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Medical Robots for Infectious Diseases

Lessons and Challenges From the COVID-19 Pandemic

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Medical robots can play an important role in mitigating the spread of infectious diseases and delivering quality care to patients during the COVID-19 pandemic. Methods and procedures involving medical robots in the continuum of care, ranging from disease prevention, screening, diagnosis, treatment, and home care, have been extensively deployed and also present incredible opportunities for future development. This article provides an overview of the current state of the art, highlighting the enabling technologies and unmet needs for prospective technological advances within the next five to 10 years. We also identify key research and knowledge barriers that need to be addressed in developing effective and flexible solutions to ensure preparedness for rapid and scalable deployment to combat infectious diseases.

Digital Object Identifier 10.1109/MRA.2020.3045671
Date of current version: 25 January 2021

Background

Since the first reports of a novel coronavirus (SARS-CoV-2) in December 2019, more than 44.7 million patients have been infected worldwide, and more than 1.17 million patients worldwide have died from COVID-19, the disease caused by this virus (numbers as of 29 October 2020) [1]. Among them, 19% of infected persons were hospitalized, while 6% were admitted to intensive care units (ICUs) [2]. Health-care professionals acted as the front line against the virus, resulting in a large exposure risk to infection and imperiling any mitigation efforts. The robotic community also took charge of an important role in providing aid to manage the pandemic [3], [4], and great efforts were made to adapt preexisting devices to the new challenges, which translated into a number of helpful solutions [5]. The shortage of time to design and develop ad hoc robots pushed experts to reflect on the methods to get a ready response to future infectious disease crises, analyzing the challenges and opportunities for advancements in the technologies.

This article covers the deployment of robots in the health-care workflow across the continuum of care that goes from prevention, screening, and diagnosis to treatment and home care, as depicted in Figure 1. For each category of medical robots, the discussion starts by describing the current state of practice (i.e., robots deployed during the COVID-19 pandemic) and the state of the art (i.e., research prototypes not deployed during the COVID-19 pandemic), providing a review of the most advanced research progress. Then, we aim at providing a look ahead to a midterm perspective, analyzing the major challenges and the enabling technologies that may be leveraged to make progress.

Reported systems are chosen according to the following inclusion criteria:

1) They are provided with some automated features that allow for at least a basic degree of autonomy, including shared autonomy or teleoperation.
2) They are either research prototypes or commercial products that have been already experimentally tested at least on a mockup (Technology Readiness Level greater than 3 according to the classification by the European Commission [6]).
3) They had or may have direct deployment in response to the COVID-19 pandemic.

With innovations in design, perception, actuation, and control, we envision that, in the near future, robots may play a valuable role in assisting hospital personnel, relieving them from low-skilled or high-risk tasks, and improving the quality of care of people who are ill or isolated because of infectious diseases.

Clinical Background and Unmet Needs

COVID-19 is a respiratory viral disease with transmission via respiratory aerosols and microdroplets. This places clinicians and health-care professionals at risk of contracting the virus when caring for patients infected with COVID-19. The primary morbidity and mortality of COVID-19 are related to pulmonary involvement, and pneumonia is the primary cause of death in 44% of cases [2]. Between 15 and 20% of patients who develop COVID-19 will require ventilation in an ICU at some point during their illness [7]. Some of the most in-demand resources during COVID-19 are health-care workers, personal protective equipment (PPE), and ventilators. The infection risk for staff and the strain on PPE resources are exacerbated by the fact that health-care workers must put on and take off PPE every time they enter an ICU or engage with a patient, even if only to perform a simple task such as changing a setting on a ventilator or dosing medication.

Despite common traits, health-care needs and responses have not been identical everywhere. In many hard-hit countries, including the United States, the COVID-19 pandemic has also ground elective surgeries and routine health checkups to a halt, imperiling public health and negatively impacting economic recovery [8].

