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Humans and Robots: A Mutually Inclusive Relationship in a Contagious World

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Abstract: The coronavirus global pandemic has spread faster and more severely than experts had anticipated. While this has presented itself as a great challenge, researchers worldwide have shown ingenuity and dexterity in adapting technology and devising new strategies to combat this pandemic. However, implementing these strategies alone impedes the nature of everyone′s daily life. Hence, an intersection between these strategies and the technological advantages of robotics, artificial intelligence, and autonomous systems is essential for near-to-normal operation. In this review paper, different applications of robotic systems, various aspects of modern technologies, including medical imaging, telemedicine, and supply chains, have been covered with respect to the COVID-19 pandemic. Furthermore, concerns over user′s data privacy, job losses, and legal aspects of the implementation of robotics are also been discussed.

Keywords: COVID-19, coronavirus, telepresence, delivery robots, medical robots.

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1 Introduction

Coronaviruses are a large family of viruses that can cause illness in animals[1] and humans. There are several types of coronaviruses, which have emerged from animals. Out of the known seven types of coronaviruses, four have caused mild to moderate disease. While the remaining three causes serious and fatal diseases, among which middle east respiratory syndrome (MERS) and severe acute respiratory syndrome (SARS)/(SARS-CoV) have already shown their wrath, the third one which has emerged recently is known as COVID-19.

There are a few challenges responsible for the global spread, like asymptomatic carriers of the virus. In this scenario, the virus carrier individual does not show any symptoms of illness but can spread the virus. The carrier individual is not aware of their situation, and hence never consults a doctor. For the infected person, it takes 2−14 days for any symptoms[2], and once it′s been diagnosed, the symptomatic person can be treated in quarantine/isolation. However, prior to diagnosis, the person is still a carrier of the virus. Accentuating this typical scenario, there is limited healthcare capacity worldwide in terms of the available number of hospital beds, trained staff, and medical equipments to support the symptomatic patients, including the critically ill cases in intensive care units (ICUs). Globally, there was shortage of medical equipment, certain types of medicines, testing kits, ventilators, personal protective equipment (PPE), face mask, face shields, etc. Overall, the pandemic has majorly impacted trade, jobs, and economies.

Because of no proven antiviral treatment, precautions in terms of good hygiene, social distancing, travel restrictions, lockdown, health screening of the population, separate quarantine arrangement, and hospitals have been encouraged[3−5].

To get one step ahead in terms of safety, things can be remotely monitored and managed by robotic and autonomous solutions, so that the risk of exposure should remain low. Also using robotics and autonomous solutions restricts human interference to fewer subject areas, hence the risk of exposure is low[6]. The key is social distancing and avoiding touching exposed materials and in fact any other human too without any safety gear[7, 8].

In this paper, it will be shown how robotics and automation solutions have deeply impacted human life and helped to manage the situation on every front. Detailed global coverage on possible use and application of robotics and automation under COVID-19 is discussed and shown in Fig. 1.

Review
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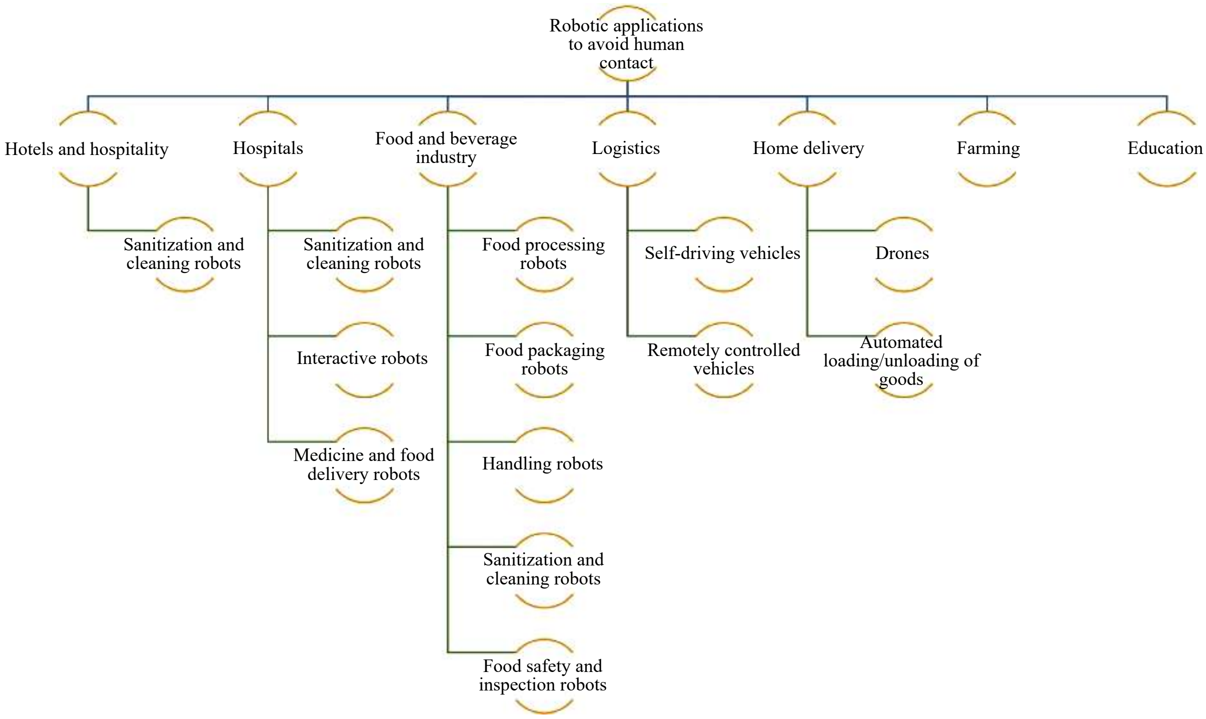


Fig. 1 Overview of robotic applications during coronavirus outbreak

2 Robotic applications during COVID-19

In this section, various sectors of implementation of robotics under the COVID-19 scenario are discussed.

2.1 Telemedicine, telepresence in healthcare

The well-being of the health care workforce is the prime importance of a well-functioning health system, and due to the pandemic, medical healthcare providers are under an enormous amount of workload pressure along with increased total health expenditures. It is not only creating psychological distress for health workers but also sleep disturbances, fatigue, and the risk of getting an infection due to long working hours.

