many researchers in this area and added new perspectives to the research.

4. Robots in COVID-19

The COVID-19 disease is highly contagious which put all contacts of the patients in danger, including the medical personnel. So robots, which are immune to infection and easy to be disinfected, are recommended to play a vital role in the war against the pandemic. More research efforts are invested in the robotic applications during the pandemic. As the method in stage 2, i.e. searching, defined in Section 2, the reference collection focuses on the robotic technology for pandemic only. Until Nov 2020, there have been 280 publications in this area. The publication statistics can be found in Fig. 3. Before 2020, there were only several research proposals in this area. Naturally, the majority of the papers were published in 2020 after the breakout of COVID-19. The publication trend is compliant with the one for infectious diseases shown in Section 3, and the number is also increasing rapidly when this literature survey is conducted.

Similar to Fig. 2, the keywords and connections between these publications are illustrated in Fig. 4. The COVID-19 is naturally located in the centre of the knowledge map. Artificial Intelligence (AI) methods and Machine Learning (ML) algorithms have been mentioned many times to strengthen the robotic applications. Telemedicine has also been proposed to minimise the contacts to the infected person. Information and Communications Technologies (ICT), including the Internet of Things (IoT), big data, and blockchain, are also linked to the robotic applications to improve the performance. In this section, the literature is discussed in different categories to identify the influential technologies so far and technology trends in the future. Since this paper focuses on engineering science only, the papers focusing on medical research are omitted as mentioned before.

4.1. Theoretical identifications of using robot during the pandemic

Robots are widely suggested to be deployed in different scenarios during the pandemic, to help reduce the infection by performing disinfection, monitoring, delivering, food preparation, and telepresence [8-16]. Robots are also recommended to make intelligent decisions based on the inputs data from the population, which can be analysed through AI [17]. With the development of robots and AI technologies, various intelligent robots for emergency prevention and control in complex conditions have emerged, and they have played paramount roles in disease prevention and control, diagnosis, treatment, and nursing [18].

Baba et al. [19] studied the effectiveness of different government policies that preventing travelling to their countries, especially those from the countries with confirmed COVID-19 pandemic. A strategy model is developed accordingly which use robots to identify COVID-19-positive patients. One of the best practices is concluded as combining robot identification with migration restriction. Forman et al. [20] also discussed the lessons learned from the pandemic management during COVID-19. Similarly, it is identified that some countries have successfully slowed down the spread of the pandemic, by using modern technologies, e.g. robotic cleaners and facial recognition systems, to conduct the contact map and take actions accordingly.
4.2. Examination robot

The use of robot starts with the test of patients, where the robot is capable of mass screening to rapidly confirm the COVID-19 cases [21]. A semi-automatic oropharyngeal swab robot was developed to take swabs test with the patients (Fig. 5) [22]. A remote camera is equipped on the swab robot, which helps the medical staff to perform the sampling with a clear vision but without close contact with the patient. The results of the collections are satisfying, whose sampling success rate is 95% percent.

In Evans et al.’s research [23], the sonographer and the patient were isolated based on the remote robotic ultrasound equipment, to minimise the exposure to the disease. Meanwhile, the patient does not have to be transported to the imaging facilities far away. Similarly, obstetrical ultrasound exams are taken remotely based on a telerobotic ultrasound system [24]. The system is located in a remote region in Canada, which does not have sufficient access to the obstetrical ultrasound devices. Based on the telerobotic system, the ultrasound probe and settings are remotely controlled by a sonographer 605 km away. Even though the test is limited, the result is still promising with the 81% success rate (nine cased out of eleven), while one exam is adequate with some reservations, and one inadequate. In the future, it is possible to enhance the connectivity to the remote devices via low-latency communications, e.g. 5G network.

As a matter of fact, Wu et al. [25] integrated the tele-ultrasound device with the 5G network and proposed a robot-assisted approach. In their implementation, the patients are located in isolation wards in different cities (Fig. 6). Ultrasound specialists, located in two other cities, carried out the robot-assisted tele-ultrasound and remote consultation to perform an early cardiopulmonary evaluation.