The COVID-19 pandemic is having a major impact on the global health-care system, with telemedicine being one of the key drivers of the change. While the COVID-19 pandemic has driven the strong expansion of contactless telemedicine use for urgent care and nonurgent care visits [9], further technological advances are necessary to expand the use of telemedicine to areas that require physical interactions such as for swab testing, imaging, nursing, or interventional treatment. Medical robots have the unique capability to bridge the gap between remote health-care providers and patients by interacting with imaging and therapeutic equipment and with patients, ushering in the next generation of telecare. But for

Challenges	UVD Robotics, Denmark	Boston Dynamics, United States	Lifeline Robotics, Denmark	Zhejiang University, China [42]	Italian Institute of Technology
Mobility	x	x			
Manipulation			x		x
Actuation					x
Control	x		x	x	
Sensing		x		x	
Human–Robot Interaction		x			
Physical Human–Robot Interaction	x		x	x	x

Figure 1. In terms of the continuum of care, five categories of representative medical robots have been deployed during the COVID-19 pandemic to assist with health-care needs associated with an infectious disease. For each category, the table outlines the three challenges (crossed cells) that, according to the authors, have the highest potential to enable key advances in that specific area. Further details are provided in the relative sections.

robots to robustly and safely perform physical tasks such as swabbing a patient, changing a ventilator setting in an ICU, or performing an ultrasound scan, advancements in the areas of sensing, actuation, control, autonomy, and artificial intelligence (AI) are required.

The Role of Medical Robotics in Infectious Environments

Robotics can play a key role in combating infectious diseases in four areas, including clinical care, logistics, reconnaissance, and continuity of work and maintenance of socioeconomic functions [3]. Here, we focus on the first area, within which we identify five categories of medical robots (Figure 1) in the continuum of care, including prevention, screening, diagnosis (e.g., biological sampling and laboratory automation), treatment, and home care (e.g., nursing).

Robots for Prevention

Disinfection is one of the key measures against infectious diseases. A common method adopted for the disinfection of public spaces, such as hospitals, is ultraviolet (UV) disinfection. It consists of exposing the surfaces to be disinfected to a specific UV light bandwidth, so-called UV-C (200–280 nm), corresponding to the peak of germicidal effectiveness [10]. In general, UV robots are comprised of a mobile base equipped with an array of lamps mounted on the top, spanning 360° coverage. The positioning of the device can be manual or autonomous. For instance, the LightStrike Germ-Zapping Robot (Xenex, United States) is operated by trained hospital environmental services staff [11], while the UVD Robot (UVD Robots, Denmark, Figure 1) relies on simultaneous localization and mapping to scan and navigate the environment on its own. As UVC light may be harmful to humans, the operation of these robots is typically suspended when opportune occupancy sensors detect the presence of a person in the space undergoing disinfection.

The possibilities offered by all of these UV robots are strictly confined to the line of sight. To overcome this limitation, the University of Southern California developed a semi-autonomous mobile manipulator for UV disinfection by readapting its Agile Dexterous Autonomous Mobile Manipulation System [ADAMMS, Figure 2(a)]. It was endowed with UV-light wands, augmented vision guidance, and a teleoperation framework that relies on autonomous path planning algorithms to comply with high-level directives by a human operator. Exploiting human-in-the-loop control, it can handle targeted disinfection tasks through challenging scenarios that involve the approach to objects of interest and their manipulation.

Another class of robots uses chemicals to disinfect surfaces. Nanyang Technological University developed the eXtreme Disinfection roBOT [XDBOT, Figure 2(b)] that explores the environment and identifies objects to be disinfected using lidar and cameras. The wheeled mobile base supports a 6-axis robotic arm that handles an electrostatic sprayer and is remotely controlled by a human operator.

As a common shortcoming, disinfection robots typically operate over a predefined temporal horizon while not providing any direct measurement of the decontamination evolution (e.g., mapping of the disinfection dose), which prevents the application of any feedback control on the accuracy of the process. Yet factors like distance and orientation of surfaces play a crucial role in the effectiveness of UV decontamination. Chemical decontamination with robots needs to consider or control multiple parameters, including the concentration and quantity of disinfectant, contact time and temperature, residual activity and effects on material properties and surface roughness, and pH scale and interactions with other compounds. Future research is needed to understand how to better control disinfection with robotic systems, possibly by exploiting feedback to enhance the reliability of the process. Other opportunities are related to the development of AI to turn current semi-autonomous devices into fully autonomous robots with enhanced efficiency.

(a) (b)

Figure 2. Robots for disinfection. (a) The ADAMMS (University of Southern California, United States) is a mobile robot with manipulation capabilities for UV disinfection. (b) The XDBOT (Nanyang Technological University, Singapore) uses an electrostatic sprayer to carry out chemical disinfection.