Due to the pandemic, the number of patients arriving at hospitals increases too which warrants an increase in the number of tests conducted in hospitals and labs. These tests like a blood test, temperature measurement, in most cases are repetitive in nature which make them a prime candidate to be outsourced to robots. This outsourcing of repetitive tasks can increase productivity considerably even when there is a rise in the workload. To explore the cost-effectiveness of collaborative robotics, Copenhagen University Hospital used 2 universal robots (URs) which allowed them to deliver 90% of the test results within 1 hour even when there was a 20% surge in the number of incoming samples[9, 10]. Another successful example of a hospital robot is Aethon′s TUG autonomous mobile robot that is used to deliver medicines, food trays, transporting samples, etc. It reduces the load on the hospital personnel who can focus on more important duties hence increasing productivity[11]. Similarly, COVID-19 has caused a severe workload for hospital staff all around the globe. Hospitals are equipped only with a specific number of beds and to accommodate more patients, open spaces are being used as makeshift wards, e.g., Wuhan Hongshan Stadium which is staffed by robots. CloudMinds placed many robots in the stadium which clean, deliver samples and medicines, take patient temperatures, and provide mental comfort by communicating with patients[12, 13]. Hospitals in Varese, Italy make use of a similar robot nicknamed Tommy for limiting their exposure to infected patients. These robots make use of a tablet and monitor that allow patients to communicate with doctors using audio and visuals. Tommy also constantly monitors the oxygen level and blood pressure of patients on ventilators and relays them to doctors in a remote location[14].

Telemedicine based support is surging in demand amid the COVID-19 pandemic, as more and more people are referring to first-hand symptoms as a diagnostic tool. Moreover, telemedicine support by various companies has been taken on health grounds and has been made free. This has not only eased the health care sector but also helped in checks with fake information and scarcity. From many people′s perspective, telemedicine provides faster care and helps to avoid hospitals[15, 16]. In the bigger picture when most of the countries are observing complete or partial lockdown, telemedicine has helped to check people inside their home, resulting in big support for keeping people inside their home. It has facilitated rapid assessment and the saving of essential protective gear like PPE, face masks, face shields, gloves, etc., limiting potential exposures, and possible spread of the disease[17].

One thing which telemedicine cannot do for asymptomatic patients is testing, instead it tries to coordinate between health care centers and patients resulting in a check on symptomatic patient movement[18].

The only concern is the sustainability model of telemedicine[19, 20]. As in the past, it's been experienced that there is always a surge during tornados, hurricane, and bushfires or in fact during the SARS pandemic in 2003, but after that, the use is again limited.

Telemedicine support by robots makes it possible for medical professionals to communicate with patients remotely, saving time, and allowing possibly contagious patients to stay isolated, as shown in Fig. 2(a). Not only can robots communicate (also known as telepresence) with individuals quarantined due to coronavirus, but they can also acquire vital patient information and help doctors treat patients[21, 22]. It has reduced the wait time in primary health care networks[23].

One of the major benefits of telepresence robots is every time a doctor or a care worker needs to walk into a room with a COVID-19 patient, they must put on all the protective gear and later dispose of the same. It might look not that time-consuming but repeating the same cycle, again and again, is tedious[24].

2.2 Robots in hospitals

Due to the severe influx of patients and shortage of medical staff and to reduce the exposure of medical staff to patients, and also to maintain the social distancing guidelines, robots were deployed in hospitals and field hospitals to assist. The use of robotics allows us to still have a close to normal lifestyle, and even more so, helps us to eliminate challenges presented due to COVID-19, one such example is the application of teleoperated surgical robots[25–27]. One of the main challenges presented is to curb the spread of the virus in places that are unavoidable such as hospitals, food factories, etc. These robots have been used to clean and sterilize (disinfect), measure patient temperatures, deliver medicine, food, and other amenities, and comfort patients by communicating or entertaining them. Sterilization robots emit a specific wavelength of ultraviolet light to the exposed surface to kill viruses and bacteria without exposing any human personnel to infection[28]. Due to the congested and complicated workspace, these robots are generally remotely controlled from a safe distance. Hospitals around the world are accepting these robots on trial and real-time basis to get rid of viruses and bacteria on rooms, halls, and on door handles. To reduce hospital-acquired infections, UVD Robotics, a Danish robotics company, is launching robots that use powerful short-wavelength ultraviolet-C (UVC) light to disinfect hospital rooms and contaminated surfaces, as shown in Fig. 3(a). The robot comprises an array of UVC light emitters which is powerful enough to shred the DNA or RNA of the virus. The robot uses light detection and ranging (LIDAR) sensors to map the environment and then uses simultaneous localization and mapping (SLAM) to navigate in the environment. Following in these footsteps, many other companies such as Xenex, YouiBot, LightStrike, etc. have also started to produce their versions of UVC light autonomous disinfectant robots[29–32], as shown in Fig. 3(b). This pandemic has accelerated the "testing" of robots and drones in public use, as officials seek out the most expedient and safe way to grapple with the outbreak and limit contamination and spread of the virus, hence for testing samples too, robots have been used, as shown in Fig. 2(b).

2.3 Food and beverage industry

The two biggest manufacturing sectors that make use of robotics today are automotive and electronics. Other industries such as food processing, healthcare, hospitality,

(a) (b)

Fig. 2 Robotics in telemedicine: (a) Remote observation of patient using a robot; (b) Blood sample handling robots.

(a) (b)

Fig. 3 Sanitizing robot: (a) UVC disinfection robot by UVD Robotics; (b) LightStrike germ zapping robot with pulsed Xenon UVC

and logistics are also adapting to the recent developments in the market due to COVID-19. The current market share of robots in the food industry is expected to reach by \$2.5 billion by 2022 from its current \$1.3 billion[33]. The use of robotic technology during a pandemic has many advantages when it comes to fulfilling the prime objective of social distancing. While the pandemic spreads aggressively, robotic devices to transport and sanitize the food products and production environment can help prevent community spread of the outbreak. These robotic devices with appropriate sensors and actuators can autonomously work in between the supply chain of food-producing organizations. This deadly outbreak has affected nearly every continent. Due to globalization and interdependence of all the economies, almost all the countries have been affected by COVID-19[34].

Against the backdrop of the current pandemic, robotics and automation in the food industry have become a growing part of the discussion due to factors such as safety and hygiene[35]. Robotic devices can help humans maintain social distancing without disrupting production in the food and beverage industries. Automated handling, food processing, packaging devices have greatly contributed towards minimizing human participation in these tedious tasks.

With the least human interference, industrial food robots can be employed in large numbers to ensure mass food production. Though such devices are a pressing priority, even in the small-scale businesses, they still need regular service and human inspections. These human inspections present great challenges and increase the probability of contamination of these devices. Table 1 shows the persistence of coronaviruses on different types of inanimate surfaces[36].