Yu et al. [26] also evaluated two cases of patients, who were diagnosed with COVID-19, by robotic ultrasound based on 5G-powered technology 700 km away using MGI robot. The advantages of remote ultrasound scanning were demonstrated and could become a feasible and safe method for the diagnosis and assessment of COVID-19. Similarly, Wang et al. [27] used 5G network and MGIUS-R3 robotic system to perform remote diagnosis. The proposed method is feasible for lung, heart and vasculature exams, while the medical stuff is protected and resource/result can be easily shared over the network. In the future, the remote diagnoses can be assisted by AI approaches, e.g. image processing and pattern recognition. Meanwhile, haptic control can be considered for the system to support medical staff and improve exam accuracy.

4.3. Robot-based sample test, and medicine production

After the exam sample is collected, the next step is to speedily test the sample and collect results. In 2001, robotic workstations were suggested already to rapidly extract nucleic acid from large numbers of samples for the diagnosis of regular coronavirus [28]. In 2006, a robotic device was developed to perform the storage, sealing and handling of test plates [29]. The system is utilised to diagnose the SARS virus, which is categorised later as a new member of the coronavirus family. Similarly, a robotic approach was proposed for throughput screenings match
Fig. 4. Top research keywords based on 280 publications.

Fig. 5. A semi-automatic swab robot [22].

Fig. 6. Robot-assisted teleultrasound [25].
towards identifying definitive drug targets against the virus [30]. In 2012, a robotic system was utilised to prepare and dispense the mix formulation against the coronavirus types HKU1 [31]. It is a common practice to use a robot and automated platform to identify the virus and related drug targets.

During the sample test, many of the processes are sensitive, which needs to amplify the viral RNA via costly lab devices and robots [32]. Aitken et al. [33] proposed a schematic of the test and reporting pipelines, in which the robot platform was utilised for RNA extraction. Domachowske [34] proposed robotic applications aiming to high spotting densities. The microarrays on one single slide can contain maximum 50,000 genes. The genetic signature can be quickly identified consistent with the novel coronavirus. Marvis et al. [35] proposed a rapid sample preparation method based on liquid handling robots to detect the SARS-CoV-2 virus. Similarly, the sensitive and specific detection of SARS-CoV-2 antibodies is also taken on an automated liquid-handling robotic system [36]. So far, the testing robots are manipulated based on the pre-programmed codes with low flexibility and adaptability. In the future, remote connectivity can be introduced to the solution to adapt to different scenarios and results. The testing results can also be synchronised with other online solutions, e.g. cloud, to archive fast diagnosis and results.

After the disease case is confirmed, it is necessary to produce medicines and vaccines rapidly. In 2012, Wirz et al. [37] proposed an approach to perform quick response in the pandemic or bioterrorism scenario (Fig. 7). Robots and automated machines are utilised to produce plant-based vaccines and pharmaceuticals automatically. Similar to the testing device, the flexibility of the automated production system can be improved via the adoption of remote control technologies. Meanwhile, sensors can also be included in the system to dynamically monitor the status of the production and to make smart decisions rapidly.

To recap, Cresswell [38] argued that, the robotic applications in patient-facing scenarios were still limited, despite the fact of positive potentials of the implementations against SARS-CoV-2 so far. The reason is more about the high cost of the robot, limited patient-facing function, and potentially negative impact on the patient, medical staff, and the interaction between them. Instead, the lab-based robot is predicted with high safety and sufficient gains, in the application of sample extraction and amplification.

4.4. Healthcare, telepresence and monitoring robot

After the disease is confirmed, the patient needs to be admitted in the hospital and isolated. The service robot has been developed and improved to bridge the interactions between the penitents and care team. The service robot can perform a simple task like medication and supply delivering, which allow the caregivers to work on more important activities [39-41]. It is widely agreed that robots can be employed in the healthcare system in forms of nurses, receptionists, serving robots, telemedicine robots, cleaning and spraying robots, and surgical robots. Also, robots can boost the efficiency of healthcare practices, since not only do they reduce the workload of medical staff and physicians, but also aid them to cope with problematic situations more precisely [6].

Rosen et al. [42] proposed an information system for healthcare, which can link tertiary medical specialists to other applications like telemedicine, smartphones, and wearable sensors. In the proposed system, the smart robot can also be adopted to conduct lab test, interpreted results, and other remote supports at home. The basic remote function can be performed like telemedicine, taking blood pressure and dispensing pills. Meanwhile, it is also suggested to integrate robot with the gas release system to sterilise the area and prevent disease spreading [43]. In an application in China, a robot was also utilised to collect air samples in the hospital [44]. Robotics is needed in an advanced HealthTech ecosystem, together with photonics, biomaterials, smart systems, digital health and textile [45].

