ROBOTS AND SOCIETY

Progress in robotics for combating infectious diseases

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The world was unprepared for the COVID-19 pandemic, and recovery is likely to be a long process. Robots have long been heralded to take on dangerous, dull, and dirty jobs, often in environments that are unsuitable for humans. Could robots be used to fight future pandemics? We review the fundamental requirements for robotics for infectious disease management and outline how robotic technologies can be used in different scenarios, including disease prevention and monitoring, clinical care, laboratory automation, logistics, and maintenance of socioeconomic activities. We also address some of the open challenges for developing advanced robots that are application oriented, reliable, safe, and rapidly deployable when needed. Last, we look at the ethical use of robots and call for globally sustained efforts in order for robots to be ready for future outbreaks.

INTRODUCTION

As the global spread of coronavirus disease 2019 (COVID-19) continues, it is apparent that dealing with the disruption caused by the pandemic will be a long, challenging process. The effective use and innovative development of robotics can play a vital role in mitigating infection risks and restoring normal social and economic activities, either at a regional or a global scale (*1*, *2*).

As of February 2021, more than 192 countries and territories have reported over 113 million infected cases of COVID-19 (*3*). Infectious diseases are caused by pathogenic microorganisms—such as bacteria, viruses, parasites, or fungi—and can spread directly or indirectly from one person to another (*4*). The longstanding threat of infectious diseases can confront us in multiple phases, from outbreak and evolution to resurgence. The impact of infectious diseases, as demonstrated by COVID-19 on a dramatic scale, has revealed major weaknesses in our health care systems and government responses to major health crises. Responses have been hampered by geopolitics, the public's attitude, and limited knowledge of hazards posed by newly emerging viruses, as well as a shortage of personal protection equipment (PPE) and a qualified workforce. Despite an improved biological understanding of the COVID-19 infection (*5*), more efforts are needed to fully assess the virus characteristics and explore viable solutions to mitigate disease transmission.

Historically, robotics and automation technologies have been designed to assist humans in executing dirty, dull, and dangerous tasks, including machine assembly (*6*), firefighting (*7*), mountain rescue (*8*), and dealing with nuclear disasters (*9*). Small-scale deployment has also been used to combat infectious diseases and manage public health crises, including COVID-19 (*1*). Some of the requirements for robots in dealing with infectious diseases include the following:

1) Biosafety: As reported by the World Health Organization (WHO) for COVID-19 (*10*), biosafety level 2 (BSL-2) or equivalent facilities are required for specimen handling for testing, and BSL-3 facilities or above are mandatory for culturing the virus for research purposes. For viruses such as the Ebola virus, experiments must be performed in BSL-4 laboratories. Thus, robots for infectious material handling should adhere to stringent biosafety requirements.

2) Decontamination: Robots for infectious diseases must meet or exceed decontamination standards, similar to the demands of nuclear accidents, chemical spills, and disaster recovery. Solutions are required to minimize disease transmission due to robot-to-human, robot-to-robot, or robot-to-environment interactions.

3) Adaptability: The working environments of robots may be public places—such as hospitals, subways, buses, shopping malls, and restaurants—or private spaces, such as apartments or houses, during different containment stages or lockdown. Robots must be able to operate safely in the environment under the stringent biosafety criteria.

4) Duration: Infectious diseases can last for many months, or even years, and evolve over different phases. Thus, robots need to be durable and sufficiently general purpose to support different phases of the disease transmission and containment cycles.

5) Capacity: A pandemic by definition affects a large portion of the global population, unlike other natural disasters that are limited in geographic scope. Robots are needed to help health care systems cope with increased and sustained demand for services.

Although a variety of commercial and prototype robots—including those for disinfection, screening, logistics, and transport—have been used during the COVID-19 pandemic, there is a lack of systematic approaches and a common architecture for the deployment and sustained development of robots for infectious diseases. As pointed

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out in (*1*), lessons need to be learned to react effectively and reduce the risk to which the public and especially frontline workers are exposed.

Categorization of robots for infectious diseases

Before discussing key technical challenges and unmet clinical and public needs for robots for infectious diseases, it is useful to establish a detailed categorization of these robots. Here, we focus on systems and underpinning technologies described in peer-reviewed publications. Commercial systems, prototypes, and those repurposed with ad hoc modifications as reported in news channels or social media are summarized in the Supplementary Materials. Figure 1A illustrates robots by application categories and usage scenarios. The four major categories, as highlighted in different colors, include (i) clinical care; (ii) public safety; (iii) laboratory and supply chain automation; and (iv) out-of-hospital care, quality of life, and continuity of work and education. They are used to assist or substitute humans in the presence of an outbreak or pandemic. The literature search was conducted using Web of Science, IEEE Xplore, and Google Scholar. The keywords included, but were not limited to, the combination of "infectious diseases," "robots," "robotics," "automation," "public health," "coronavirus," "COVID-19," and "Ebola virus disease (EVD)."

CLINICAL NEEDS

Patient management

Figure 1B shows a typical journey of an infected patient. At each phase, robots can cater for different clinical needs in the continuum of care to facilitate screening, diagnosis, treatment, and recovery, as displayed in colors corresponding to Fig. 1A.

1) During the initial phase of an outbreak, the priority is to track sources of infection; to understand the interaction of infectious agents and their hosts, vectors, and environment; to determine the main transmission routes and mechanism; and then to deploy effective mitigation, isolation, and treatment regimens. For example, the new coronavirus can be transmitted through small airborne droplets from the nose or mouth and remain active on surfaces for up to 72 hours (*11*, *12*), whereas Ebola transmits only through direct contact with blood or bodily fluids, rather than in the air (*13*). Frequent disinfection is the key to mitigating pathogen contamination. Robots deploying continuous noncontact ultraviolet (UV) surface disinfection may be used to mitigate transmission, e.g., disinfecting public spaces and hospitals (*14*), and to enforce isolation, e.g., surveying high-risk areas and enforcing public safety measures.

2) When a person shows symptoms of infection, a period of self-isolation is required (or enforced). During this stage, autonomous robots may deliver food and essential medical supplies to the individual to minimize person-to-person contact, whereas teleoperated robots can perform remote diagnosis and sampling. Tasks from the COVID-19 response included robot-assisted nasopharyngeal and oropharyngeal swabbing, taking a blood sample, and measuring the patient's vital signs and temperature (*15*).

3) If the test is positive, then the patient needs to be quarantined or taken to a hospital for treatment. There are clear advantages in using teleoperated robots for diagnosis, treatment, and assistance of daily activities of quarantined patients to minimize the risk of infection for frontline health care workers. In hospitals, robots can also be used for bedside nursing assistance, aiding with intravenous access (*16*); laboratory automation of handling test samples and biological specimens; disinfection of wards; and managing clinical waste to handle the surge in patient numbers.