The data mentioned in Table 1 shows that the persistence of coronavirus on the aluminium surface is very short. Interestingly, most robotic devices make use of aluminum and its alloys as their primary structural material. These robotic devices will not require frequent sanitization as compared to other mechanical equipment made up of different metals and plastics. However, the wiring, hoses, and end effectors in these robots that are generally made up of plastics and rubber would require regular sanitization or replacements

The robotics industry is predicted to grow at a compound growth rate of 11.5% annually in the period 2020−2027[37]. The major growth drivers of the robotics industry are high labor cost, food and beverage industry demand, reduced workspace, and efficiency of robotic devices. Fig. 4 shows the predicted growth rate of the robotics industry by 2027.

According to a New York Times report[38], robots are being employed in dairy firms to reduce the workforce from fifteen to five as shown in Fig. 5(a). Eight robots can

Table 1 Persistence of coronaviruses on different types of inanimate surfaces

Type of surface	Virus	Temperature	Persistence
Steel	MERS-CoV	20°C	48 h
Aluminum	HCoV	21°C	2–8 h
Metal	SARS-CoV	RT	5 d
Wood	SARS-CoV	RT	4 d
Paper	SARS-CoV	RT	4–5 d
Glass	SARS-CoV	RT	4 d
Plastic	SARS-CoV	22–25°C	≤ 5 d
PVC	HCoV	21°C	5 d
Silicon rubber	HCoV	21°C	5 d
Surgical glove (latex)	HCoV	21°C	≤ 8 d
Disposable gown	SARS-CoV	RT	2 d
Ceramic	HCoV	21°C	5 d
Teflon	HCoV	21°C	5 d

MERS = middle east respiratory syndrome; HCoV = human coronavirus; SARS = severe acute respiratory syndrome; RT = room temperature.

milk 400 cows, thrice a day. Cows are equipped with sensors on their collar to signal to the robots when it is time of milking.

An example of food packaging robots is the Universal Robots' collaborative industrial robot arm, also known as Cobot[39]. These cobots have been specifically designed to reduce the risk of dust accumulation on their surfaces. These robots can be employed in a harsh food production environment or an environment unsuitable for the human workforce for a prolonged time as shown in Figs. 5(b)–5(d).

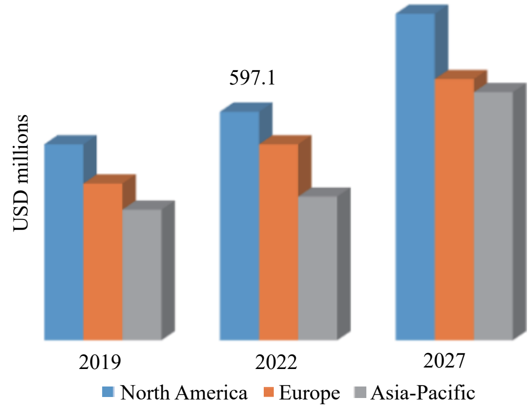


Fig. 4 Robotics industry growth rate

Various companies like Fanuc, Kuka, ABB, and Yaskawa have developed food-grade robots that are in service for many years. These manufacturers are primarily building packaging, material handling, and cleaning robots like FANUC LR Mate 200iB/5WP, FANUC M-420iA, FANUC M-430iA/2PH (as shown in Fig. 5(e)), Yaskawa Motoman DA20, ABB IRB 1 200-5/0.9, KUKA KR 360, etc.

2.4 Supply chain and logistics

The COVID-19 crisis is prompting companies to invest in robotics and automation for better management of logistics without employing significant manpower. The coronavirus has dealt a stunning blow to gross domestic product (GDP)[31], which in turn affects the supply chain, logistics, and can involve shutting down businesses rapidly to protect their workers[41–43]. But unlike any previous epidemic, pandemic, or natural disaster decades ago,

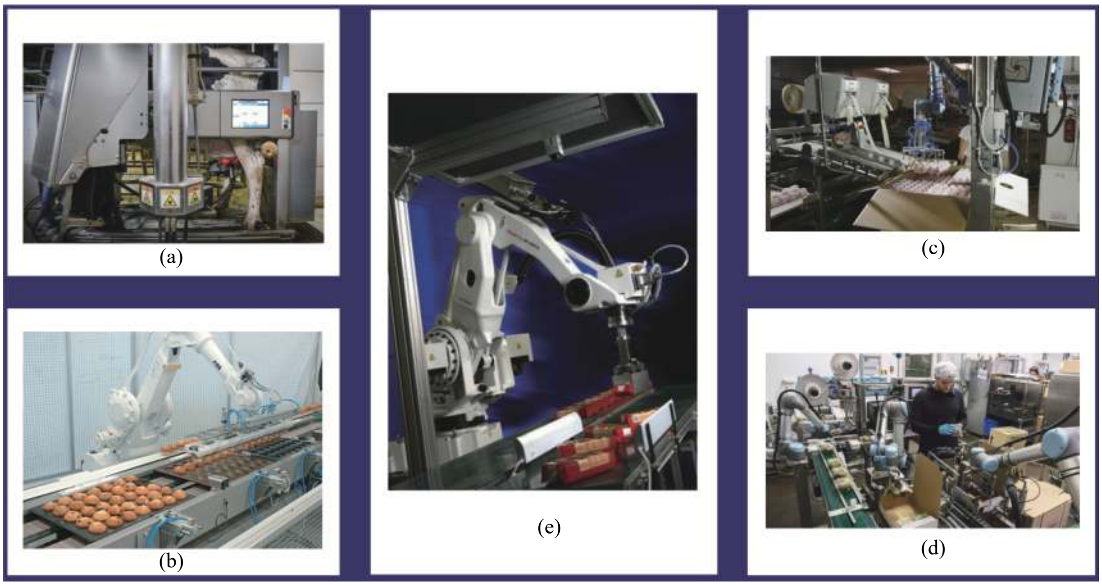


Fig. 5 Robotics in food and beverage industries: (a) Robots used for automated milking of cows[38]; (b) UR cobots in processed food on automated conveyor belt; (c) UR cobots in eggs packaging; (d) UR cobots in fruit packaging; (e) FANUC M-420iA high-speed material handling and packaging robot[40].

robotics and automation technology are here to do the tasks that were primarily restricted to humans. The COVID-19 crisis is forcing consumers to shop online. There has also been significant bulk buying to stock up goods due to fear of scarcity, putting extra pressure on logistics, supply chain, and e-commerce businesses., The extra pressure on the supply chain requires more manpower for picking, packing, and the shipping of goods and forces more and more workers to flout social distancing norms and work round the clock to deliver the products. The need for speed, resilience, and efficiency to meet the increased consumer demands is being fulfilled by employing autonomous mobile robots in the logistics and supply chain. In 2018, the total stock of robotics devices around the world was 24.4 lakh units. Now it is expected that another 20 lakh units of the new industrial robots will be installed in factories around the world between 2020 and 2022 – nearly doubling the robot stock[44].