Abdel-Basset et al. [9] analysed the intelligent technologies and proposed a technology framework. AI-based robots were identified to burden from the healthcare team some duties to perform the medical examination of patients [46]. Drone technology and autonomous robots are also suggested to work in special areas like infected communities, quarantined homes, and hospitals. An auto-guided vehicle was developed, which could be remotely controlled [47]. The infrared sensors equipped at the bottom of the robot is capable of identifying the path and the ultrasonic sensor in front can detect the obstacle dynamically.

Regarding telepresence, a robot was used with the virtual platform at a hospital in Brazil [48]. The screen allows the patient to see the nurse from the remote location, and the camera enables the nurse to see and interact with the patient efficiently. Similarly, a framework of a teleoperated robot in isolation ward was developed in different scenarios to keep the safety of the healthcare workers via remote medicine delivery, auscultation, daily consultation, and UV disinfection [49]. The ABB YuMi robot is utilised as the end effector, while the data gloves capture the figure motions to teleoperate the gripper. Brunda et al. [50] proposed structure and workflow in a COVID centre using humanoid robots. The doctor and patient can also interact through the screen on the Vici robot [3].

A mobile robot platform was proposed with a multi-functional arm based on the human-robot interaction towards personalised care and assistance [51]. The proposed robot is then modified to perform extra functions like disinfection and body temperature detection during the COVID-19 pandemic. A Tele-Robotic Intelligent Nursing Assistant (TRINA) was also utilised to deliver nursing jobs and the results are promising [52]. Until now, the remote servicing robot can provide basic communications and interactions with the patient. However, mobility and functionality are still limited. The 5 G network can be a valuable support for wider coverage of the working area with low-latency communication. Meanwhile, haptic control methods can be adopted in the robot-arm solutions for better service performance. Regarding the Human-Machine Interaction, AI methods can be used for voice, image, and gesture recognition and decision making, to support the needs of the visitors and patients.

Besides the robot hardware, robot software, e.g. Robot Operating System (ROS), was also utilised as a common platform to connect
multiple assisting components and systems [53]. Lanza et al. [54] proposed a beliefs-desires-intentions multi-agent architecture for smart medical care. The result will manipulate the robot to take care of the pending cases and communication with the physician for validation and permission.

A hybrid Operating Room (OR) as conducted gives remote access to others via the VisitOR1 robot [55]. The live feeds, e.g., video, fluoroscopy and echocardiography, are transmitted through the digital interfaces controlled by the onsite team (Fig. 8). The camera mounted on the end of the robot can be manipulated by the remote expert, to change the operating field, and communicate with the local team in real-time. In the future, the AI method can be supportive to process the image and data streamed to the remote participant, and make suggestions for better decision making.

The mobile robot based on Raspberry Pi microcontroller is also utilised for the surveillance inside the hospital [56]. The robot is controlled and moved by the user while transmitting the live video footage continuously. Self-engineering systems, like self-adapting robots, were predicted to be helpful in the complex working environment [57]. Even though the reported results are preliminary, the proposal of the surveillance robot opens new possibilities in the medical scenarios. The robots can be further strengthened by more advanced sensors with more functionalities and adopted in the 5G network towards bigger and better coverage of the service area.

In the community scenario outside the hospital, Wei et al. [58] proposed non-contact community robot to allow citizens to perform self-diagnosis and initiate remote diagnosis when necessary. The proposed method can recognise speech, detect keywords, classify cough and convert the user’s coughing audio into structured data for future processing. The audio and video results can be potentially processed and diagnosed by the AI network. Additionally, the rich collection of the information can be maintained based on the big data management method and cloud, to offer trustworthy analysis.

Podpora et al. [59] presented a conceptual human-robot interaction system based on AI (Fig. 9). The humanoid is equipped with sensors, actuators, and integrated with cloud computing services, which are capable of human identification, visual identification and audio-based interlocutor. In the future, the data collected in the system can also be processed and managed by the big data methods, while communication and coverage quality potentially improved by a 5G network.