Robots for Screening

Early identification of infected persons is a critical function in the management of infectious diseases. In hospitals, triage is the first step to receive people who need medical attention and arrange the sorting of treatment before they arrive in the emergency department. Telemedicine enables forward triage via smartphone [12], allowing physicians and patients to communicate without direct contact.

Incorporating thermal sensors and vision algorithms into autonomous or remotely operated robots can increase the efficiency and coverage of screening. Robots for temperature screening have been employed during intake at many hospitals in China [Figure 3(a)]. Moreover, some preexisting devices were adapted for the same purpose. Besides wheeled telerobots for indoor navigation like Diligent Robotics and Ava (iRobot Inc., United States), legged robots (Boston Dynamics, United States, Figure 1) were adapted for telepresence and vital sign monitoring, both indoor and outdoor, thanks to its versatile mobility. Other robots were also deployed for rapid drive-through temperature screening, such as the SHUYU robot [Tsinghua University, China, Figure 3(b)] [13], which locates human faces through computer vision and takes the temperature using a noncontact infrared thermometer.

The main challenges for improved outcomes regard the accuracy and robustness of the sensors. For instance, thermal cameras may fail in detecting the correct temperature when particular conditions are encountered, such as when sweat or a mask covers the face of the subject. Increasing the environment and context awareness of the robot would be beneficial to tackle these difficulties so that similar errors could be compensated for with the aid of additional sensors and computational processing.

(a) (b)

Figure 3. Robots for screening. (a) A robot used for temperature monitoring at a hospital in Shenyang, China. (b) The SHUYU robot developed by Tsinghua University, China, allows for rapid drive-through temperature screening [13].

Robots for Diagnosis

Bio Sampling and Image-Guided Diagnosis

Depending on the disease, a host of samples may need to be collected, such as blood or stool samples in the case of nonairborne diseases like Ebola and cholera, or saliva, oral, or nasal swab samples in the case of airborne diseases like COVID-19. Conventional testing methods typically require interaction between a potentially infected patient and medical workers, thus representing occasions for the potential spreading of the virus. Additional issues may also stem from the handling of collected samples prior to, during, or after testing. Hence, robotic solutions for collecting, handling, testing, and disposing of these samples may allow for a valuable reduction in transmission of and exposure to a disease.

Telerobots with manipulation capabilities are able to achieve physical human–robot interaction, which is not feasible with conventional telemedicine solutions. As an example, the Chinese Academy of Sciences developed steerable telerobots for throat swab sampling of coronavirus tests [Figure 4(a)] [14]. During traditional throat swab sampling, health-care staff is in close contact with patients, which poses a high risk of cross infection. In addition, health-care workers' operating skills affect the accuracy and quality of swab results. To overcome those limitations, health-care workers can teleoperate the robot with both haptic and visual feedback from the high-definition 3D anatomical view of binocular endoscopes.

A further step was taken by a joint team from Lifeline Robotics and the University of Southern Denmark, who developed the first fully automatic throat swab robot (Figure 1). Another work presented a portable robot [Figure 4(b)] for needle placement to draw blood or deliver fluids through image-guided autonomous operation [15]. Multimodal image sequences (both ultrasound and near-infrared optical imaging) were decoded by predictions from a series of deep convolutional neural networks to guide the real-time actuation of the robotic cannulation process.

Another important method for diagnosis, especially during the COVID-19 pandemic, is ultrasonic examination, which is well suited for monitoring the condition of the lungs, unlike the computerized tomography scan, which causes radiation and is not in real time. Tsinghua University evaluated a force-controlled ultrasound robot [Figure 4(c)] that fuses cross-modal sensory information from ultrasound and force measurements for remote diagnosis to minimize the contact between health-care staff and patients. The University of Maryland developed a semi-autonomous system for hemorrhage detection using robotic ultrasound [16] and explored using the system for COVID-19 lung imaging [Figure 4(d)]. A similar study was conducted to evaluate the feasibility of a remote-robot-assisted ultrasound system in examining patients with COVID-19 [17].

(a) (b) (c) (d)

Figure 4. Robots for sampling and diagnosis. (a) A steerable telerobot for throat swabbing from the Chinese Academy of Sciences [14]. (b) A portable robot exploiting deep learning for blood testing at Rutgers University, United States [15]. (c) A robotic platform for lung ultrasound at Tsinghua University, China. (d) A robotic system for remote trauma assessment at the University of Maryland, United States [16].