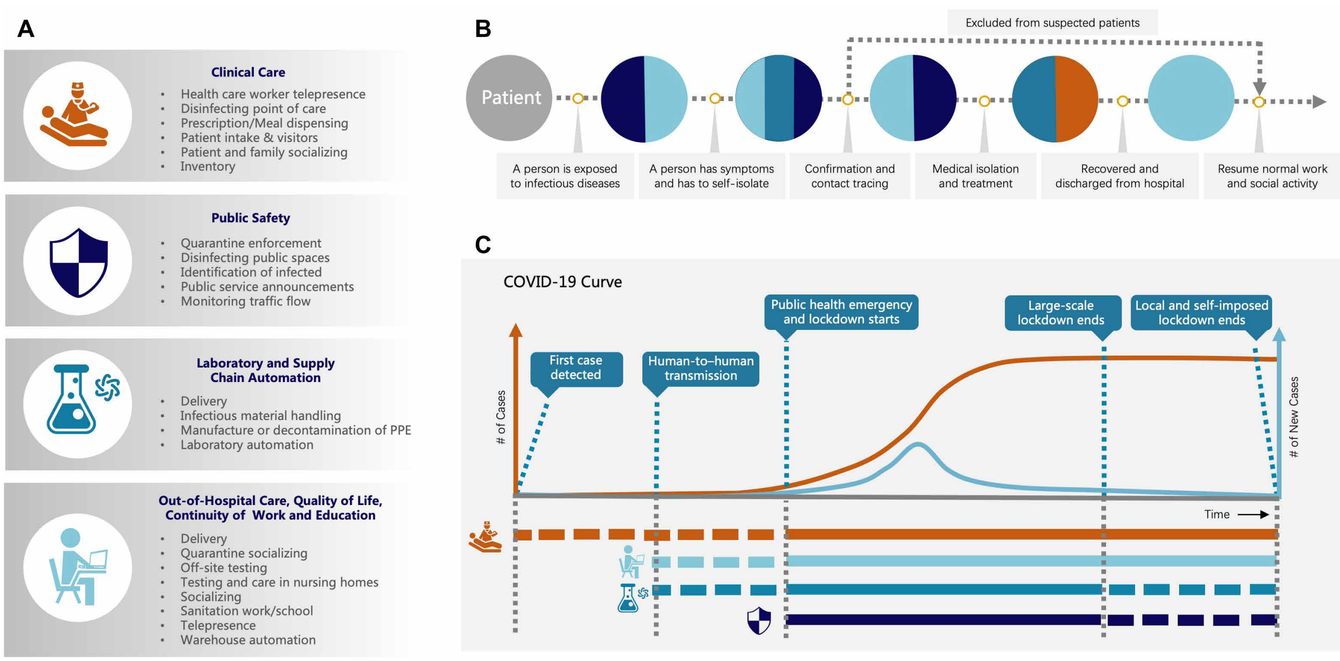

Fig. 1. Robotics and automation technologies for infectious diseases. (**A**) Potential application categories of robots. (**B**) Different usage scenarios for robotics, illustrating potential applications of robots at each phase of the disease transmission using the colors corresponding with (A). (**C**) Phases of COVID-19 pandemic showing different critical time periods and the associated usage of robotics.

4) After treatment and discharge from hospitals, patients may still need to recover at home for a period of time before resuming normal activities. At home, robots can continue to support the large-scale need for telehealth and the delivery of food and medicines. Mental stress is a major issue during an extended period of social isolation, as we have experienced in many parts of the world during the COVID-19 pandemic. The use of social robotics (*17*) can present unique opportunities for maintaining both social interactions and mental well-being, especially in conjunction with patients in high-risk categories that can face long periods of isolation (*1*).

Public demand

Figure 1C shows a schematic overview of anticipated responses to COVID-19 if robots were ready for the pandemic.

1) First, robots should be used routinely in high-risk areas of hospitals for the prevention of hospital-acquired infections, dispensing meals and prescriptions, as well as providing telehealth.

2) When an outbreak grows in scale with human-to-human transmissions, rapid deployment of robots will allow immediate clinical capacity expansion, prevent direct patient contact, and allow coordinated remote teleoperation support by public health and infectious disease specialists. The primary drivers for robots during this phase are to protect health care workers and vulnerable populations, as well as to facilitate rapid testing.

3) When the situation escalates into a pandemic, public health and safety agencies can deploy robots for quarantine enforcement and disinfection of large-scale public spaces. Because a sizable number of people may be quarantined, robots for logistics, delivery of food and essential medical supplies, and telehealth are essential. Lockdowns can impose major strains on both local and global economies, as well as education, social life, and well-being of the public. At this phase, in addition to the need to protect health care workers and vulnerable populations, medical robots can alleviate the pressure due to a surge in demand for health care support and help maintain the continuity of work, education, and activities of daily life. Industrial robots can also play an essential role in maintaining economic output.

4) Even after large-scale lockdowns are lifted, local and self-imposed restrictions often remain in place or are reinstated after new cases, either local or imported due to renewed movement of people and relaxed travel restrictions. The main drivers for the postcrisis phase are to prevent a new surge of infections, maintain public confidence, and sustain economic recovery.

Laboratory workflow and testing

Laboratory testing and diagnosis are critical for infectious disease management. In such settings, all staff should be appropriately trained, and protective equipment should be available according to the required biosecurity levels (*18*). The use of robotics not only offers personal protection but also maximizes efficiency, allowing rapid scale-up during times of high patient influx and increased clinical workload. Figure 2 illustrates potential applications of robots for laboratory testing, and Table 1 shows the characteristics of EVD and COVID-19 to highlight the need for appropriate robotic technologies.

Molecular biomarkers represent an important part of the laboratory workflow. Other technologies used for research and surveillance include serological assays and rapid disposable tests for antigen detection. Polymerase chain reaction (PCR) testing of asymptomatic or mildly symptomatic contacts are used. The rapid collection is conducted for suspected cases with nucleic acid amplification tests

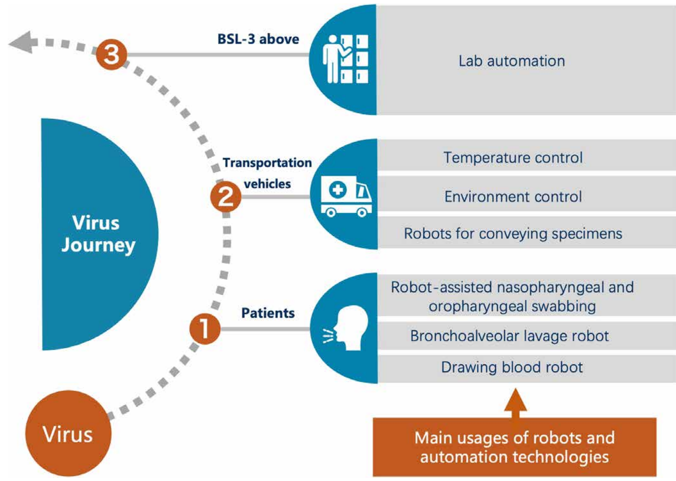

Fig. 2. Laboratory workflow and testing, samples from infected patients to transportation and to BSL-3 above for further confirmation. The operations involved in diagnosis and transportation are shown to illustrate potential applications of robotics and automation (*163*).

(NAAT), such as reverse transcription PCR (RT-PCR). As reported in an early study (*19*), the mean incubation period for COVID-19 was 5.2 days. The respiratory samples have the greatest yield, and the specimens from stool and blood can also be used for the detection of the virus. Appropriate specimen collection, storage, packaging, and transport need to be performed by trained staff. All standard operational procedures for specimen collection should rigorously adhere to infection prevention and control guidelines. Robots and automation technologies can accelerate laboratory workflows; help reduce biosafety risks; and allow remote operation of specimen collection, transportation, and laboratory testing.

Collection of specimens

For screening of COVID-19, the specimens can be collected from the upper respiratory tract by nasopharyngeal and oropharyngeal swabs or washes in ambulatory patients and/or from lower respiratory by sputum (if produced) and/or endotracheal aspirate or bronchoalveolar lavage in patients with more severe respiratory disease with due consideration of the risk of aerosolization. Collection must strictly follow infection prevention and control protocols (*19*). Additional clinical specimens are also used, including blood and stool, autopsy material including lung tissue for the deceased patients, or serological assays.

Robot-assisted oropharyngeal swabbing has been reported for teleoperated specimen collection (*20*). A swab is inserted into the patient's mouth to collect the virus, and then its tip is put into a tube of either viral transport media or saline. Last, the tube is stored in a specimen bag contacting absorbent pad and kept in a freezer with an ice pack until ready to be packaged and transported. In addition, ultrasound-guided robots for drawing blood also have advantages to locate difficult-to-find veins for sample collection in a safe, easy, and accurate manner.

Transportation of specimens

Normally, 2° to 8°C is a suitable temperature for storage and delivery of specimens. Considering the delay of delivery, −20°C or ideally −70°C is required by using viral transport medium. During transportation, the sealed storage bag is stored in a Styrofoam box. This procedure should strictly follow local regulations. Sensing and automation—including continuous temperature control, environment

Table 1. Comparison of disease transmission, symptoms, affected groups, and management regimes between EVD and COVID-19.

	EVD	COVID-19
Outbreak	Mostly in 10 countries	Worldwide
Transmission	EVD is less contagious than COVID-19, but much deadlier. It transmits only through bodily fluids, rather than through the air. Human-to-human and animal-to-human have been found.	It transmits through respiratory droplets and contact routes, but airborne transmission is not confirmed. Human-to-human has been found.
	The reproduction number of EVD is estimated to be ~1 to 2 (*164*).	The reproduction number of COVID-19 is estimated to be 2.5 (*165*).
Characteristics	Symptomatic transmission	Symptomatic transmission
		Asymptomatic transmission
Symptoms	High fever, headache, muscle pain, sore throat, fatigue, lack of appetite, vomiting, diarrhea, abdominal pain, etc. (*164*, *166*)	Fever, cough, fatigue, anorexia, shortness of breath, myalgias, sore throat, etc. (*167*)
Vaccine	Yes	Yes
Lockdown	Yes	Yes
Most affected groups	Children	Adults over 60 with underlying health conditions; children seem to experience milder symptoms

monitoring and tracking, and automated guided vehicles (AGVs) or drones—for secure transportation of specimens may be considered in the future.