Multi-access Edge Computing (MEC) is utilised towards contact-less healthcare [60]. In the proposed system, the robots and sensors that are placed in the medical wards and connected to the edge to assist the mediation of COVID-19. Moreover, Rane [61] proposed a preliminary humanoid to introduce, alert and scan the entering people to prevent the spread of Coronavirus. Although there is a lot of room for improvement, the design shows the potential of deploying humanoids for daily works with the consideration of social distancing. It needs to be noted that the costs of robots are still the main limitation of the utilisation of automated healthcare, telepresence and monitoring. More consideration of cost-effective design and production needs to be included in future research.

4.5. Surgery and rehab robots

In early 2019, Yeganeh [62] predicted the increased risks of global pandemics in a globalised world. In his work, the globalisation of healthcare and technological innovations are reviewed including robotics, digitisation, and nanomedicine. Robot and robot-assisted surgeries are especially recommended in a complex and minimally invasive procedure. In general, the patient’s staying length can be decreased by robotic surgery, which directly increases the availability for other patients. It is particularly valuable during the pandemic [63–66]. As mentioned, currently it is widely agreed that robot can play as a shield, which separates the medical staff and patient physically. The surgery robot also reduces the possibility of the contact of the body fluids, compared with conventional surgeries [67]. The robotic surgery also allows staff to be more remote from the patient and other staff, thus facilitating better social distancing within the operating room [68,69]. Moreover, the sensors and feedback methods also help the clinicians to establish a digital fidelity to help them to touch, see and hear the object with high sensitivity [70]. As a matter of fact, the surgery robot does not mainly focus on the advancement of robotic technology itself. Instead, it is more about the extending of the human’s capability and improving performance.

It needs to be admitted that in some cases, the laparoscopic and robotic surgeries bring a high risk of aerosol dispersal, since the circulated CO₂ and smoke may carry viral particles, including Coronavirus [71]. Some researchers recommended the restriction of robotic procedures.
with the IoT to support the patients remotely. Similar to the surgical coverage of 5G network and advanced decision-making powered by AI. The scenarios before, during and after the operation were outlined by Zemmara et al. [82], and robots and AI were suggested to reduce the infectious contamination and support the patient management, especially in the scenario of immense patient influx.

In some operations, multiple robotic arms were deployed for one surgery [83]. Samalavicius et al. [84] utilised 4 robotic arms during Senhance® surgery robotic platform. The need for supporting staff during the surgery is minimised to one gynaecologist and one scrub nurse only.

At the control layer of surgical robot, different control approach was compared to explore a suitable method to guarantee the accuracy of manipulator’s position and the link’s flexibility [85]. The Linear Quadratic Regulator (LQR) shows promising response and reliable performance during simulation. In the future, remote-controlled surgical robots can be further improved by 5G-based communication. Meanwhile, the image processing method, e.g. AI networks, can also be helpful for the remote surgery staff to analyse the case and make decisions.

Pinto et al. [86] summarised the emergent technologies under the COVID-19 background. Robotics is identified valuable in various areas including environment control, neurological evaluation, and neuro-rehabilitation. More robots and exoskeleton interventions are suggested to be deployed for both rehabilitation centres to reduce the patient–physiotherapist contact, while home rehab devices can be utilised to avoid infectious spreading during travelling [7,87]. The patient with mobility difficulties can be assisted by remote rehabilitation, which also relieves the pressure of hospitals and medical facilities during the pandemic. An IoT-based elbow rehabilitation method was introduced based on biofeedback and fuzzy logic methods (Fig. 10) [88]. The gesture control and fuzzy logic-based decision system are integrated with the IoT to support the patients remotely. Similar to the surgical robot, the performance of the prototype system can be enhanced by the coverage of 5G network and advanced decision-making powered by AI.

### 4.6. Disinfection and cleaning robots

Robots are also recommended to perform cleaning tasks to avoid human-to-human contact [89]. Ultraviolet surface disinfection was demonstrated in some countries and 99.99 % disinfection rate was achieved in 15 min in the hospital ward room [3]. The growth in orders of disinfection robots was predicted to reach 400–600 % due to the efficiency, safety and efficacy [90].