Despite these valuable contributions, substantial technological gaps remain in dexterity, haptics, multimodal sensor integration, and autonomy, which complicates the operability of the devices. In the case of ultrasonic examination, it turned out that training physicians to operate the robot was challenging, especially for the problem of hand–eye coordination. On the other hand, ultrasonic devices and, in general, existing medical devices are not designed for remote use by robots, so they usually need to be modified to be operated remotely.

Lab Automation

There is a new trend to use robots in laboratories for tasks, including sample processing, goods delivery, and conducting experiments. The primary purpose is to automate manual processes to protect personnel from infectious agents, alleviate the human workload, and achieve high throughput. The widespread COVID-19 disease has sparked a need for mass testing capacity. Lab automation has been the application most frequently requested during the Ebola and COVID-19 pandemics. To address this need, the Innovative Genomics Institute (IGI) at the University of California, Berkeley, established a SARS-CoV-2 testing lab in three weeks [18]. Due to the technical challenges of establishing a fully automated workflow, the IGI designed a workflow that supports two workstreams in parallel, a semimanual approach and an automated approach in RNA extraction and liquid handling (Figure 5), so that the testing efforts could reach the community as early as possible.

The Rapid Automated BIodosimetry Tool [RABIT, Figure 6(b)] [19] developed at Columbia University is a highly automated,

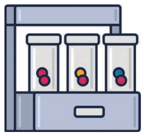
	Extract RNA	RT-qPCR	Analyze Data	Interpret Data
				
Thermo Fisher EUA Protocol	Collect Patient Samples Followed by Manual or Automated RNA Extraction	Perform RT-qPCR	Analyze Data Using Commercial Software	Interpret Result Based on Thermo Fisher's EUA
Phase 1 Semi-Automated	**Manual** RNA Extraction From Previously Arrayed Patient Samples Using an Automated Liquid Handling Robot	Manual RT-qPCR Plate Setup, Perform RT-qPCR	Analyze Data Using **Custom Software**	Interpret Result Based on Thermo Fisher's EUA **and Criteria Established in the IGI's Validation Assays**
Phase 2 Automated	**Automated** RNA Extraction From Previously Arrayed Patient Samples Using an Automated Liquid Handling Robot	**Automated** RT-qPCR Plate Setup by a Liquid Handling Robot, Perform RT-qPCR	Analyze Data Using Custom Software	Interpret Result Based on Thermo Fisher's EUA and Criteria Established in the IGI's Validation Assays

Figure 5. The workflow of manual and automated protocols proposed by the IGI at the University of California, Berkeley [18] (blue background). Their implementation of the workflow is built upon Thermo Fisher's authorized Emergency Use Authorization (EUA) protocol [23] (yellow background). Phase 1 of the IGI's workflow requires the manual implementation of the Thermo Fisher kit, while phase 2 is automated. Bolded words indicate elements changed from the implementation mentioned earlier. RT-qPCR: quantitative reverse transcription polymerase chain reaction. (Icon source: Flaticon.com.)

(a) (b) (c)

Figure 6. Robots for laboratory automation. (a) An automated liquid-handling robot (Hamilton STARlet) at the University of California, Berkeley will be used to analyze swabs from patients to diagnose COVID-19 [18]. (b) The RABIT from Columbia University [19]. (c) A mobile robotic chemist for conducting experiments [21].

ultrahigh-throughput biodosimetry workstation for radioactive materials handling. It can output a dose estimate with no further human intervention than the manual placement of the test tubes. The initial version of the RABIT system had a capacity of ~6,000 samples/day, and the goal is to reach 30,000 samples/day after parallelizing various steps. Its high throughput is partly due to predetermined processing sequences and homogenous features of the test tubes.

However, this is hardly the case in broader scenarios. For example, the mass screening of COVID-19 among a vast population led to a significant increase in the number of performed polymerase chain reaction tests and antibody tests, which require a massive amount of heterogeneous test tubes. Despite the automation in extraction and detection, a remaining problem is the autonomous preparation of the examination plates. Osaka University [20] developed a robotic system that uses 3D vision and AI planning for autonomously arranging test tubes. Without specific instructions, the robot is able to efficiently manage the examination samples. Since the system does not require expert knowledge by human operators, it has the potential to significantly increase the throughput as well as protect and free people for more important work.