Laboratory testing

Laboratory confirmation of COVID-19 is based on the detection of unique sequences of SARS-CoV2 RNA by NAAT such as RT-PCR with confirmation by nucleic acid sequencing. Laboratory automation has already been used with minimal user intervention in microbiology laboratories (*18*). This is critical when massive testing programs are required.

Biological laboratories that handle genetically modified organisms and pathogens are subject to strict regulations and safety precautions. In the United States and Europe, these are classified as BSL-1 to BSL-4, where a higher number indicates a higher risk level. In what follows, we will focus on BSL-3 and BSL-4 laboratories that are known as high-containment biological laboratories (HCBLs). These are built to house lethal viruses and bacteria that can infect humans and/or animals. These pathogens can be a serious hazard to workers but are either treatable (BSL-3) or have no effective prophylaxis or treatment available (BSL-4). BSL-4 is the highest category of biologically hazardous material (see Table 2). There has been a proliferation of such HCBLs in recent years because they have become indispensable in national security programs and the preparation against epidemics, accidental spread, and intentional misuse. A recent study found that more than 80 countries have or are now building HCBLs, with an estimate of 60 BSL-4 facilities and more than 3000 BSL-3 laboratories worldwide (*21*).

The facilities have become essential, for example, in the search for a cure for Middle East respiratory syndrome (MERS), caused by MERS coronavirus (MERS-CoV); severe acute respiratory syndrome (SARS), caused by SARS coronavirus (SARS-CoV); and, more recently, COVID-19, caused by the coronavirus SARS-CoV-2. In fact, the availability of these expensive and high-tech laboratories made the response to pandemic outbreaks such as COVID-19 faster in terms of both research and diagnosis where virus culture and isolation or neutralization assays are required. However, one concern is that these facilities can also pose a threat in case of accidents and accidental dissemination. An example is a 2007 incident, where it is suspected that wastewater leaked from an HCBL and contaminated the surrounding soil with foot-and-mouth disease, one of the most highly infectious livestock diseases (*22*). The use of robots for continuous surveillance therefore presents unique opportunities.

The laboratory instruments inside HCBLs are, in general, similar to those found in BSL-1 biochemistry and microbiology laboratories. The main difference is that to protect the laboratory workers and prevent any microorganisms from being disseminated into the environment, BSL-3 and BSL-4 laboratories require complex safety procedures and special installations that contain the pathogens (*23*). There are different HCBL designs, and all of them include a primary containment that protects the worker and the immediate environment; this includes primary containment devices such as safety cabinets and suits where the worker wears a fully enclosed positive pressure suit with its own air supply. In addition, HCBLs have strict secondary containment protective measures to prevent high-hazard pathogens from leaking into the environment. This includes a combination of laboratory designs and operating procedures such as access restriction, air handling, and safe disposal of waste.

Generally, work in HCBLs requires multiple and complex layers of protection around each instrument, which, in turn, requires expensive customized installations for the laboratory equipment in addition to bulky protective suits. As part of the PPE inside a BSL-3 and BSL-4 laboratory, multiple layers of gloves are worn. Repetitive and even simple tasks can become cumbersome and cause fatigue. Regardless of the safety level and the exact laboratory design, the stringent safety protocols require long training periods, which can last up to 6 months before new personnel can be certified to work in these laboratories handling hazardous materials.

CURRENT STATE OF ROBOTIC SYSTEMS

During the 2015 Ebola outbreak, three broad areas (clinical care, logistics, and reconnaissance) of robotic technologies for infectious

Table 2. Regulations for BSL-3 and BSL-4 laboratories worldwide.

	BSL-3	BSL-4
Typical safety settings	BSL-1/BSL-2 regulations and the following:	In addition to BSL-3 considerations, BSL-4 laboratories have the following:
	Locking doors with access away from the general building.	Dedicated supply and exhaust air.
	Restricted access, only certified and trained people, controlled for 24 hours.	Personnel required to change clothing before entering and shower when exiting.
	PPE must be worn, as well as respirators depending on hazards.	Full-body, air-supplied, positive pressure suit depending on the agent.
	Work must be performed within an appropriate biological safety cabinet (BSC).	A class III BSC.
	Sustained directional airflow and exhaust air cannot be recirculated.	Located in a separated (preferentially isolated) area of low transit.
Examples of pathogens and diseases	SARS-CoV, MERS-CoV, SARS-CoV2, yellow fever virus, West Nile virus, prions that cause BSE, influenza-A virus H1N1 flu, avian flu H5N1, anthrax, TB, etc.	Ebola, Lassa, smallpox, Marburg, etc.
Estimated worldwide laboratories (*21*)	>3000	>60

diseases have been identified by the White House Office of Science and Technology Policy and the National Science Foundation. The COVID-19 pandemic has once again highlighted the central role of technologies in responding to infectious diseases. In this section, emerging robotic platforms are discussed, covering (i) clinical care; (ii) public safety; (iii) laboratory and supply chain automation; and (iv) out-of-hospital care, quality of life, and continuity of work and education. Representative examples are shown in Fig. 3 and summarized in Table 3.

Clinical care

During clinical care, robots can help facilitate biological sample collection and telepresence. The former contains robots used for performing the cannulation or taking swabs; the latter contains telepresence robots for point-of-care (POC) diagnosis, intensive care units (ICU), and surgical intervention. Especially, robots are desired for clinical diagnoses and ICU monitoring/treatment/care.

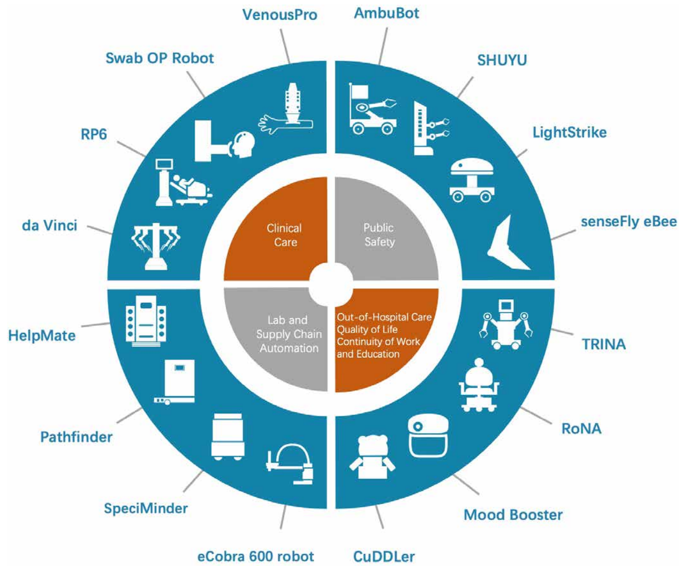

Fig. 3. Examples of robotic systems that may be deployed to combat infectious diseases.

Biological sample collection

Diagnostic blood testing is a routine clinical procedure. However, it depends on the skill of the operator and patient physiology. Automatic blood testing has been used to relieve medical staff from the risk of infection. Existing research has led to the development of HaemoBot (*24*) and VenousPro (*25*). Both systems rely on ultrasound guidance and force sensing to automatically locate the vein on a person's forearm and perform the cannulation. A more recent prototype of VenousPro has been tested on humans (*26*–*28*). A hand-held robot has been developed for peripheral venous catheterization for pediatric applications (*29*). With further development, these systems can find applications for patients with infectious diseases (*16*, *30*).

For the diagnosis of COVID-19, oropharyngeal and nasopharyngeal swabbing is widely used (*31*). Preliminary clinical trials of an intelligent oropharyngeal swab robot have been conducted (*20*). In practice, nasopharyngeal swabbing has proven to be more effective than oropharyngeal swabs (*32*). The process of collecting nasopharyngeal specimens is risky for medical staff because they need to be in close contact with the person to be tested. A low-cost, miniature robot that can be easily assembled and remotely controlled has been developed for collecting nasopharyngeal specimens (*33*). The system includes an active end effector, a passive robot arm for positioning, and a detachable swab gripper with integrated force sensing.

Telepresence

Teleoperation and telepresence, also known as telerobotics, are in great demand during a pandemic (*24*, *29*). By combining a human operator and a remotely controlled robot, telerobotic systems can leverage the skills of a human operator as well as the accuracy and local autonomy of the robot. To this end, many technologies derived from robot-assisted minimally invasive surgery can be adapted. For infectious disease management, these robots can be used for POC diagnostics, intensive care, and surgical intervention.

1) Telepresence robots for POC diagnostics. During COVID-19, many clinics and hospitals have stopped in-person outpatient consultation. Instead, patients consult physicians via teleconferences. The main drawback of online consultation as now carried out is that

Table 3. Robotic systems for infectious diseases.