One of the leading organizations that makes use of a large number of innovative robotics and automation devices in the supply chain is Amazon. Amazon has been innovating with its use of robotics and artificial intelligence (AI) within its warehouse and logistics operations.

The robots that are currently operating within its warehouses including:

1) Palletisers. The operation of loading objects such as cartons on a pallet in a defined pattern is referred to as Palletizing. Amazon has 30 globally, as shown in Fig. 6(a).

2) Robo-stow. A robotic arm that lifts pallets to different levels within a fulfillment center or places them on drive units to be carried to their destination. Currently, Amazon has six around the world, as shown in Fig. 6(b).

3) Drive unit. To transport packages around a fulfillment center, Amazon employs a robot unit. Currently, Amazon has 100 000 worldwide[46].

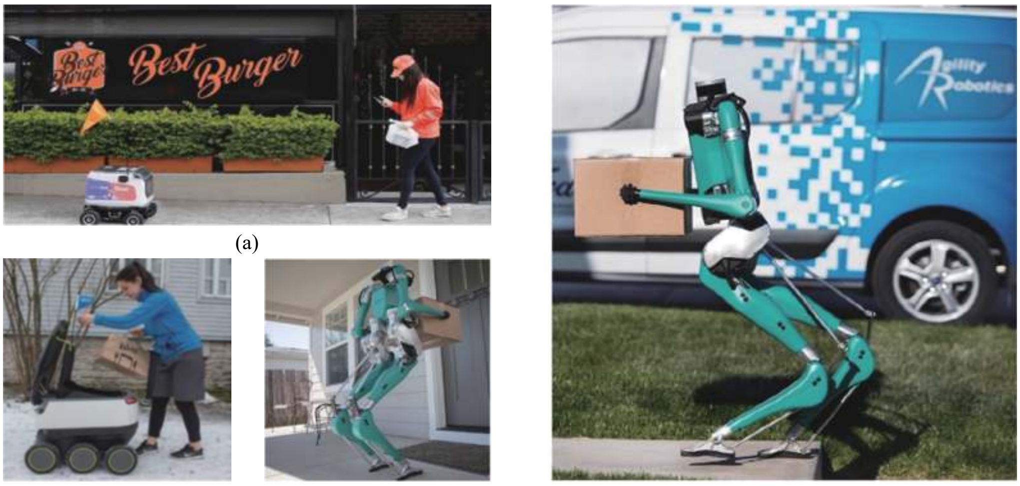
According to International Data Corporation (IDC), 72.8% of respondents to the supply chain survey 2020 believe employing robotics and automation technology will improve the efficiency of their organization within the next three years. South Korea is reported to have 7 robots per 100 workers and by 2030, nearly 12.5 million jobs will be automated in China. Figs. 6(c) and 6(d) show the sorter system employed in the logistic section in India and an automated Amazon supply chain in the USA.

2.5 Food delivery

Due to the contagious nature of COVID-19, it is safer to minimize human-to-human contact. Tech companies such as JD.com and others have stepped up to the challenge to get more robots out in force to deliver, e.g., medical supplies within healthcare environments. Robots are also proving to be valuable when delivering essential items to people who shop and purchase online and are quarantined at home.

Online shopping needs to be supported by a reliable logistics system. Currently, the in-person delivery may result in the spread of COVID-19 and the rate of active cases may increase exponentially. This threat is even more when the deliverables contain food items. The world is still decades short of advancements in cooking robots and AI that can autonomously handle the kitchen in a restaurant or home. But with the available technology, the in-person delivery can be replaced with delivery drones and robots. In China, the e-commerce giants are ramping up the development of delivery robots[47], as shown in Fig. 7(a).

Fig. 6 Robotics in supply chain and logistics: (a) Amazon Robo-stow at Amazon fulfillment center at Dallas, USA; (b) Amazon robotics drive units at fulfillment center; (c) Sorter system of GreyOrange, India[45]; (d) Amazon fulfillment center in the USA[41].



(b) (c) (d)

Fig. 7 Robotics in material delivery: (a) Food delivery via robot without any human contact[47]; (b) Starship technologies autonomous food delivery robot[48, 49]; (c) and (d) Ford and Agility Robotics autonomous legged robot[50].

Another startup Starship Technologies[48,51] has launched its unique autonomous food delivery robot, as shown in Fig. 7(b). The startup has the potential to bring the restaurant and food delivery business back after it suffered huge losses due to the COVID-19 lockdown. The demand for contactless delivery services has been on the high side since the World Health Organization (WHO) declared human-to-human transmission of this disease. This robot has the capacity to carry as much as 20 pounds and the customers are required to book the service by using the Starship application on their smartphone. Ford and Agility robotics have unveiled an autonomous legged delivery robot. The robot is carried along in a self-driving car. The vehicle parks itself near the delivery location and the robot, also called Digit-1, unfolds itself to make a delivery. The robot can climb stairs, walk on uneven surfaces, and avoid obstructions on its path. The robot also relies on the vehicle to recharge its battery. Unlike many bipedal robots developed to date, this bipedal robot does not rely on continuous human supervision, as shown in Fig. 7(c) and 7(d).

2.6 Crowd management

Managing people during COVID-19 to ensure the social distancing is always challenging, be it airports, shopping malls, parks, walkways, etc. Most of the places have adopted limiting people flow, marking social distance markers, investing in protective equipment, contactless payment options, etc. Despite all these efforts, managing people in public places is still a challenge. For these AI-based computers, vision solutions are keeping track of headcount as well as the proximity between people.

Shenzhen company MicroMultiCopter deployed more than 100 drones to many Chinese cities that could patrol areas and observe crowds and traffic more efficiently. Those not wearing masks in public spaces could be identified[52]. Indian states like Maharashtra and Assam used UAV's to strictly enforce lockdown in critical hotspots[53]. These flying robots are also used to broadcast information to a larger area than traditional loudspeakers can. Another way drones are used to fight coronavirus is to spray disinfectant in public spaces. Through thermal sensing, drones are also helping officials with crowd management and to identify people with elevated body temperatures, which could indicate they have the virus.

2.7 Education

Traditional ways of delivering education have taken a severe hit due to the COVID-19 pandemic all around the world, the fields of formal education are headed for a systematic change[54]. According to educational, scientific and cultural organization (UNESCO), about 1.18 million learners in 186 countries have been affected by COVID-19[55].

At this point in time, we don't know the extent to which the future of traditional learning & education will be altered following the pandemic[56]. AI[26], a part of robotics is contributing largely to the online education platforms for schools and universities.

One study[57, 58] found that telepresence robots were preferable to distance learning tools for remote learning, and the students noted the robots' ability to keep them more engaged, expressive, and self-aware. Fig. 8 shows the application of a telepresence robot in education during the pandemic.