Instead of automating laboratory analysis procedures, robots can also automate the function of conducting experiments. Burger et al. used a KUKA mobile robot to automatically search for better photocatalysts for hydrogen production from water in a laboratory setting [Figure 6(c)] [21]. Thanks to its modularized approach, the robot could be used in conventional laboratories for research experiments other than photocatalysis.

Robots for laboratory automation have the potential to alleviate the workload by automating manual processes and protecting personnel from being exposed to infectious agents. However, it takes significant time and resources to develop specialized robots that enable high throughput and accuracy. Thus, modular design is an opportunity to make robots adaptive to the needs of different kinds of infectious agents. Besides, all of the robots need to undergo extensive benchmark and reliability tests and meet government regulations before they can be used. Per the U.S. Centers for Disease Control and Prevention guidelines [22], the SARS-CoV-2 virus can be cultured only in laboratories with a biosafety level of 3 or higher, which significantly limits the number of facilities allowed to study the virus and thus hinders the development of new treatments or vaccines. All of these obstacles affect how soon robotic solutions can be available to the public.

Robots for Treatment

One in every six patients with COVID-19 experienced severe conditions involving bilateral pneumonia and acute respiratory distress syndrome [24]. Therefore, endotracheal intubation was one of the most required treatments to allow for mechanical ventilation. Intubation is a complicated procedure with high complication rates, and it strongly relies on the manual dexterity of experienced physicians [25]. It is performed by placing a tracheal tube into the trachea of the patient while lifting the jaw with a laryngoscope. This procedure implies direct contact with contagious airways, and, in the situation of infectious disease like COVID-19, it exposes the operator to a high risk of infection. Robots as protective devices can provide valuable help to ensure the safety of doctors and patients during operation, especially in emergency situations. As shown in Figure 7, intubation teams involved in airway management procedures are composed of several members with

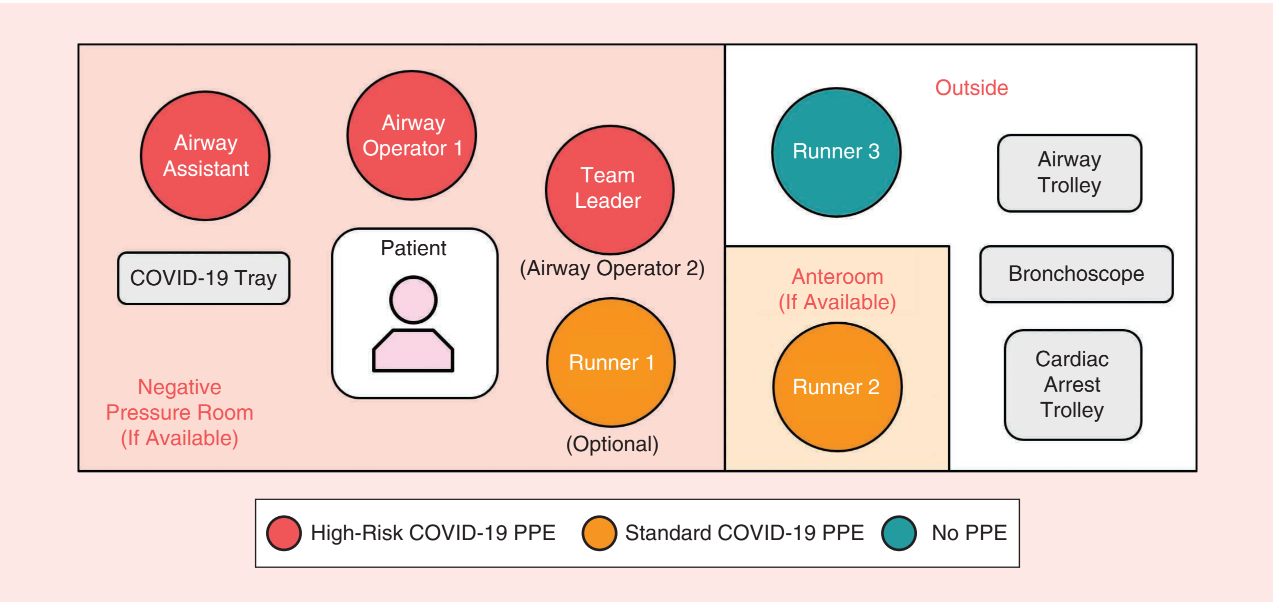
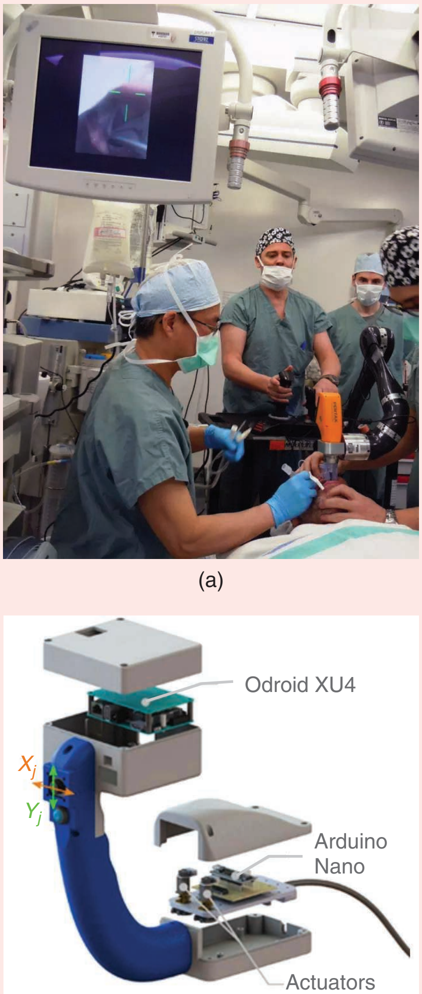