Viruses, bacteria and superbugs could be destroyed by the UltraViolet-C (UVC) light equipped on the GermFalcon robot, which was originally designed for aeroplane hygiene to improve the safety of travelling [91]. The UVC light was also utilised as a germicidal add-on on the mobile robot, for the disinfection in both industrial and civil environments [92]. Similarly, eight UVC lamps were equipped around the central column of a mobile robot, with two extra lamps on the top [93]. The mobile base integrates different types of sensors which is capable of avoiding obstacles and measuring working environment, e.g. temperature and humidity.

Besides UVC-based approach, Cresswell and Sheikh [94] reviewed the current generation of cleaning and disinfection robots in healthcare settings, and concluded that the effectiveness of these robots is still inadequate to face the complex environment in care homes and schools during the pandemic. To improve performance, a wall-following robot was proposed to perform wall disinfection based on fuzzy logic [95]. The simulation presents the results of wall-following behaviour in heterogeneous wall scenarios and it shows promising performance than the conventional approach.

Hu et al. [96] proposed an adaptive robotic disinfection approach for indoor areas. The object affordance concept is utilised to segment and map areas of potential contamination based on the deep-learning method. The robot’s trajectory is generated based on the potentially contaminated area and the short-wavelength ultraviolet light equipped on the robot performs the efficient disinfection process accordingly. Similarly, AI-enabled framework was proposed towards automated cleaning tasks with the help of a Human Support Robot (HSR) [97]. The deep-learning method is utilised in the detection function to process the image space and guide the robot accordingly (Fig. 11). A robot dispensing sanitiser was also demonstrated in isolation wards in India [98]. As proven in some of the approaches, the AI method can be supportive for process in a complex environment, while 5G network offers better communication quality.

### 4.7. Delivery and logistic robot

It is observed in the 2003 SARS outbreak that the health care workers

![Fig. 10. Remote rehab robot [88].](image-url)
were in high risk of infection, which reduced the chances of adequate treatment for both themselves and the patients. To reduce the medical staff’s exposure, daily procedures were suggested to be performed by robots as much as possible [99]. Social distancing was also encouraged by robotics research in both public and healthcare scenarios [100,101]. The future cities were also discussed with the consideration of AI and the robotic restructuring [102]. Coombs [103] analysed the relationship between COVID-19 and intelligent automation. Simple processes, e.g. food delivery, medication distribution, etc., were proven feasible to be performed by semi-autonomous robots [104]. The public acceptance of autonomous robots was evaluated under the background of COVID-19 pandemic [105]. Six types of consumers are identified, i.e. direct shoppers, e-shopping lovers, COVID converts, omnichannel consumers, e-shopping skeptics, and indifferent consumers. According to the results collected in Portland, US, it is shown that the majority of consumer shows positive willing-to-pay. If the delivery is performed by autonomous robots, an extra fee is acceptable by 61.28% of consumers.

Peanut robot was utilised for food delivery and medical supply in some cities in China (Fig. 12) [106]. The robot is beneficial especially in the quarantined area or suspected of the virus. A low-cost mobile robot was developed to support the virus affected and disabled people [107]. The mobile robot agent can recognise the patient’s gestures based on sensors, without the need for an image processing module in the system. Similar to the disinfection robots, it is challenging for the delivery robot to work in a complex environment, which can be helped by advanced sensors and AI methods.

Regarding logistics, a minimarket prototype is presented to minimise direct contact during shopping [108]. Artificial neural network and machine learning methods can be utilised to predict the customer’s weekly expenditures and to deliver the purchased products in the robotic shopping chart accordingly. Similarly, at the community level, a contactless robotic system is utilised to prepare and dispense food and survival-kits when needed (Fig. 15) [109]. The proposed design is validated through simulation, to guarantee the feasibility of future implementations. However, it needs to be admitted that robotic adoption rates may not increase instantly since current capabilities of the AI methods are narrow in their own domain, while the human intelligence and dexterity cannot be matched. However, the robot-based logistic system can be improved by the wireless sensor network to acquire the dynamic status and queries, and then be driven by remote control methods towards trustworthy performance.