The use of robotics for cleaning/disinfecting surfaces has seen the largest surge due to COVID-19. The degree of autonomy and reliability provided by these cleaning robots makes them ideal to be used en-masse in hospitals and other hazardous areas while allowing humans to follow social distancing guidelines. Despite being designed and produced in different parts of the world, cleaning/

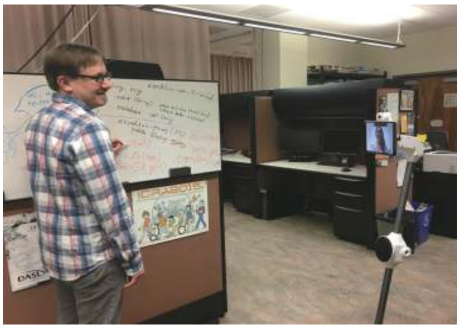


Fig. 8 Telepresence robot at Oregon State University[59]

disinfecting robots share some common characteristics:

1) Most of the robots are autonomous/ semi-autonomous in nature. However, some of them are capable of operating in both autonomous and manual mode.

2) They are capable of disinfecting odd-shaped surfaces and rooms.

3) Disinfecting is done using one of the following:

i) C band ultraviolet (UVC) lights

ii) Fog/ Mist disinfectant

The method of disinfecting is chosen based upon the application and environment in which the robot will be used. UVC based methods are used in environments where cleaning and disinfecting of surfaces such as tables, beds, walls, floors, etc. are required. UVC light is not preferred in environments with people since UVC can be absorbed by organic tissue and cause damage. Hence, in an environment with a large number of people and movement, fogging based disinfecting techniques are used[60]. Furthermore, most UVC light arrays are installed on mobile platforms, and the areas exposed to the UVC light are limited by the degree of freedom of the platform, rectilinear propagation of light, the geometry of the surface, i.e., the UVC light may not completely irradiate irregularly shaped surfaces such as L shaped air vent, zig-zag surfaces, etc. Hence, fogging based disinfecting methods provide a better scope for eliminating the virus. The two most widely used disinfectants are sodium hypochlorite and hypochlorous acid. However, due to a few drawbacks of sodium hypochlorite, such as its corrosive nature to metals and unwanted leftover residue on surfaces, hypochlorous acid is preferred to sodium hypochlorite to be used for fogging purposes.

Public hotspots such as airports, schools, subways have started to use AI-enabled body temperature monitoring systems, which can measure temperature with an accuracy of $\pm 0.3°C$. Schools have started implementing infrared mass fever screening system to detect fever and robots to provide rinse-free hand wash[61]. To help with the heavy workload on hospital staff, various autonomous robots have been introduced to perform tasks such as taking patient′s temperature, monitor patients′ vitals, perform ultrasounds, taking mouth swab samples, and delivering drugs and samples. One such example is the robot developed by John Hopkins University and University of Maryland which allows medical personnel to remotely control ventilators to moderate the volume of oxygen being administered[62]. Another robot, developed at University of Southern Denmark is capable of swabbing throats and sealing the sample in a glass jar using a disposable 3D printed swab holding tool[63]. This allows the medical personnel to operate at maximum permissible capacity while reducing the risks of exposing themselves to the virus. Similarly, to reduce exposure to ill patients, the use of telemedicine has seen a considerable spike. Telemedicine services provide virtual consultation or on-demand consultation, and in many cases, an app is used for initial diagnosis purposes. It provides low-risk urgent care for COVID-19 and non-COVID-19 patients, and a further medical consultation can be provided as appropriate. In cases where a patient is tested positive for COVID-19 and requires a routine check-up, medical personnel use telepresence robots to interact with the patient via audio and video without being exposed to the virus or putting on PPE. Telemedicine robots are also used to perform a task such as getting patient consent, making inspections around wards, social services, and restoring the mental well-being of the patient. Not only are telepresence helping patients with their mental well-being but they also helping university students to learn more effectively while remotely attending classes. Fritter et al.[58] found that the implementation of telepresence in distance learning kept students more engaged as compared to other distance learning tools.

As the governments across the world are searching for viable options to contain the virus, drones are being used globally to broadcast information, monitor public spaces, enforce social distancing, spraying disinfectants and delivering essential items such as food and drugs. Autonomous robots have also been used to deliver food and other essential items. These robots operate autonomously and are capable of delivering food with minimal to no contact, which eliminates the need to interact with other humans and hence reduces the risk of spreading the virus. In addition, restaurants have also started to use robots instead of waiters and chefs to reduce human-human interaction. Qianxi Robot Catering Group opened a restaurant using robots capable of cooking clay pot rice and mini ice cream in less than 20 seconds which is essential to reduce queue waiting times in populated countries such as China[64]. Restaurants in the Netherlands have started using robots to assist waiters and reduce human-human interaction[65]. A Robot greets the customer, takes their temperature, and if customers do not display COVID-19 symptoms, it seats them to be served before another robot takes theirs order and brings their food, followed by clearing the dishes after the meal[66]. Most of these robots are implemented in constrained and dynamic environments hence techniques like adaptive fuzzy full-state feedback control[61] and admittance-based control[67] have been proposed to effectively improve the compliance of interaction.

3 Technological boon due to COVID-19

History has shown that a crisis can bring about technological innovation and development[68]. Due to the advancement in artificial intelligence and microelectromechanical systems, robotics has increasingly grown, and due to the current pandemic situation, the demand and adoption of them has become more viable across all sectors[69–71]. Before the COVID-19 outbreak, technologies like telemedicine, telepresence, autonomous delivery robots, sterilization robots, etc. showed significant pragmatic promise however they did not achieve the success everyone hoped due to one issue or another. In the current COVID-19 world, a lot of these technologies have been fast-tracked and being heavily used to provide a near-to-normal lifestyle for the public. Few of the commercially used robotics under different areas of work have been summarized in Table 2. Telemedicine, which was not used by 82% of Americans before COVID-19, has now been endorsed by disease control and prevention (CDC) and WHO to monitor patients remotely, provide Americans access to telehealth to reduce human contact, and thereby reduce the spread of the virus[115, 116]. In another effort to reduce human contact and curb the spread of the virus, digital contact tracing apps are being used in various countries to identify individuals who have been in contact with an infected individual. These apps use bluetooth and/or the geographical location of the user which is obtained via either the cellular network or an app installed on a smartphone. Even though these raise questions for one′s privacy given the mass surveillance while presenting legal and regulatory challenges, the COVID-19 may be the right inducement for regulatory bodies to call for an open-source platform for all applications requiring access to sensitive users data. In America, prior to COVID-19, restriction on patient location during video visits was there but the same has been waived by the Centers for Medicare and Medicaid Services as well as by most state medicaid programs and private insurers[117, 118].