Figure 7. According to the Safe Airway Society principles of airway management and tracheal intubation, intubation teams are composed of multiple operators with specific roles. Hence, the adoption of robotic solutions may substantially relieve the workflow by replacing/assisting some personnel [34]. (Used with permission of Wiley Online Library.)

defined roles. Thus, a robot can potentially assist or replace some personnel, relieving the annexed workflow and reducing the probability of disease transmission.

Researchers at John Hopkins University designed a Cartesian robot with an integrated camera that enables the remote control of a ventilator [26]. Airway management in infectious conditions is a challenge that may greatly benefit from robotic assistance to make intubation safer and more efficient.

Nonetheless, unintended issues and undesired consequences may arise from the deployment of robots, like reducing the ergonomics and maneuverability of operators or the introduction of additional contamination sources. Therefore, it is critically important that the use of any additional tool is adequately considered and handled [27], [28]. Researchers explored general-purpose surgical robotic platforms, such as the Da Vinci surgical system [29], and purposely designed devices to address specific issues.



(a)

(b)

Figure 8. Robots for intervention and treatment. (a) The Kepler Intubation System (McGill University, Canada) [29]. (b) REALITI (ETH Zurich, Switzerland) [33].

Ad hoc solutions span the entire spectrum of robotics, from fully manual teleoperation to assisted sensing and actuation and up to the eventual deployment of fully autonomous systems [30]. One interesting result is the development of intubation systems remotely controlled by the user via a joystick. This strategy was embodied in both a fixed platform [Figure 8(a)] [29] and a portable device, the Remote Robot-Assisted Intubation System [31], for hospital and prehospital treatment, respectively.

Yet the main challenges of robot-assisted intubation are related to the lack of tactile feedback. Researchers from Columbia University developed InTouch, an advanced laryngoscope with a tactile sensing blade [32]. Even though it demonstrated a decrease in the complication rate and the time required for correct intubation, it does not include any automation feature and still relies on visual recognition of the airway and manual steering by its user. A step further in this direction is taken with a Robotic Endoscope Automated via Laryngeal Imaging for Tracheal Intubation [REALITI, Figure 8(b)], developed at ETH Zurich [33]. It handles the task of guiding the tracheal tube into its correct position by performing the automated detection of anatomical landmarks within the throat and the automated steering of endoscopes toward the recognized features. While this system has been successfully tested on mannequins, there is a long way to go before it can be effectively deployed on human subjects.

A key challenge is the necessity of a robust method for accurately identifying the anatomical features in a large and multifaceted population, whereby variations in airway anatomy, local pathologies, and other particular conditions may hinder regular tracheal intubation. To this extent, significant improvements might derive from the constantly progressing tools of computer vision and AI. Other opportunities come from the enhancement of sensing and actuation technologies. Besides visual feedback, force sensing is crucial to enhance the reliability of robotic intubation. Its success rate could significantly benefit from distributed and accurate force/pressure sensors, made possible by advancements in stretchable electronics. From the actuation perspective, a promising approach could derive from the achievements of soft robotics. A vine-inspired robot, for instance, may represent a feasible way to create a conduit to the lungs via a failsafe and easy-to-use device, with the ability to grow into multiple branches to deal with different morphologies [35].