Robotic platform	Category	Application	Key features	Ref.
VenousPro	Clinical care	Biological sample collection	Automatic drawing of blood samples; ultrasound guidance and force sensing; tested on humans	(*25–28*)
Swab OP robot	Clinical care	Biological sample collection	Semiautonomous oropharyngeal swab robot; force control; tested on 20 patients (95% success rate)	(*20*)
RP-6	Clinical care	Telepresence	Used in neurosurgery ICUs; teleoperated over the internet using a joystick and webcam	(*40*)
da Vinci	Clinical care	Teleoperation	Teleoperated surgical robot widely used in laparoscopy applications such as urology, gynecology, etc.	(*52*)
AmbuBot	Public safety	Emergency assistance	Ambulance robot developed to assist patients who requires urgent assessment in dangerous environments	(*58*)
SHUYU	Public safety	Temperature monitoring	Automatic system for temperature screening in outdoor environments	(*168*)
LightStrike	Public safety	Disinfection	Autonomous robot for fast and effective disinfection of health care facilities using UV light	(*169*)
senseFly eBee	Public safety	Reconnaissance	Drones used to figure out where human beings and macaques are possible to interact	(*72*)
HelpMate	Laboratory and supply chain automation	Delivery and logistics	Automated robotic system to transport small-size cargos between hospital departments	(*82*)
Pathfinder	Laboratory and supply chain automation	Delivery and logistics	Autonomous transportation of material in hospitals with simultaneous localization, navigation, and mapping	(*84*)
SpeciMinder	Laboratory and supply chain automation	Delivery and logistics	Autonomous handling of laboratory specimens in hospitals that can accelerate their speed of distribution	(*83*)
eCobra 600 robot	Laboratory and supply chain automation	Manufacturing of medical supplies	OMRON's smart robot used in the production line for developing rapid COVID-19 antibody tests	(*91*)
TRINA	Out-of-hospital care	Home-based nursing	Teleoperated nursing-assistant robot; some nursing tasks can be automated	(*109*)
RoNA	Out-of-hospital care	Home-based nursing	Carry people from a bed to a smart wheelchair equipped with autonomous navigation capabilities	(*99*)
Mood Booster	Out-of-hospital care	Socially assistive robots	Personal assistant robot focusing on user's mood by sensing the emotion through audio and visual sensors with AI techniques	(*108*)
CuDDLer	Out-of-hospital care	Socially assistive robots	Robotic teddy bear to provide emotional and psychological support to people in isolation	(*170*)

doctors are unable to perform physical examinations. Over the past few decades, diagnostic technologies have become increasingly sophisticated, leading to smaller, faster, more precise, and more cost-effective systems (*12*). To protect frontline health care workers, a telerobotic system (*34*) composed of a mobile base and dual-arm manipulators was developed for remote auscultation and consultation. In addition to its diagnostic functions, the robot also has capabilities to operate medical instruments (e.g., control panel of ICU ventilators) and deliver medicine. In addition, POC robots can provide rapid test results to patients, supporting on-the-spot clinical decision-making (*35*). POC robots can be used for teleconsultation and remote health care services (*36*) and could combine portable imaging or sensing devices with integrated hospital information systems (*37*). The remote operator can control the robot's locomotion and camera angles. To ensure effective human-robot interaction (HRI), voice and face recognition can be used. The use of eye-tracking further enhances its capability for intention detection and seamless user interaction. As an example, systems for teleultrasound and remote consultation over 5G were developed and tested on patients with COVID (*38*, *39*), demonstrating the initial feasibility of imaging assessment of patients with COVID.

2) Telepresence robots for ICUs. ICU robots can be used to provide access to off-site patients, supervising physicians, and other specialists, making otherwise very difficult procedures possible. In 2005, the University of California Los Angeles (UCLA) Medical Center used an RP-6 robot (InTouch Health, Santa Barbara, CA, USA) in its neurosurgery ICU. It was controlled by a webcam and joystick over a broadband connection (*40*). In addition to autonomous navigation and obstacle avoidance, robots for infectious ICUs need to cater for the specific requirements of care workflow. For example, bidirectional videoconferencing and wireless communication functions should be developed. A 5G-based robot-assisted remote ultrasound system for cardiopulmonary assessment of patients with COVID-19 has been investigated (*39*), and the techniques can be used for telepresence in infectious ICUs. A recent study demonstrated in a simulated environment the feasibility of robotics in a COVID ICU, demonstrating potential reduction of PPE utilization and staff exposure to the virus (*41*).

3) Telepresence robots for surgical intervention. Over the last two decades, robot-assisted minimally invasive surgery has enjoyed a rapid surge in clinical applications, particularly in urology, gynecology, general surgery, and neurosurgery (*42*). These have been demonstrated in pediatric surgery, urology, and gynecology during the COVID-19 pandemic (*43*–*48*), showing potential to reduce the risk of coronavirus infection to medical professionals.

A critical shortcoming for telesurgery has been the lag of signal transmission. High-speed wireless connections, including 5G networks, have overcome this problem (*49*), allowing teleoperated surgical systems, such as the da Vinci surgical system, to become more feasible, therefore safely performing procedures from a distance (*50*–*52*).

Another considerable obstacle has been the safety and adaptability of robotic technology in surgical environments. The surgeon's workflow may be affected when systems do not seamlessly integrate into the known working environment and procedures, creating extra steps that result in prolonged operative time and increased cost or safety risk. To avoid these hurdles, a close interaction between engineers, clinicians, and other team members is necessary from the early development stage onward, and systems should be designed with consideration to the above-mentioned aspects in mind. Thus far, many other teleoperated surgical platforms have been developed, and reviews of such systems can be found in (*53*).

Public safety

An essential step toward the prevention of the spread of infectious diseases is monitoring and diagnosis, from simple measures such as temperature monitoring to more clinically informative tests such as nasopharyngeal swabs, oropharyngeal swabs, and blood tests for antibodies in asymptomatic individuals.

Temperature monitoring and emergency assistance

Autonomous and teleoperated robots mounted with thermal cameras for temperature monitoring, combined with vision sensors, can enable screening and tracking people in large public areas, such as hospitals and airports, allowing for efficient screening. For example, Lio, a mobile robot with a multifunctional arm designed for HRI, was deployed in several health care faculties during the COVID-19 pandemic to perform temperature measurement and also disinfection (*54*). Although the accuracy of temperature monitoring has not been established, it is an area of research. Many systems can be mounted on AGVs and can scan multiple passengers simultaneously. It is important to define and introduce appropriate rules and global standards that ensure safety, efficacy, and privacy (*55*). Robots can also use artificial intelligence (AI) to help medical facilities cope with an emergency by automatically interacting with patients and detecting possible cases of infection. This is the case of Chatbot (*56*), an AI-based robot that was deployed in the Medical Department at UDLA University in Ecuador to detect possible cases of COVID-19, to help alleviate the saturated health system, and to collect information to prevent the dissemination of the infectious disease. A smart virtual assistant was developed to quickly and easily answer people's questions related to COVID-19 [e.g., frequently asked questions (FAQ) and statistical data] with the objective of creating awareness among people to combat the pandemic (*57*).

In addition to temperature monitoring, ambulance robots, such as AmbuBot (*58*), have been developed to assist patients who require urgent evaluation when affected by infectious diseases, particularly in busy areas or those under quarantine. This robot is equipped with vital sign monitoring, AED (automated external defibrillator), coronavirus test equipment, and can be controlled remotely. A "robotic bed" was developed to transfer patients from the ambulance to the hospital, reducing contact between clinicians and patients (*59*).

Disinfection

Since the outbreak of COVID-19, disinfection robots have become widely available (*14*). Robotic disinfection embraces multiple approaches, but the most widely used ones use UV light to kill microorganisms. A recent study demonstrated the effectiveness of UV treatment against three different viruses, including SARS-CoV-1 (*60*). Common UV robots use a specific wavelength (254 nm) within the UVC bandwidth, which has been shown to be effective for germicidal purposes (*61*). However, the energy associated with this wavelength can be dangerous for human tissues and harmful to the eyes. Thus, this method of disinfection needs to be performed in vacant spaces (e.g., evacuated hospital rooms). An alternative wavelength (222 nm) of far-UVC light has been shown to be safer to use around humans (*62*). It demonstrated more than 99.9% success in killing seasonal coronaviruses after a very low UV exposure. If effective for SARS-CoV-2, then this would also allow UV disinfection in occupied spaces, such as stations, restaurants, hospitals, and schools. Most disinfection robots use two-dimensional (2D) maps, but they are insufficient to identify and ensure that all 3D surfaces are disinfected. To overcome this limitation, a method for projecting surface dosage using light properties was developed to create 3D maps of disinfected areas (*63*).