With the spread of COVID-19 and social distancing guidelines being put into place, almost all non-essential workers were ordered to work from home. The largest work-from-home campaign in the world was facilitated with the rise of telepresence robots and videoconferencing apps like Zoom, Microsoft Teams, etc. which were a mere convenience tool in the pre-COVID era as opposed to a necessity in the current world. This necessity and vulnerable security protocols of Zoom have triggered an innovation race between researchers to develop a secure and lightweight application for countries with poor internet speeds[119, 120]. On the other hand, telepresence has been heavily adopted by doctors to monitor and examine patients using a tablet or PC while not exposing themselves to a contaminated environment or patient. Various vital health parameters can also be tracked using specialized health monitoring[121] wearable devices[121, 122] which can relay the patient′s data to the doctor′s tablet remotely.

Human-robot interaction (HRI)[61, 67, 123, 124] has significantly advanced in terms of interpreting emotional signals and reacting accordingly in real-time with human beings. Social robots in public places like airports, hospitals, malls, etc. have been used for guiding and entertainment purposes. Mobile robots have been heavily used for logistics purposes, be it industry or hospital, hotels, etc. for transporting medial kits, medicine, food, delivering amenities, cleaning, and providing safety and security services.

Before COVID-19, drones were used for the delivery purposes at an experimental level but during COVID-19, it has been used as a prominent and fast solution to reach far-flung places for sample and drug deliveries[94, 95]. In the United States, the use of drones is restricted to the federal aviation regulations (FAA), who has now waived operating limitations for operators to fly drones at night, fly over people and beyond the line of sight which allowed operators to deliver cargo (food, supplies, medicines) in a larger area[125]. Co-corporations like Flytrex, AHA, Google′s Alphabet have already started delivering food on a commercial scale in North Carolina, Virginia, and Australia[126]. Not only are robots being used in delivering items from a warehouse/restaurant to a consumer′s address, but robots are also being used within warehouses to streamline and fulfill orders. Due to social distancing guidelines, it is challenging and hazardous for humans to work in warehouses and factories. The only way social distancing guidelines can be observed is to reduce the number of people working which in turn reduces productivity. Hence, supply chain managers are implementing pick and place robots, unloading robots, and robots for inventory tracking.

The silver lining of the COVID-19 pandemic is the acceleration of open-source research in robotics and collaborative approaches across nations and fields of studies. In recent weeks, scientists and researchers from all countries and fields of knowledge have been working tirelessly to fight the outbreak. In an initial response to the outbreak, a team of Australian and Chinese researchers released the genetic map of the virus to the researchers globally for free. White House and the Allen Institute for AI has put together the COVID-19 Open Research Dataset (CORD-19) which proves epidemiology, bioinformatics, and molecular modeling datasets to researchers all around the globe[100]. Nocca Robotics used the open source data of MIT′S low cost ventilator design[127] to produce ventilators for India[128]. This demonstrates the significance of the combination of open-source data, improvisation, and collaboration in times when they are needed the most. Adoption of driverless vehicles[129] in small circuits for delivering food and beverage is another significant achievement towards the acceptability of driverless vehicles.

Table 2 Various commercial applications of robotics in COVID-19

Cleaning/ Disinfection	
Closed public places like hospitals, airports, etc.	
eXtreme disinfection roBOT (XDBOT) by NTU, Singapore[72]	1) Semi-autonomous, wirelessly controlled. 2) Disinfect odd-shaped surfaces (doorknobs, light switches, etc.) or anything above ground level (under tables, beds, etc.). 3) Uses electrostatic-charged nozzle via 6-axis robotic arm.
Aertos 120-UVC by digital aerolus[73]	1) Can fly through tight spaces indoors. 2) Uses UVC lights. 3) Actual efficacy is questionable, as various agencies are using the UVC light for different amounts of exposure at different distances[74] which are in contradiction with the nature journal article[75].
UVD robots[76]	1) Uses UVC lights. 2) With single charge works for 2−2.5 h, which is sufficient to disinfect 9−10 rooms.
LightStrike robots by Xenex disinfection services[77, 78]	1) Uses ultraviolet lights (pulsed xenon), an extensive range of germicidal UV (200−315 nm) that includes both UV-B (280−315nm) and UV-C (200−280nm). Disinfects a patient room in 5 minutes. 2) Uses Xenon bulb instead of UVC mercury vapor.
XPlanet drones and R80 robots[79]	1) These are primarily agricultural robots which are used for large scale disinfection by using an intelligent JetSprayer. The capacity of 80 liters with a centimeter-level navigation system, disinfects targeted areas from different angles. 2) R80 could atomize the disinfectants into micron particles as small as 50 μm, and spray as wide as 12 meters, which enabled better adherence and therefore improved the effect of disinfectants on hospital surfaces.
YouiBot's Aris-K2[30]	1) Dual-purpose robot; monitors customer temperatures during the day and disinfects during night. 2) Uses UV light of intensity up to 270 uv/cm^2 to disinfect. 3) Equipped with infrared cameras to monitor customer's temperatures.
CoDi BOT[30]	1) 360° coverage, using UVC light-emitting diodes covering the entire spectrum of germicidal UV. 2) Autonomous navigation using pre-planned maps. 3) Access thermal imaging, live video, disinfectant system, power system information from the robot.
Neo[78, 80]	1) Works in manual and autonomous mode, with the capacity of cleaning autonomously up to 3 900m^2/h. 2) Scrubs cleans and sanitizes floor with a speed of 1.35m/s.
LIBERTY SC50[78, 81]	1) Works in manual and autonomous mode. Functionality to calculate the optimized path and cleaning procedure. 2) Scrubs and cleans the floor with a speed of 1.055m/s. 3) Retrofitted with UVC to sanitize the floor, used in Pittsburgh International Airport[82].
CAREtaker disinfection robot (GoGaS CAREtaker is the model B from its partner and manufacturer UVD robots, Denmark)[83]	1) Operated manually, semi-automatic, or in a full predefined autonomous mode with automatic shut off and safety mode. 2) Uses UVC wavelength of around 254 nm, with a 360° coverage, disinfects the air, and surfaces up to around 250 cm from floor level in one cycle.
Whiz[84]	1) Works in manual and autonomous mode. 2) With single charge works for 3h and covers 464−557m^2/ h at a maximum speed of 1.77 km/h.
TMiRob series-intelligent sterilization robot (ISR)[85]	Works autonomously, disinfects in three modes: ultraviolet rays, ultra-dry mist hydrogen peroxide, and plasma air filtration.
Breezy One[86]	1) Cloud-based autonomous mobile robot. 2) Uses fog for disinfection, which reaches to the areas where UV light cannot. 3) Disinfect a 9 290m^2 facility in 1.5h.
Connor UVC disinfection robot[87]	Works autonomously with a maximum speed of 1m/s using UVC ultraviolet germicidal lamps and atomizing nozzles.
Violet[88, 89]	Works autonomously using UVC ultraviolet germicidal lamps.
Tru-D smart UVC[90]	1) All-round 360° coverage, using UVC ultraviolet light. 2) Efficient disinfection for reducing the risk by calculating the time needed to react to room variables – such as size, geometry, surface reflectivity, and the amount and location of equipment in the room. Based on these calculations, it delivers the proper UVC exposure.
Helios UV[91]	1) Works autonomously using UVC ultraviolet germicidal lamps for sterilization and disinfection. 2) In autonomous mode, it works in fixed-point and multi-track depending on the size of the space, according to the pre-set route and time requirements. 3) Apart from this, it sterilizes and disinfects the air by passing through high-power UV lamps.