4.8. Social and assistance robots

During the long battle against the COVID-19, social isolation and loneliness are also growing challenges. New technologies, e.g. social robots, are suggested to initiate human-to-human interactions remotely to reduce the loneliness, minimise the risk of direct contact, and share the workload of healthcare providers [3]. Thus the overall health condition of the receiver can be improved. Social robot’s advances in speech recognition and natural language processing provide more humanlike robots that offer cognitive assistance, social interaction, and stimulating activities [110]. The role of companion robots during the pandemic was analysed based on 595 online descriptions [111]. The companion robot shows the potential of reducing the feeling of aloneness, which is an important indicator of mental health. Supportive relationships can be built under the integrative framework in different ways, i.e. personal assistant, relational peer and intimate buddy. Similarly, a robotic service typology is proposed to help the user during social isolation. The role of...
a social robot includes entertainer, social enabler, mentor and friend, while future research agenda is also identified.

During the pandemic, it is specifically necessary to consider the needs of the special group of citizens. The pandemic-related challenge for elder adults was reviewed and the design of life-like robots was suggested, since their capability of fostering the sense of social rapport was considered to a certain level of comfort. A phenomenology-inspired design perspective was proposed towards efficient emotional and social robots for eldercare. The uniqueness and respect for elder citizens are considered based on their motor, cognitive, emotional, and social skills. It is especially valuable during the isolation and social distancing caused by the pandemic.

In the health care scenarios, phonetic interface and speech-recognising methods are popular due to their capability of smart guidance and interactive services. Multi-modal gestures, gaze, and behaviour recognition were utilised on a socially assistive robot. The robot aims to adopt AI algorithms too and become part of the healthcare community in the future.

During the pandemic, many residents living in nursing homes or long-term care facilities cannot have visitors as usual. The need to remain confined in their rooms with companion robots, such as Paro, was also suggested to be deployed. In general, both social and companion robots can be upgraded by the AI methods for better human-robot interactions, together with wide communication access based on 5G network.

Regarding the negative attitudes toward social robots, the potential resistance and ambivalence were warned including the risk of uncanny valley phenomenon. Future research is still needed to investigate the user’s experience with social robots, especially during the pandemic. An EU-funded research project was established to design an expression system to improve the assistive robots’ support to the weak users at home or assistance facilities. To avoid the uncanny valley phenomenon, a dynamic and friendly system is demanded to recall real facial expression, but not too much human-like.

4.9. Robots supporting the manufacturing industry

Under the background of pandemic, the manufacturing systems and supply chains, are required to be flexible and resilient. To meet the high manufacturing demand of ventilators, a human-robot collaborative team was proposed to integrate the strength of both sides, while keeping the social distancing in the manufacturing environment. The proposed manufacturing model describes the design guideline of the workstation aiming to the fast integration of collaborative robot. As shown in Fig. 13, social distancing is considered in the proposed approach, in which human interacts with robot only and the two-meter distance between operators is maintained.

Ech-Chhibat et al. proposed an automatic loading and unloading method based on a numerically controlled teaching machine, to reduce the manual manipulation of machine’s parts and organs as much as possible, thus limiting the COVID-19’s spread by touch. The direct and inverse geometric model, kinematic model and dynamic model are determined, together with a robot’s position and speed control methodology. The preliminary proposal can be strengthened by revised mechanical design. Besides, Human-Robot Collaboration (HRC) approach can also be considered to offer a symbiotic and safe working environment for the workers.

4.10. Robots supporting the tourism, catering, and hotel industry

In a broader scope, the robotic technology gains attention in different industries due to the pandemic. Tourism scholars were suggested to seize this opportunity to adopt robotics research that enhances tourist experiences and protect people from the pandemic. Tourism and hospitality companies were also recommended to complement robots to overcome the negative impact on the business caused by social distancing restrictions.

In the tourist industry, three service robot models were summarised, i.e. robotic, human-based, and mixed. The requirements, advantages, disadvantages, and potential target markets of those models are analysed in the (post-) pandemic era. According to the results of this research, the hospitality companies first need to investigate the expectations of the tourists, analysis the data, and identify how they can
differentiate and position themselves in the competitive industry. Multiple methods can be utilised during the analytics, e.g. a holistic perspective consisting of the resource-based view, value chain, stakeholder, and PESTEL analyses. As a start, tourists’ perceptions of using humanoid robots were investigated in the tourism domain [125]. The result shows that humanoid robots are more popular compared with other types of robots. Similar to the service and companion robots, deploying humanoid robots in tourism industry potentially lead to more experiential value. However, negative emotions, e.g. frustration, sadness and disappointment, of using robots in the human-centred applications also need to be carefully handled in the future.