Chemical-based disinfectants, such as hydrogen peroxide and peroxyacetic acid, have also been used extensively during the COVID-19 pandemic. An AI-enabled framework for automating cleaning tasks through a human support robot (HSR) was developed (*64*), targeting high-touch areas such as door handles. Disinfecting robots with intelligent disinfection mode have also been developed (*63*, *65*, *66*). A portable handheld cost-effective disinfection robot was developed as a measure to combat COVID-19 (*67*). Opportunities lie in the development precision disinfection with accurate machine vision to identify high-risk areas, without spraying disinfectants indiscriminately.

Most of the existing disinfection robots are mounted on AGVs, which is a mature technology in mobile robotics. For remote areas and those with complex terrains, drones can be deployed for disinfection. To this end, technologies developed for spraying pesticides on agriculture fields can be repurposed to spray disinfectants.

Reconnaissance

Detailed surveillance of the infectious areas is essential for data collection, source tracking, and monitoring during an outbreak. Drones have been used to assist the surveillance, epidemiological study, or microbiological study of infectious diseases (*68*–*71*).

Drones or unpiloted aerial vehicles/systems (UAVs/UASs) with cameras and sensors can provide detailed information over large areas to collect real-time surveillance data. An epidemiological study was conducted using a UAV to collect data between 2013 and 2014 (*72*, *73*). It aimed to use the UAV to obtain the spatial information about the dynamics of land use and land cover to understand the factors for human infection with the zoonotic malarial parasite *Plasmodium knowlesi*. Low-cost unpiloted aircraft systems (UAS) were also used to investigate the epidemiology of tuberculosis (TB) by collecting high-resolution images (*74*). These data can help model the species-host abundance at a spatial scale. Drones were used to lay traps and collect and transport mosquitos in specific places that were too far from the reach of humans (*75*). In addition, UAVs also enabled the measurement of aerosols in remote and inaccessible areas to evaluate the air compositions (*76*).

In epidemiology, drones have been used to assess hard-to-reach areas to conduct microbiological studies. UAVs were used to collect high-resolution multispectral images to analyze water bodies (*77*) to detect the flight range of *Nyssorhynchus darlingi*, the most efficient malaria vector, and thus the malaria vector breeding sites. During the COVID-19 pandemic, drones were deployed to facilitate data collection and impose social distance measures in public areas (*78*). However, issues related to privacy and its regulated use have been raised (*79*).

Laboratory and supply chain automation

During the COVID-19 pandemic, robots for laboratory and supply chain automation have shown their potential to improve efficiency and avoid cross infection.

Delivery and logistics

To use robots for hospital logistics, path planning, localization, 3D map reconstruction, and obstacle avoidance are common requirements. These technologies have matured in recent years, driven by advances in autonomous vehicles and AGVs (*80*). Most of these robots are now wirelessly linked to building or lift management systems, allowing them to travel to different floors with ease. Dedicated tracks, such as those adopted for pharmacy robots in hospitals, may also be used (*81*).

HelpMate (HelpMate Robotics Inc., Danbury, Connecticut, USA), an automated robotic system for hospital logistics, was used to transport cargos between different departments. It can navigate inside the hospital automatically, take elevators, and avoid obstacles (*82*). Other examples include SpeciMinder (*83*) for laboratory specimen handling and Pathfinder (*84*) for hospital transport. Robots can also be used to help reduce the cost of maintaining drug inventories in pharmacies, with which automatic drug dispensing can be realized (*85*). Outside hospitals, the use of autonomous vehicles and UAVs would ensure uninterrupted service for medical supplies and managing hospital waste, especially during partial or complete lockdowns.

Manufacturing of medical supplies

The COVID-19 outbreak has caused industries and businesses to close (*86*–*88*). These changes have affected the medical devices sector, with a huge increased demand for critical equipment—such as PPE (e.g., masks and visors), ventilators, and testing kits—and a consequent shortage of these devices. Lockdown protocols imposed worldwide to tackle the outbreak have changed most companies' daily functions (*89*). Therefore, industries have tried to keep pace with this unexpected demand by rearranging their production lines and uprooting many of their usual supply chains, and according to the National Association of Manufacturers (NAM), 53% of manufacturers anticipated in March 2020 a change in operations because of COVID-19 (*90*). Through all of these, robotics and automation have become essential to guarantee continuity of production in a more efficient way, to allow people to work separately, and to safely bridge the gaps generated by restrictions imposed by the lockdown.

Recent progress has been made in the use of robots for manufacturing, and there is also a trend in the use of robots for manufacturing, from big companies to small- and medium-sized enterprises, to enable mass manufacturing for one-off products, such as those required by the health care sector. The COVID-19 outbreak has been a good opportunity for roboticists and robotics companies to demonstrate the potential of robots for health care and public applications. Areas of urgency include diagnostic, medical care, medical countermeasures, and PPE. For example, Senova (Weimar, Germany) is a medical technology company developing rapid COVID-19 antibody tests, using OMRON's (Kyoto, Japan) smart robots in the production line (*91*). Siemens (Erlangen, Germany) is spearheading research into developing robots for rapid PPE production and assembly, rapid diagnostic kit discovery, and antimicrobial copper coating to kill coronaviruses (*92*).

Looking ahead, there is the need to create more resilient supply chains and improve the way that human workers are integrated. New generations of miniaturized, complex products with short life cycles require assembly adaptability, precision, and reliability beyond the skills of human workers. Therefore, robots with higher precision and levels of autonomy are highly desirable, providing improved process automation, communication, and self-monitoring and diagnosis. It is equally important to combine the strengths and speed of robots with the creativity and judgment of human workers. Therefore, improved HRI is required, as well as remote control through teleoperation and telemonitoring. The reduction and flexible location of human co-workers with increasing levels of local autonomy would ensure smoother and more resilient manufacturing processes in situations such as those encountered during the COVID-19 pandemic.

Out-of-hospital care, quality of life, and continuity of work and education

The COVID-19 pandemic highlights several key challenges that our society has to address as a consequence of social distancing while maintaining a functioning economy and continuity of work (*93*). Outside hospitals, the use of robots for nursing, social interaction, and education (*94*) are three tangible examples.

Home-based nursing

Vulnerable groups and those with chronic diseases are badly affected by shortages of medical staff and travel restrictions (*95*). Nursing robots could offer a good substitute for clinical staff to take care of patients recovering at their own homes (*96*). In the case of epidemic diffusions, such as the COVID-19 pandemic, these systems may help in triaging and monitoring patients at home, therefore reducing the risk of contagion (*97*). General nursing robots include, for example, RIBA (Robot for Interactive Body Assistance) (*98*) and RoNA (Robotic Nursing Assistant) (*99*), which can carry people from a bed to a smart wheelchair (*100*) equipped with autonomous navigation capabilities. Robotic nursing during the outbreak of infectious disease needs to consider many other factors that are different from normal situations because on-site human supervisory control may not be available, demanding safer, more robust, and autonomous solutions. Current technologies are still underdeveloped, and a more comprehensive review of general robotic nursing techniques has been provided in (*101*).

Socially assistive robots

Prolonged social isolation is known to have a negative impact on mental and physical health (*102*, *103*). Social robotics can be designed to act as a personal companion or to facilitate remote or virtual social interactions (*102*). It has been shown that socially assistive robots can be deployed to provide emotional and psychological support for people in isolation (*104*), which can help address issues arising from social distancing (*103*).

Socially assistive robots can also help patients, particularly the elderly, follow their dietary and therapeutic regimens (*105*) or even perform gymnastic exercises (*106*) and entertainment activities (*107*). Mood Booster (*108*) was developed to serve as a personal assistant to focus on the user's mood by sensing the emotion through audio and visual sensors with AI techniques. Social robots can also be used to deliver education, making virtual classes more engaging, especially for young children (*109*). ARI is the newest robot from PAL Robotics (Barcelona, Spain) that can be used for first-care attention, providing emotional support to people who live in isolation because of infectious diseases such as COVID-19 (*110*). However, the use of social robotics is a challenging area of research in the context of social isolation during pandemics, where social models and emotions are not well understood (*111*).

GENERIC TECHNOLOGIES

The impact of COVID-19 has highlighted the fact that applications of robotics, despite their enormous potential, are still limited and not yet ready for large-scale deployment, requiring major efforts in research and collaboration among academia, industry, and government. This is important to ensure that we can not only manage through the remaining phases of the COVID-19 pandemic but also be ready for future outbreaks. From unmet demands and the lessons learned, it is important to examine the current state of the art in robotics and relevant underpinning technologies. Figure 4 summarizes some of the most relevant ones.