Continued

Cleaning/ Disinfection		
	THOR UVC[92], STERIPRO[93]	1) Works autonomously using UVC ultraviolet germicidal lamps, which uses room mapping for an effective dose of continuous-wave UVC. 2) Due to its height adjusting and distance to energy inverse relation, floor to ceiling disinfection is possible.
Supply chain/ Logistics		
Drug and sample delivery		
	Antwork[94], Terra Drone[95], Aethon's TUG[11], UR[9, 10], Relay[96]	1) Transport medical samples and quarantine materials. 2) Its automatic and unmanned operation mode significantly reduces the contact opportunities between samples and personnel in the transportation process and improves the delivery speed.
Food		
	Hercules by UDI[97], Tug by Aethon[11]	Autonomous food delivery vehicle powered by deep learning.
	Novus Carry[98, 99]	Different applications like food and material delivery, disinfection of hospitals.
	Starship Technology[28, 29]	Autonomous and contactless food delivery robot capable of carrying 20 pounds.
	Digit-1[30]	1) Legged autonomous robot encapsulated in a self-driving car. 2) Capable of climbing stairs, avoid obstacles, and does not constantly rely on human supervision.
	Flytrex, AHA, Google Alphabet[100]	Food delivery via drone.
	Cobot by Universal Robots[39]	1) Explicitly designed to reduce dust accumulation on the surface. 2) Food packaging.
	AIMBOT by UBTECH[101]	1) Delivers food to patients. 2) Disinfect hospital premises. 3) Measures body temperatures of 200 people per minute. 4) Mask detection. 5) Warning broadcasting.
	PTR Robots	The multi-tower robot is a mobile, flexible, and modular patient-lifting robot intended to be used primarily in hospital patient rooms and in correlated situations where patient-moving is required.
Warehouse management		
	Amazon's Robo-stow[46]	Robotic arm to lift pellets to different levels within a fulfillment left.
	GreyOrange[45]	Sorting system with modular design for faster deployment.
Telemedicine		
Airport, shopping malls, subways		
	Cloud Infrared Temperature Measurement System (CITMS-200)[102]	1) An AI-enhanced, infrared, large-scale, body temperature monitoring device for rapid detection of high temperature in the human head. 2) Optimal scan distance of 2–8 m. 3) Accurate temperature detection (±0.3°C), automatic warning.
Hospitals		
	Tommy[14]	1) Monitoring oxygen levels and blood pressure and relaying them to doctors. 2) Allows communication with doctors via video and audio.
	CareClix[103], Callondoc[104], Galileo Health[105], HeyDoctor by GoodRx, K Health[106], One Medical[107], SteadyMD[108], ENDORSE[109]	1) On-demand consultation by setting up an appointment with a doctor or immediate virtual consultation. 2) A few of them are paid and a few are fee waived. 3) For initial diagnosis purposes, some of the apps take user symptoms and health needs as a questionnaire.
Telepresence		
	Ginger[110], GoBe Robots[111], RoboELF[99]	1) Robotics dance and exercise for the mental well-being of patients. 2) Consultation to ease out physiological pressure of patients.
	AVA 500 by Ava Robotics[24, 112]	1) Autonomous navigation, scheduling capabilities. 2) Integrated wireless via embedded Cisco Aironet 1 600 wireless access point (HIPAA-certified communications system from Cisco) for data privacy between patient and doctor.
	Prof. Gang-Tie Zheng from Tsinghua University[113]	The mobile robot platform consists of a robotic arm that can perform ultrasounds, take a mouth swab sample, and can use the stethoscope.
	Stevie[114]	1) Keep seniors socially connected. 2) Helps caregivers in the delivery of group-based wellness activities.
Information broadcasting		
	Various drone companies and the user with retrofitting of payload	1) Loudspeakers on drones to encourage physical distancing and staying home. 2) Mixed reactions like onlookers instead of dispersing, started gathering. The sound of the rotor of the drone is more than a loudspeaker. Not audible from a far distance. Requires placing of the loudspeaker at a specific angle.

4 Deployment factors under COVID-19

The deployment of robots during the COVID-19 is happening quicker than expected. Futuristic seeming services like food and essential delivery via robots, robot nurses in hospitals, disinfestation robots, etc. which might have taken a few more years to become the norm, are now being used on a global scale. Due to the growing popularity of robotics, their deployment is getting better, cheaper, and more accessible. Furthermore, this allows the regulatory bodies to fast track policies regarding the deployment of robots for general use. One such example is the Part 107 waivers granted by the FAA to drone operators, which allows them to operate drones "beyond visual line of sight" (BVLOS) while relying on the drone′s camera to navigate. This waiver in policy, no doubt, allows the drone operator to operate the drone freely; however, it compromises on safety. The skill of the drone operator can justify this trade-off between productivity and safety; hence the human factor should be considered while making policies for the deployment of robots. One should also consider the human factor when defining the workspace for a robot since the workspace between humans and robots is continuously shrinking. The recent surge in collaborative robotics and telemedicine can be attributed to the same, which in turn raises novel occupational safety and health issues. The safety of humans is paramount while deploying robots in a collaborative environment hence industrial standards like ISO 10 218-1 which is the international safety standard for robots and robot systems integration and ANSI/RIA R15.06, the current US robot safety standards are established to ensure that robots are not hazards to humans while performing a task. Another safety measure that is often overlooked is cybersecurity, which will ensure the safety of robotics operations. Cybersecurity is essential since most robots nowadays are connected to the internet via ethernet or Wi-Fi and soon via 5G. However, this introduces significant security vulnerabilities owing to the fact robot manufacturers are not well-versed with cybersecurity standards as other industries since they are not seen as potential targets for hardware attacks, Firmware/OS Attacks, and Application Attacks by hackers[130].