In the catering industry, the acceptance of using robots in a contactless coffee shop increases due to usefulness and innovativeness [126]. When a customer demands contactless service, the robotic service is an important strategy for sustainable business management during and after the pandemic. Similar to the medical robots, the service robot plays the role of the shield between the tourists and employees in the catering industry. The customers’ opinion of robot-serviced restaurants was investigated in Korea [127]. Utility, attractiveness, subcultural appeal, and originality are identified as the top impactors to the motivated consumer innovativeness of the customers. The restaurant marketers are suggested to consider those matters because contactless service is increasingly essential under the COVID-19 background.

In the hotel industry, social distancing also works as an effective strategy against COVID-19. AI and robots were recommended to be adopted in the high-contact scenarios at hotels, to protect both service employees and the guests. [128]. Some technologies are identified to potentially replace face-to-face service, including robot receptionists, facial scan check-ins, robot delivery, robot concierge assistants, voice guest control, etc. Then the robot-based service quality is evaluated in a real hotel setting (Fig. 16) [129]. The actual performance experience is collected from 201 guests who are serviced by robots. The results show that assurance and reliability are the top priority of the customers. Besides, the robots’ responsiveness is not satisfying during the test, but it is a low-priority objective for the customers. In the future, the hotel robots can be enhanced by the 5 G network to potentially provide the remote control and decision-making support, while AI and HRC methods can offer better response to the users.

4.11. Educational robots

Regarding education in the pandemic period, technological developments are predicted to change procedural tasks, both through replacement of skilled practitioners in some fields with automation and robotics and through changes to teaching and training [130]. Havenga [131] reported the challenges, opportunities and insights gained from an introductory robotics course during a rapid transition to an online learning environment during the COVID-19 lockdown. Results indicate that, although students experienced some challenges, they are also exposed to new opportunities to collaborate online. Certain insights emerging from the rapid transition from full-time to online learning are gained to enhance responsible and active learning when introducing robotics to students. Moreover, robot mannequins were utilised in the pandemic influenza drills [132]. Life-like medical scenarios are created with real-time stressors, to establish realism in disaster drills through humanoids.

Considering the needs of special learners, the effectiveness of robotic treatment is compared with conventional treatment, for children who are diagnosed with Autism Spectrum Disorder [133]. The result reveals
that both children and their parents are satisfied with the robot-based contents. The home-based psychoeducation studies during the pandemic and post-pandemic period were also investigated [134]. Friendly-technical equipment is adopted, e.g., robots and remote-monitoring apps. The results are promising by promoting knowledge effectively and supporting decision-making from the providers.

5. Discussions and identification of future research trends

As mentioned in Section 3, a big portion of the literature so far are conceptual research ideas or proposals suggesting robotics during the pandemic. Only some of them developed feasible methods and implementations on the real robotic devices. The representative researches are summarised in Table 1, together with the identification of Technology Readiness Level (TRL) and future research trends. A wider TRL category is utilised, in which Low refers to the basic principles and experimental proof of concepts (TRL1-3). Medium represents the technologies validated or demonstrated in the lab or relevant environment (TRL4-6). High indicates the ones with demonstrated or proven in the operational environment (TRL7-9).

In the research achievements so far, robot arms are widely utilised as the manipulator and replica of human movements, while mobile robots provide the mobility supporting the moving process like delivery, disinfection, cleaning, etc. Naturally, telecommunication technology plays an important role between the above-mentioned robots and the human operators. Automated devices and controls are also essential in many of the applications, like sample testing, medicine/vaccine production, logistics, etc.

In general, robots are expected to be progressively more autonomous, flexible, and cooperative in the post-pandemic world [135]. Regarding future research trends, the technologies underneath are suggested to enhance robotics research in the intra- and post-pandemic era:

- AI: AI is expected to be seen in almost every field from household applications to automated robot-assisted health services provided [136]. Robot applications are suggested to be combined with AI technology towards intelligence and flexibility in the complex working environment [106,137]. The AI algorithms will be an essential support for different areas like data analytics, image processing, and decision-making.