Sensing and imaging

Effective sensing is fundamental to the management of infectious diseases (*112*–*114*). Key vital signs include body temperature, respiratory rate, pulse rate, oxygen saturation, and blood pressure. Infrared-based noncontact thermographic cameras are widely used during COVID-19. In addition to SARS-CoV-2 test kits and rapid diagnosis devices (*115*), the use of chest radiographs (x-rays) and chest computed tomography (CT) have demonstrated their ability to provide diagnosis and screening (*116*, *117*). POC pulmonary ultrasound has also shown uses for managing patients with COVID-19 (*118*) and robot-assisted remote ultrasound system for cardiopulmonary assessment (*39*). Blood gas index is an important biomarker for diagnosis and evaluation (*119*), elucidating the state of human blood's acid-base balance or disorder and oxygen delivery by quantitatively measuring the pH of the human blood and bicarbonate, partial pressure of carbon dioxide (PCO_2), hemoglobin, arterial oxygen saturation, and the partial pressure of oxygen (PO_2). Recently, the use of low-field pulmonary magnetic resonance imaging (MRI) combined with ultrashort echo time sequences (UTE-MRI) has shown both patient- and lesion-based interobserver agreement with CT, thus opening the door to safe public screening and serial examination of patients with COVID-19 after infection to assess the efficacy of therapeutic measures and their long-term side effects (*120*).

An ongoing direction is to leverage the functionality of robotics for noninvasive, automatic, and continuous screening (*121*). One possible solution would also be the development of wearable or implantable devices with integrated sensing technologies (*122*). For patients with COVID-19, screening with surrogate markers—such as fever, cough, or shortness of breath—can capture about 80% of those infected with COVID-19 (*123*). New soft, wireless sensors (*124*) based on mechanoacoustic sensing of physiological processes and body motions placed at the suprasternal notch can be used to identify these key symptoms of potential patients. Wearable sensors enable real-time data collection and, when combined with the wireless transmission, can facilitate rapid, remote monitoring of key physiological indexes.

Teleoperation

Teleoperation enables specialized health care services over long distances, eliminating the need for co-physical presence of patients and specialists (*125*). This is particularly important when patients are located in isolated areas where access to specialized medical care is difficult. As listed in Table 3, existing functions that telerobotics can provide include (i) bidirectional audio and video communication between staff and patients; (ii) measurement (e.g., vital signs and other biomarkers), clinical data collection, and assessments; (iii) remote and mobile interaction with patients; and (iv) general consultation, remote operation, and intervention.

Telerobots also allow people to be efficiently monitored or screened in population-dense areas, including hospitals and public transportation, to protect patients, clinicians, and the community from exposure. Currently deployed robots are typically preexisting and adapted with ad hoc features for COVID-19. For example, Spot Mini, developed by Boston Dynamics, has been used to measure the vital signs of patients, and teleoperated robots have been developed for throat swab sampling of coronavirus tests. The technique using a teleoperated multimodal robotic interface for remote auscultation has shown its potential for telemedicine (*126*). The incorporation of haptic feedback and tactile sensing, combined with high-definition 3D vision with low latency, can enhance the fidelity and reality of the teleoperation experience. In addition to medical applications, telerobots can also work as assistants, teammates, companions, and caretakers of patients (*14*). To this end, effective HRI is important. In addition to capabilities of autonomous locomotion, effective interaction and communication with the human users will require due consideration of the mood, emotion, cultural habits, as well as the context and environment of interaction (*127*).

Navigation

Self-navigating robots are mature technologies that can be potentially lifesaving during pandemics. Recent advances in robotics and

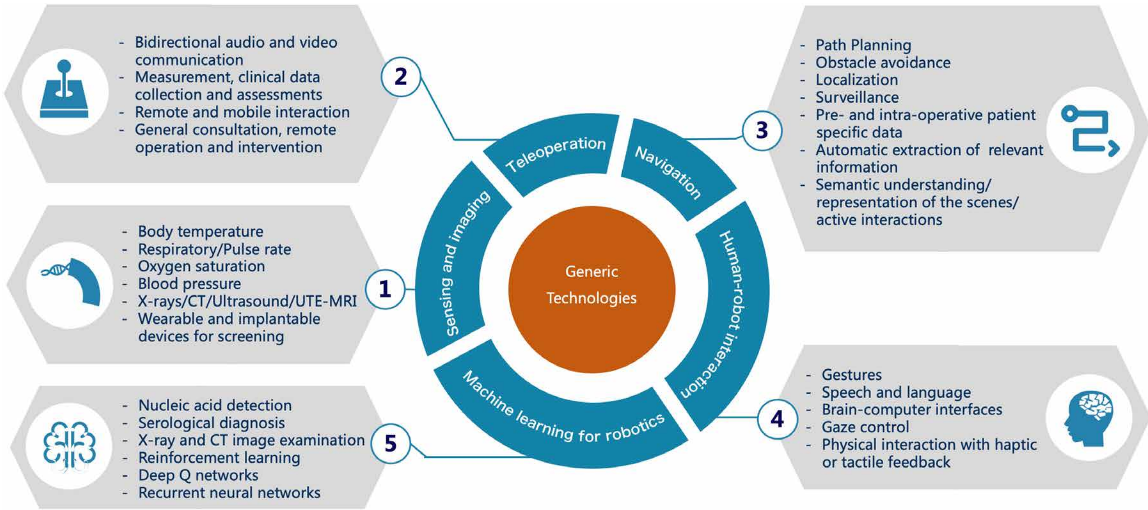

Fig. 4. Generic technologies for robots used for infectious disease. Five underpinning technologies with detailed illustration are shown, including ① sensing and imaging, ② teleoperation, ③ navigation, ④ HRI, and ⑤ machine learning for robotics.

computer science have resulted in the development and refinement of autonomous vehicles, drones, and medical robots with a high level of autonomy supported by decision-making from imaging and sensing information (*128*). As highlighted in previous sections, many of the robotic systems deployed to combat COVID-19 already feature navigation technologies such as path planning, obstacle avoidance, localization, and surveillance (*129*, *130*). Combating infectious diseases may involve environments or scenarios that are unpredictable and unsuitable for humans, and these robots should be designed to be highly adaptive and flexible. In principle, we already have technology available that can be improved, tested, and deployed during future outbreaks. Examples are from robots used in dangerous and extreme conditions, such as robots undertaking nuclear decontamination (*9*) or robots deployed in the oceans (*131*) and space (*132*), but extensive changes and adaptation would be necessary. Drones and swarm robots can be deployed to combat infectious diseases because they have great potential for exploring unknown environments. This requires adequate navigation strategies such as the SLAM (simultaneous localization and mapping) (*133*) and the SGBA (swarm gradient bug algorithm) (*134*).

Other requirements come from medical robotics, where the integration of imaging and sensing into robots enables autonomous or semiautonomous navigation features. Here pre- and intraoperative patient-specific data are acquired and used to guide a robot to support the clinical team (*42*). The integration of machine learning will enable automatic extraction of relevant information and knowledge, contributing to better decision-making and intervention guidance (*135*). These technologies are needed for remote assistance in ICUs. Undoubtedly, current navigation and mapping techniques will continue to evolve, paving the way for autonomous execution of medical tasks. Robots will be able to make medical decisions under human supervision or to perform certain tasks or a part of a procedure autonomously (*136*). According to Yang *et al.* (*137*), the grand challenge for robotic navigation is to develop systems able to effectively learn from unmapped/unknown environments and dynamically adapt to them, similar to how human perception works. Robot navigation requires semantic understanding and representation of the scenes and active interactions. Future systems designed for managing infectious diseases should also present high levels of autonomy, leading to complex self-monitoring, failure handling, and autorecovery.

Human-robot interaction

HRI aims to establish uni- or bidirectional communication/interaction between robotic systems and humans. Current technologies mainly involve (i) gestures, (ii) speech and language, (iii) brain-computer interface (BCI), (iv) gaze control, and (v) physical interaction with haptic or tactile feedback (*138*). Physical HRI may comprise master input for teleoperation or cooperative manipulation between a human and a robot. This mode of operation is used for interacting with multi–degree-of-freedom industrial or medical robots to accomplish common tasks such as object handling or dexterous manipulation (*139*). Those basic approaches can be combined with learning from human demonstration to gain autonomy for task execution (*140*). Designs of HRI are governed by task-specific requirements, ergonomics, and guidelines as summarized in (*141*). Some systems presented in the previous section already partially make use of advanced HRI strategies for pandemic use cases.