The ISA/IEC 62 443 standard currently serves as the cybersecurity standards for Automation and sets the following seven guidelines: the device must be protected from unauthorized use; verify the identity of an authorized user; the system′s integrity should prevent unauthorized manipulation; data confidentiality; restricted data flow; security violations must be reported to the proper authority; the device must have access to all the resources required to provide necessary service[131].

Policies and safeguards should be put in place to ensure that robot manufacturers follow the same cybersecurity standards as other industries. Another factor that should be highlighted is the economic aspect of the deployment of robots on a large scale. An average robot can cost between \$100 00−\$150 00 (including attachments) but can go up to 2 000 000 for surgical robots like Da Vinci. Additionally, we have to account for human training, especially for collaborative robots, which requires more investment than robot-only tasks. Hence, we must consider the nature of the task to be accomplished to gauge the investment that would be required to deploy robots on a commercial scale.

In recent months due to social distancing guidelines and stay-at-home orders, the use of robotics has accelerated to do the jobs of humans like cleaning the floor in grocery stores and warehouse management. Pre-COVID-19, a majority of people had reservations about the use of robots and AI to do human jobs, however, now in these times of pandemic, people are overlooking their previous skepticism since the value provided by technology outweighs the anticipated downsides. In the current scenario, more people are finding themselves accustomed to the automation provided by robotics and AI in their daily life. Companies who invested in robot solutions may find themselves permanently laying off human workers, and customers may barely feel any difference between a human delivery or a robot delivery.

With each passing day, robots take on more and more tasks that were earlier performed by humans to provide us with a sense of normalcy. However, we, as a society, have not yet contemplated the place of these robots when the pandemic is over since the technology is serving a higher purpose and preserving our well-being. Hence, it is imperative that the topic of the coexistence of humans and robots as a society is explored[132].

5 Future scope-post COVID-19

In a post COVID world, technology will be operational and innovative. COVID-19 has worked as an undesired catalyst, when it comes to supporting the acceptance of robotics in the industry, enabling us to empower experiences like never before. When the entire world is starting to open up and daily life wants to be normalized, robotics and automation are the first line of defense to safeguard the happiness of humans. People′s experiences in contactless and digital interaction have significantly improved the qualitative behavioral insights, which has helped in the easy place of the technology in individual experience.

A Canadian startup Bluedot uses machine learning (ML) and natural language processing (NLP) to detect disease outbreaks. BlueDot studies airline data, information from animal disease control networks, and news telecasts in 65 different languages to detect the outbreak and spread of the disease. Epidemiologists analyze the output from the system to verify and derive conclusions to make sense in a scientific way which is then relayed to public health officials[133]. Once the world became aware of the presence of the virus, the scientific community galvanized to develop tests and find the vaccine to the virus. DeepMind used its UltraFold system to generate 3D models of several proteins associated with COVID-19. The models generated are entirely based on the genetic sequence of the protein and are more accurate than any other previous techniques[134, 135].

AI has also allowed researchers to use computational techniques to detect positive COVID-19 cases early from computed tomography (CT) scan images and X rays. Li et al.[136] proposed a three-dimensional convolution model implemented on volumetric chest CT scan images to detect COVID-19. The model has an area under the curve (AUC) value of 0.96 meaning that the model predicts 96% of the cases correctly. Gozez et al.[137] used a fifty layer deep convolution neural network on CT images of 157 patients and had an AUC of 0.996. Researchers have also used AI to model and monitor the spread of COVID-19 in real-time. University of Chicago Medical Centre uses an AI system named Ecart which takes into consideration 30 variables associated with patients′ electronic medical records, the respiratory rate being the most crucial variable, assess the probability of a patient going into cardiac arrest, need to transfer to the ICU and patient′s death, all of them are predicted within 8 hours[138].

To forecast the confirmed COVID-19 cases in China, Hu et al.[139] used a modified stacked autoencoder deep learning model consisting of four layers that grouped cases into regional areas to be investigated further. Ye et al.[139] proposed an AI system, alpha Satellite, to collect various demographics such as positive cases in a region, population density, deaths, social media posts. Based on this data, the system would assess the risk of infection in a certain region. Similarly, in an effort to study the numbers and effect of undetected COVID-19 cases, Chan Zuckerberg Biohub in California researchers build a model that studies the mutation of the virus while it spreads through the population to find instances where the virus′ detection might have gone undetected[133].

In a different approach to using AI, information chatbots are being developed and deployed to provide information about COVID-19 to the public. They are also helpful in the contactless screening of COVID-19 symptoms in self-diagnosed patients. A French startup, clevy.io, uses real-time information from the World Health Organization and the French government to answer questions related to COVID-19 without having to burden the already available resources[133].

With days passing, practicing social distancing and monitoring may be the only way we can contain COVID-19 from spreading. In the COVID-19 management strategy, some countries have underpinned their AI model by the implementation of "safe city initiatives"[140]. China, Japan[141] implement their facial recognition systems to monitor and track citizens with the help of advanced AI and closed-circuit television (CCTV) cameras. Using this system as a foundation, the country repurposed the existing Robotic and AI systems to aid the fight against the virus. US-based computer vision startup, Camio, uses ML and AI to turn existing CCTVs into social distancing detectors. These CCTVs give out a warning when the social distancing guideline are violated. The need for not installing new hardware gives the system unique flexibility to adapt to the ever-changing situation[142, 143]. China has other practices. For instance, China has implemented a quick response (QR) code-based ranking system for all its citizens according to a citizen′s identification number, medical history, and lifestyle habits[144]. The system generates QR codes of three colors: green, yellow and red. Green indicates that a person may move unrestricted in the city, the yellow color holder might be asked to stay at home for seven days and a red QR holder goes into a two-week quarantine[145].

In a post COVID world, we need to leverage technology and embrace a mindset where robotics and automation are enablers. This will help us to accelerate towards a future founded on creating world-class experiences for the citizens of the countries in which we live and work.

6 Conclusions

Robotics and automation are playing a significant role all around the globe by safeguarding humans and performing jobs such as delivering food and sanitizing hospitals and medicines. One of the possible solutions is keeping social distance. This remains a challenge in many developing countries due to population density[146].

The COVID-19 situation has shown an aggressive behavioral change in the adoption of technologies across the world through necessity. This pandemic has exposed many weaknesses of our health care system and challenged them to be addressed. But at the same time, it has given ample opportunities for robotics, artificial intelligence, UAVs, telehealth, telemedicine, etc. to overcome the current gap and show their effectiveness. Telemedicine and telehealth technologies have helped in avoiding the collapsible state of the health care sector. Also, it is safe, cost-effective, accessible, and convenient in real-time.

Although there were technological hurdles present in implementing these solutions in terms of poor infrastructure, cost-effectiveness, optimization of services, and access to the end-user, the same has been addressed to a greater extent.

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