Robots for Home Care

The COVID-19 pandemic is causing an overwhelming load in health facilities, requiring intensive employment of the hospital workforce. Doctors and nurses strive to work extra shifts to save lives [36]. Additionally, direct contact with infectious patients puts them in the critical condition of being regularly exposed to the risk of contracting the disease. Therefore, robots capable of performing typical assistance tasks would enormously benefit the daily medical care of patients during similar circumstances.

This situation is not confined to hospitals; nursing assistance is also a fundamental service in nursing homes and domestic spaces. Such assistance covers all of the workflow of care, from the acceptance of the patient into the hospital and through the recovery and aid service at home. To date, there are no robots that can effectively carry out the versatile activities of nurses. The great challenge remaining is the ability to deal with a plethora of tasks and a myriad of different subjects, which requires both physiological empathy and physical interaction. The monitoring of patients, delivery of meals and medication, assistance with patient ambulation, and manipulation of medical equipment are only a few examples highlighting the incredible amount of required versatility.

Most nursing robots are able to perform only very basic functions, e.g., telepresence and meal delivery. An example is the Sanbot Elf robot (Qihan Technology, China), which became famous as Tommy while treating COVID-19 patients in an Italian hospital [Figure 9(a)]. Another class of nurse robot embraces robots for social assistance [37]. Indeed, psychological support is also critical during pandemic emergencies, when mental health problems are exacerbated by severe restrictions, such as quarantine and social distancing.

More generally, five primary functions have been identified for general-purpose nursing robots: communication, mobility, measurement of clinical data, general manipulation, and tool use [38]. Among these, physical interaction constitutes the key challenge; in particular, manipulation is the bottleneck toward effective deployment of nursing robots due to the necessity of a broad range of dexterity and strength, which involves dealing with both gross, powerful actions (e.g., patient assistance during lifting and walking) and delicate, precise manipulation (e.g., intravenous fluid management). Advances in soft robotics have enabled substantial progress in this direction, with the development of numerous adaptive and versatile grippers. In addition to the end-effector solution, high-torque-density actuators have demonstrated high compliance and high bandwidth in legged and wearable robots [39]. Such actuators can be incorporated into a robot arm design to enhance safety and performance during the interaction.

Another challenge is related to the use of tools, since medical devices are not designed for use by robots. An adopted solution is the use of special replaceable connectors for various grippers to reconfigure the end effector [42]. To tackle these challenges, the baseline approach relies on the employment of traditional anthropomorphic robotic arms installed on omnidirectional mobile platforms. Additional features include different levels of autonomy, autonomous 3D mapping and navigation, telepresence with two-way audio for telerobotic–human communication, patient surveillance, and assistance for patient mobility (e.g., during lifting and walking).

Some of the most advanced embodiments of these technologies include both commercial products, like Moxi [Diligent Robotics, United States, Figure 9(b)], and research prototypes, such as the Tele-Robotic Intelligent Nursing Assistant (TRINA) [University of Illinois at Urbana–Champaign, United States, Figure 9(c)] [40], the Robotic Nursing Assistant (RoNA) [Hstar Technologies, United States, Figure 9(d)] [41], and a telerobotic system based on YuMi (ABB, Switzerland) [42]. The latter was developed for remote care operation in the isolation ward and was tested in a hospital in Zhejiang, China. The robot is composed of two subsystems, one for telepresence and one for teleoperation, and can assist or even replace the medical staff when taking care of patients in tasks that include daily checkups; the delivery of medicine, food, or other essentials; the operation of medical instruments; the disinfection of frequently touched surfaces; and auscultation while wearing PPE.