From a clinical perspective, devices with close or physical contact to potential COVID-19 carriers must enable noncontact interaction such as gestures or speech. If physical contact is inevitable, such as in swab testing, then the HRI must comply with stringent sterilization procedures in terms of materials and surfaces or use disposable single-use components to avoid cross infection. The design criteria also apply to social, logistics, or delivery robots. Other criteria include reliability and intuitive use, i.e., device control must be user centered, reliable, and robust without additional cognitive burden or stress to the users (*142*). High user frustration from nonspecific HRI may erode the intrinsic benefits offered by robotic technologies.

User acceptance is another important aspect that must be taken in consideration. Perceived risk plays an important role in the confidence of users that interact with a robot. This is especially true when it comes to clinical care, where the users are usually more than one, i.e., the clinical team and the patient, and the interaction is actually between the patient and the robot. Thus, issues such as safety and comfortability may represent major concerns for the clinical staff. This is something that must be taken in consideration since the early development of a robotic system. However, recent studies (*143*, *144*) have demonstrated that the perception of robots can be changed by situational factors, and, particularly, in the context of COVID-19, users' preference for robots can increase because their use can reduce the chance of disease transmission. More studies are needed to investigate this aspect.

Prospective HRI for pandemic deployment may also incorporate three major challenges of robotics. First, emerging of AI technologies may improve, e.g., natural language processing or gesture recognition to decode user input and provide corresponding feedback with high confidences. This may improve the reliability and practical use of HRI. Second, the use of BCI may enable seamless and immersive control of robots for diagnosis and therapy or devices for social interaction during the quarantine, although the intrusive or invasive nature of current technologies would mean many years of development before they can be used practically. Last, a safe interaction workflow is essential to gain the acceptance of the medical community and, more importantly, of the patients. This may involve not only physical interaction but also psychological aspects as discussed in (*145*).

Machine learning for robotics

Machine learning underpins many aspects of the autonomous functions offered by robots for disease detection and diagnosis (*146*). As mentioned earlier, current detection and diagnosis methods mainly include nucleic acid detection, serological diagnosis, x-ray and CT image examination, and other noninvasive methods. Machine learning is used extensively in RT-PCR detection by extracting salient hematological and biochemical characteristics (*147*). Proteomics and genomic information is used to analyze the virus characteristics of SARS-CoV-2 (*148*), protein structure prediction, and microRNA prediction on the SARS-CoV-2 genome, as well as microRNA-mediated SARS-CoV-2 infection interactions (*149*).

Various machine learning methods are developed for drug and vaccine development (*150*), including reinforcement learning, deep Q networks, and recurrent neural networks (*151*). For example, a deep learning–based drug-target interaction model (MT-DTI) was proposed to predict the potential drug effect of COVID-19. Machine learning methods have also been used to predict the mortality rate of patients with COVID-19, epidemic trends, and biomarker selection. Needless to say, with increasing training data available and our improved understanding of COVID-19, machine learning will become more robust and generalizable for infectious disease management in the future.

OPEN CHALLENGES

Existing experience with the Ebola virus in 2015, and now COVID-19, highlights the central role of technology in responding to outbreaks. The examples reported in earlier sections and other recently published comprehensive reviews (*152*–*154*) demonstrated how robotic technologies could be used to combat infectious diseases in different scenarios. However, most of the deployed technologies so far have not been designed specifically for infectious diseases at a scale as we have witnessed in the COVID-19 pandemic. "Last-minute" prototypes have been quickly developed, trying to respond to the emergency demand. Although some of the robots currently being used rely on technologies that are mature enough to be deployed, there are many open technological challenges that should be addressed.

So, what did we learn from recent events? Given all the recent technological advances in different fields of science, what does the future hold for robotics? How can we get ready to fight the next pandemic? These are some of the questions that the robotics community, starting now, should answer by carefully, mapping out future research directions. Figure 5 illustrates some of the important topics, including applications, technologies, and grand challenges.

Need for technically mature, application-centered robots

In order for the technology to be effective, we must develop new types of robots that are application oriented so that they can be easily adopted by a particular set of end users. This new generation of robots must be reliable, safe, and available for rapid deployment when needed. The main applications are disease prevention and monitoring, clinical care, laboratory automation and logistics, and maintenance of socioeconomic activities of the general public as we highlighted before. For disease prevention and monitoring and clinical care, opportunities lie in improved navigation of high-risk unmapped environments. For example, autonomous robots should be able to continually navigate areas (e.g., hospitals, public venues, or public transportation) and perform sterilization. Mobile robots, either autonomous or teleoperated, for clinical care should be able to take temperature measurements in public areas or to take blood samples and swabs for initial diagnosis. Nursing robots should enhance the clinical workflow in critical areas of the hospital, such as ICUs, and be able to directly interact with patients by measuring vital signs, key biomarkers, and providing the required therapies. Automating supply chains and logistics in hospitals, for example, via autonomous delivery vehicles and drones, is also a key to lowering high-risk exposures and interactions with potential patients with COVID-19 and biosamples. Likewise, this relieves medical staff from time-consuming tasks and enables them to focus on main tasks, such as patient treatment and care.

Similarly, robots should be used to maintain socioeconomic activities, especially to deliver public services and goods to quarantined people, thus supporting daily life during social distancing. The development of such robots will require advancements in navigation and sensing technologies. New navigation algorithms must be designed to learn from the environment and to adapt to unknown situations. To this end, the technical maturity of robot solutions is a major challenge because robot failures, hidden human labor costs, or "clumsy automation" can create new problems and increase the workload of responders, and negative user experiences can hinder the adoption of innovation (*155*).

In order for application-centered robots to be accepted by health care workers, public safety officers, business owners, and individuals, the robots much be technically mature. NASA rates the technology readiness of a technology in two ways (*156*): the technical readiness level (TRL) of the individual technology (i.e., is the robot reliable?) and a technical readiness assessment (TRA) of the technology for the system (i.e., does it fit the overall system and user expectations?). Historically, the challenge of low technical maturity has resulted in responders refusing to use low TRL robots or high TRL robots with low TRA.

Robots used at previous disasters were already in use for very similar applications (*155*), i.e., high TRL and TRA, and this appears to be largely true for the COVID-19 response as well. As noted in (*157*), the most commonly reported use of robots for the COVID pandemic is the use of existing drones by public safety for quarantine surveillance.

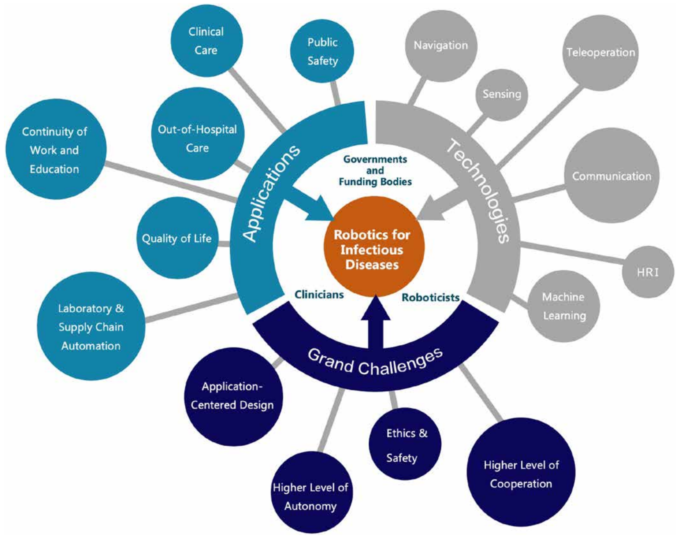

Fig. 5. Open challenges for robotics against infectious diseases. Enabling technologies, application drivers, and grand challenges to accelerate the design of new robots to combat infectious diseases. Joint effort among roboticists, clinicians, and governments is essential.

The robots themselves are at the highest TRL of 9 and plus have a TRA "heritage"—i.e., already in use for that application—rating because they were in service for nonpandemic surveillance missions. The second most commonly reported application is the use of robots for disinfecting hospitals. This is also a mature use because these robots are already commonly used by hospitals to reduce hospital-acquired infections for known and unknown pathogens. Tied for second is the use of agricultural drones for spraying disinfectant in public spaces. This is an example of where the individual robot has a TRL of 9, but the TRA is lower. In this case, the TRA has a lower "engineering" rating because the application requires some modification to the robot or protocols (e.g., change in nozzles to handle the different chemical solution) and in the use protocols (e.g., flight plans for cluttered urban areas versus fields) to adapt it to COVID missions.

In contrast to the technically mature robots typically used during disasters, including COVID, prototypes, such as a robot that takes mouth swabs, have a low level of technical maturity and serve as hospital-sanctioned experiments. However, they may add great value in combatting the pandemic. The challenge becomes how to design reliability, safety, and safeguards from unintended consequences so that suitable solutions can be rapidly deployed and scaled for a pandemic.