- 5G: many researches so far rely on the conventional IT infrastructure like local area networks and Wi-Fi. Some of the applications are limited by the bandwidth and latency of the remote communication signals. Thus, 5G can play an important role with low latency and high traffic/connection capacity. It is especially suitable for communication with remote devices like surgical robots, mobile robots, and sensors.

- Wireless sensor network: during the literature survey, there is little work on monitoring the surroundings of the robots except for potential obstacles. It is essential to detect the task conditions and the environment, e.g., patients’ temperature, air quality, etc., and trigger the robot process accordingly. The wireless sensor network can also be integrated with the 5G network, for better connectivity and communication quality.

- HRC: new technologies like human-robot interaction and collaboration were expected to play more important roles in the future medical and work environments, and the transformation was accelerated by the COVID-19 pandemic already [138,139]. HRC was suggested to be repurposed towards the production of medical devices, like ventilators [121,140]. The collaborative robot integrates the flexibility and intelligence of humans with the strength and accuracy of robots. The humans and robots can cooperate and collaborate in a symbiotic environment to share tasks and workloads while minimising the risk of virus spreading.

- Haptic control: haptic technology provides the experience of touch by applying forces, vibrations, and motions to the user. It is especially valuable during the COVID-19 context, to offer a close-to-reality environment for the user, to improve the performance of tasks like remote examination, healthcare, surgery, etc.

- Big data and cloud: the big data and cloud technologies are predicted to be accelerated together with robotic process automation and AI especially after COVID-19 [141]. After the data from robots and sensors is collected, it is important to process them instantly. The cloud can be a promising platform to maintain the huge amount of data and analyse it accordingly. The AI algorithms are a good support to big data analytics for better and faster analytical results.

6. Conclusions

In practice, digitalisation and automation did not progress fast before 2020 due to multiple reasons. The cost of robots are high and the implementation is hesitating against the cheap labour. There are

| Table 1 | Robot applications with TRL and future research identification. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Technology      | Ref.            | Supporting technology | TRL       | Future research trend |
| Swapping robot  | [22]            | Robot arm, remote control, | High     | Connectivity, 5G |
| Ultra-sound and examination robot | [23,24] | Robot arm, remote control | High     | Connectivity, 5G |
| Remote examination robot | [25,26] | Robot arm, remote control, 5G | High     | AI, haptic control |
| Testing device  | [29]            | Automated platform     | Medium   | Remote connectivity, 5G, cloud |
| Preparation device | [31] | Automated platform | Low     | Remote connectivity, 5G, cloud |
| Testing device  | [36]            | Automated platform     | Medium   | Remote connectivity, 5G, cloud |
| Automated medicine production | [37] | Automated device | Low, 5G, sensor |
| Servicing robot | [5,49,51] | Collaborative robot arm, touch screen, camera, medium | High | Connectivity, 5G, haptic control, AI |
| Telepresence robot | [55] | Remote monitoring | Low | AI, remote control, 5G |
| Surveillance robot | [56] | Telecommunication | Low, 5G, sensor |
| Community robot  | [58]            | Remote monitoring, data integration | Low | AI, big data, cloud |
| Monitoring robot | [59]            | Image processing, AI     | Medium   | Big data, 5G |
| Surgical robot  | [84]            | Robot arm, remote control | High | 5G, AI, image processing |
| Remote rehab robot | [88] | Remote control, fuzzy logic | low | 5G, AI, 5G |
| Disinfection robot | [91,92] | Remote control, sensors | medium | AI, 5G |
| Cleaning robot  | [96,97]        | Mobile robot, AI        | High     | 5G |
| Delivery robot  | [106]           | Mobile robot            | High     | Sensor, AI |
| Goods preparing robot | [109] | Robot arm | Low | Remote control, wireless sensor network |
| Object transportation robot | [122] | Robot arm | Low | Mechanical design, human-robot collaboration |
| Social robot    | [115]           | Multi-modal communication | Medium | AI |
| Companion robot | [116,117]      | Sensors, AI             | Medium   | 5G, cloud |
| Hotel robot     | [129]           | Robot arm               | Medium   | AI, 5G, HRC |
Declaration of Competing Interest

The authors declare no conflict of interest.

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