Discussion and Conclusions

Robotic systems are currently being used to perform more and more sophisticated tasks throughout our society. It is not surprising that they are playing an important role in responding to the challenges posed by the current COVID-19 pandemic. In this survey, we have focused primarily on robotic applications in health care, including those directly related to the care of COVID-19 patients in hospitals and those allowing for the provision of ordinary care at home (e.g., nursing

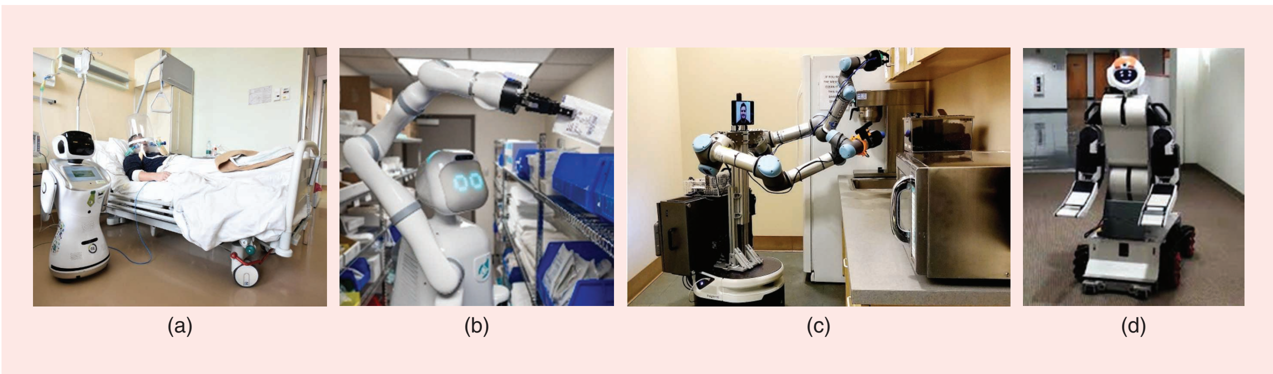


Figure 9. Robots for nursing assistance. (a) The Sanbot Elf robot (Qihan Technology, China) worked as a nurse nicknamed Tommy in an Italian hospital. (b) Moxi (Diligent Robotics Inc., United States). (c) TRINA (The University of Illinois at Urbana–Champaign and Duke University, United States) [40]. (d) RoNA (Hstar Technologies, United States) [41].

robots). Specifically, prevention, screening, diagnosis and treatment in hospital settings, and postrecovery home care were discussed. Other application areas, such as public safety, supply chain logistics, and transportation, are also important. Indeed, the adaptability of robot systems and technology means that there has been considerable crosstalk between areas. Many health-care robots discussed in this survey are essentially adaptations of robotic systems developed for non-health-care uses.

As this article is being written, the pandemic continues, and robotic systems may be expected to play an increasing role in dealing with the challenges presented. However, it is not too soon to consider some of the lessons drawn from the experience.

The first lesson is the crucial role of communication between the user communities that are most immediately affected by the disease and the engineers and robotics researchers who are developing systems to address emerging needs. Unless there is a good understanding of the unmet needs and the constraints imposed by the environment into which a robot is to be introduced, it is not likely that it will be useful. Similarly, it is important to understand the differing needs and expectations of all of the people (e.g., technicians, health-care workers, patients, and family members) with whom the system is likely to interact.

A second lesson is the importance of capability and adaptability in robotic systems. As mentioned, many of the systems discussed in the article adapt robotic capabilities developed for other uses to meet emergent needs. This adaptability is almost an inherent aspect of robotic systems, and the trend will continue, due to both research programs such as the U.S. National Robotics Initiative and the increasing commercial deployment of robots. It is crucial for those involved in developing these systems to remain sensitive to the importance of future flexibility while also concentrating on the demands of safety, simplicity, and robustness in meeting current requirements.

A third lesson concerns deployability in sufficient numbers to make a major difference in a crisis. Although the systems we discussed meet real needs, only a relatively small number have actually been installed. As more robots are installed broadly in our economy, there is at least the potential to exploit their inherent adaptability to be put to work in health-care applications. However, advanced planning and preparation for such a mobilization seem important.

A final lesson concerns the need for better preparation for the infectious-disease-specific constraints associated with operating in a pandemic environment. These include such matters as cleaning and disinfection protocols and materials choices.

The adoption of technology needs to be expedient but safe and responsible for facing disasters like a pandemic crisis. Speedy and mindful regulations that properly weigh the benefits and risks are necessary to guarantee the safety and effectiveness of robots and prevent biases and privacy issues. Joint efforts by roboticists, governments, industry, and citizen stakeholders may indeed facilitate the development and deployment of useful and validated robotic solutions for the benefit of the community. If appropriate strategies are implemented to ensure adaptable and reliable systems that can be quickly replicated and distributed on demand, robots could play a much more significant role in future crises.

Acknowledgment
Hao Su is the corresponding author for this article.

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