More focus on laboratory automation and logistics

With regard to laboratory automation and logistics, the usage of robots has a great potential for responding to disease outbreaks such as the COVID-19 pandemic. In these urgent situations, daily high-throughput processing of diagnosis samples is required in a fast, effective, and reliable way to track the virus, to understand the related epidemiology, and to suppress transmission (*158*). Although robotics has the potential to reduce exposure of humans to hazardous environments, robots are still largely absent from HCBLs. One of the challenges that the introduction of robots to HCBLs faces is that any equipment that enters a high containment biosafety laboratory must stay inside or must be sterilized before it can leave the laboratory. Typically, this means autoclaving, i.e., the exposure to hot, high-pressure water steam, which is not compatible with most robotic equipment. Although it is not trivial to overcome this challenge, other forms of decontamination exist and may be sought to permit robots to work in HCBLs, which would bring several advantages. The other hurdle is the high cost, although this is likely to be offset in the long run by savings on training and special containment installations. The implementation of robotics in HCBL will require strict identification of risks and robot-related unsafe activities. Often, most of the work in HCBLs is dedicated to routine laboratory work, particularly in diagnosis and less in research, requiring the presence of people inside HCBLs for long periods of time. Much of the work concerns the preparation of reagent solutions or the (un) loading of samples from laboratory equipment. A robot performing these routine tasks within the HCBL with high precision and repeatability would allow the people to work outside of the HCBL, work that often requires creativity and decision-making. This would reduce traffic into and out of the laboratory and hence decrease the chance of accidental dissemination of virus.

A robot needs to minimize the chance of fatigue-induced errors and incorrect practices because the worker may be located remotely without having to wear cumbersome PPE. It would also simplify the implementation of safety procedures or their more frequent execution, such as fumigation of the laboratory. The latter is the use of a gaseous disinfectant, e.g., formaldehyde vapor, for more than 12 hours as part of safety procedures. Fumigation is periodically executed and is necessary after a suspected leak, or anytime space needs to be serviced.

Looking ahead, one can see an extension of existing robotic technologies in biosafety laboratories. For instance, bar coding, automated pipetting, and liquid handlings, such as ELISA (enzyme-linked immunosorbent assay) plate washers and 96-well or 384-well readers by robotic dispensers, are already found in HCBLs. In the next 5 years, one can expect certified robots inside BSL-3 environments for sample handling and processing. This is likely to be followed by more advanced systems and ultimately mobile robots that can perform experiments autonomously (*159*), as well as sample manipulation with collaborative robots. The prospective impacts of automation on future employment scenarios are already discussed in (*93*).

Improved user experience

New generations of robots need to have a better level of interaction with end users. Improved sensor technologies will allow robots to safely interact with the environment, including objects, people, and other robots. This will require robots to have higher dexterity and deployment capabilities (*160*). For teleoperated systems, a flow-less integration with operational workflows (e.g., in a clinical environment) and high usability are crucial to user acceptance, effectiveness, and safety. Robotic teleoperation is already a mature technology used in industry and medicine (*125*). Augmented reality/virtual reality, as well as high-speed communication, such as 5G, may improve remote control of robots. For example, expert surgeons would ideally be able to perform surgeries remotely, no matter where they are in the world. While health care systems are clearly put under strain during outbreaks, it is equally important to maintain unchanged the delivery of other medical services (i.e., not directly related to the outbreak, e.g., surgeries, rehabilitation, cancer treatment, etc.). Robots can help with this by allowing remote treatment and protecting the clinical team from getting infected. Asymptomatic health care workers may become carriers of the virus in hospitals, and the ones who show symptoms cannot work. Both cases represent a problem for the health care system. Here, opportunities lie in the technological development of ergonomic and application-specific haptic devices, which allow the user to perceive the environment where the robot is deployed and make decisions accordingly. In terms of control strategies, we need to develop robotic systems with a higher level of autonomy. For example, robots can be trained by expert users to execute specific tasks. Learning from demonstration techniques can be used to teach a robot to perform clinical tasks such as preparation of general clinical workflows, drawing blood samples, taking swabs, performing rehabilitation maneuvers, or even surgical procedures.

Address ethical challenges of increase autonomy

The growth of autonomy in robots, and their interaction with humans, also poses a challenge to ethical and safety aspects. Robots, especially when operating in a health care context, such as during pandemics, are fueled by data, including people's private information. Therefore, it is important to consider potential ethical and legal barriers (*137*). Important concerns include privacy, ownership, data governance, and trust. During health care emergencies, such as any health care intervention, robots need to conform to the highest standards of ethics. However, although pandemics are a global issue, there are no global standards, which should raise concerns over privacy, individual's rights, and ensuring that robots operate within legal and ethical boundaries (*137*).

One ethical challenge is that robots used in a disaster context, such as pandemics, should be considered ethical impact agents (*161*) because they deal with the safety and health of humans. Ethical impact agents increase the professional obligations of the designer to ensure that the robot will perform reliably and to make users aware of implicit consequences of use, including dangers and hidden costs. Unfortunately, roboticists may not be aware of the hidden costs of their robots because the community typically focuses on reaching high TRL, not TRA, ratings.

A second ethical challenge for roboticists is protecting humans and the environment. For example, the use of thermal imaging to detect fevers from drones has not been proven, false positives and negatives could have severe consequences, and a general scanning approach may contradict privacy regulations. Similarly, wide-area aerial spraying with cleaning solutions intended for manual application may expose bystanders to health risks, and the runoff may pose long-term environmental impacts.

A third ethical challenge is on the rights and privacy of humans, especially in public safety applications. Unlike public safety, hospitals and public health agencies are less vulnerable because they typically have institutional review boards to determine when and how new technology can be introduced into their enterprises. Public safety instead relies on the decisions of individuals; however, these decision-makers may be unaware of the ethical ramifications. For example, before the COVID-19 pandemic, drones were controversial, being viewed by some as enabling a surveillance state by collecting large datasets from the general public. In at least two cases in the United States, drones used for COVID-19 have been discontinued as the result of citizen protests as to privacy, especially how the data was going to be used and stored, and to over-policing. It is unethical for roboticists to defer the blame to the agency; it appears that the robot manufacturers were donating equipment to encourage the agencies to conduct de facto experiments and thus bear some ethical responsibility.

Need for globally sustained efforts

An important factor for robotic integration during a pandemic is time. As seen with the 1918 influenza pandemic, COVID-19, and other outbreaks, virus spread presents in multiple waves with intermittent breaks. During these periods, the reproductive number, R, which indicates how many others are infected by an infected individual, changes (Table 1). R was high at the beginning of COVID-19, but it decreased below 1 after the first wave and is increasing again at the time of writing in many countries around the world. The reproductive number (*162*) largely determines how effective integration of robots is, i.e., if the number is around or below 1, then robotic implementation does not reduce pathogen spread because contamination rates are low as baseline. If the reproductive number is high, then robots may reduce infectious spread. Therefore, implementation of robots can be timed in reference to the reproductive number to achieve the most effective outcomes for pathogen containment and economic value. Modeling studies investigating time windows for robotic integration are needed to determine the effective implementation of robotic technologies.

The impact of COVID-19 has highlighted that the application of robotics, despite its enormous potential, is still limited and not yet ready to combat pandemics. It is valuable to assess how robotics could help establish a new norm after COVID-19, by considering not only the immediate fixes but also long-term solutions and radical changes to business, logistics, manufacturing and supply chain, transport, health care, collaborative research, and education (*2*). To address the challenges identified above, globally sustained efforts are required in order for robotics to be ready for the next outbreak. This means immediate joint plans and actions at different levels, including roboticists, health care professionals, and governments. The robotics community needs to take the lead in defining clear robotic challenges for infectious diseases. Speed is important but so is due diligence and process. This includes dialog, collaboration, and involvement with researchers from other disciplines, most importantly, with not only the clinical community but also with those who are experts in ethics and law. Only through cross-disciplinary research and joint efforts will we be able to define the requirements to develop systems that are effective, safe, and rapidly deployed. Governments and funding bodies must be aligned and provide support and dedicated funding to ensure that robots will be ready for the next crisis.

SUPPLEMENTARY MATERIALS

robotics.sciencemag.org/cgi/content/full/6/52/eabf1462/DC1
Text
Fig. S1. Worldwide user interest for general web search terms during the COVID-19 pandemic.
Fig. S2. Worldwide user interest in robotic technologies during the COVID-19 pandemic.
Table S1. Commercialized products for infectious diseases.
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