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FULL PAPER

Automating pandemic mitigation

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ABSTRACT
The COVID-19 pandemic keeps spreading across the world and, while national governments concentrate on lockdowns and restrictions to mitigate the disaster, advanced technologies could be employed more widely to fight the pandemic. This paper surveys existing robotic solutions that could be employed for pandemic care and presents a systematized description of desired robot properties based on a particular application area and target users. We propose a new generation infection hospital framework that integrates existing robotic tools toward pandemic mitigation and discuss ethical aspects of their use within the framework.

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1. Introduction

On 11 March 2020, the World Health Organization confirmed that Coronavirus Disease 2019 (COVID-19) should be considered a pandemic. Pandemics appeared occasionally throughout human history, and a poor level of medicine, education, and technology made pandemics of the past deadly and almost impossible to control.

While modern achievements in public healthcare, mass education, and medical science significantly decreased the dangerous flow and consequences of twenty-first century pandemics, global trading and faster ways of traveling made people in different countries more connected, which complicates a disease diffusion control and requires concerted international efforts.

By the time of writing this paper, over 113 million people were infected by COVID-19 with over 2.5 million confirmed deaths. Even though several companies have reported success in the COVID-19 vaccine development (e.g. Oxford-AstraZeneca [1], Pfizer [2], Moderna [3], Gamaleya Research Institute [4]), still main measures to prevent further exponential growth of infection cases and mitigate the pandemic are massive lockdowns, social distancing, and contacts' tracing.

Every person that contacts an infected person is at risk of infection. Therefore, the very first measure recommended by epidemiologists is to isolate a potential carrier of the disease. However, an infected person requires medical and home care with inevitable direct or indirect contacts. While it would be complicated to completely avoid contacts with an infected person, the number of contacts could be significantly reduced by employing modern robotics technologies.

Robots were contrived to replace human workers in 3D jobs [5], which corresponds to **D**emanding (e.g. manufacturing [6] or packaging [7]), **D**irty (e.g. pet litter disposal [8]) and **D**angerous for human beings activities (e.g. in urban search and rescue, USAR [9, 10] or mine clearance operations [11]). A well-known USAR robotic deployment methodology of Robin Murphy [12] implies integration of appropriate cutting-edge robotic technologies into existing emergency agencies' organization structure. It does not concern a complete human staff replacement. Instead, robots serve as additional tools that work together with standard canine search teams and technical search specialists. Ease of integration is reached by using existing and well-established organization principles, such as categorization of operation site into three zones with regard to a danger level.

While multiple research teams keep developing efficient robotic tools for the USAR domain, by now only a limited number of these solutions were put to test in a real-world disaster scenarios [13–16]. Yet this number grows permanently [17] as technologies improve because it is natural to replace physically and psychologically vulnerable human rescuers by high-tech robots, wearable assisting devices and sensory networks.

Pandemic mitigation is another opportunity to extend the usage of robotized solutions in order to reduce

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the number of human casualties among medical personnel and the general public, including patients. We strongly believe that within the next two decades most of the human jobs that are related to infection and pandemic mitigation will be replaced partially or entirely by autonomous, semi-autonomous, and teleoperated robotic assisting tools.

Pandemics, including the ongoing COVID-19, have been attracting attention of scientists for the past decades and two broad approaches are taken in mitigation with pandemics: pharmaceutical (medical) approaches [18, 19] and non-pharmaceutical (NPI) interventions [20–22]. Yet, there are comparatively a few research articles dedicated to applying robotic solutions for pandemic mitigation, and they significantly differ by their purposes and depth of subjects' analysis:

- In [23, 24] a wide range of technologies including Internet of Things (IoT), virtual reality, big data, machine learning is considered. These articles include frameworks for digital technologies used during an infection spread and present very generic recommendations.
- Authors of [25] focused on robotics and presented a short-list of robots that could be used for combating a virus in various scenarios. They formulated recommendations for proper robot selection, which aimed at management purposes and have less significance for robot developers.
- In [26] authors emphasized the importance of artificial intelligence (AI) and robotics technologies usage for pandemic mitigation through a review of existing tools.
- A high interest to the topic is proven by editorial texts of leading top-level robotics researchers [27] and novel robots designed especially for infectious hospitals [28, 29].
- A new robot classification is proposed in [30], with robots being differentiated by their main operating locations: hospitals, airports, etc.

While the above-mentioned research articles provided good surveys and discussions of existing solutions, they did not focus on robot designers and developers, lack practical recommendations for creating new robots for disease mitigation, and did not analyze in-depth requirements for robots that contact with an infection.

Robots' development or adaptation for pandemic mitigation requires careful planning, and developers should have a clear vision of how their new robots could be integrated into an existing workflow of a health-care facility: an environment, possible robot users, robot functioning cycle, potential risks, and ethical issues with patients, safety and security, etc. Our research is intended to fill this gap, focusing on the role of robotics within the pharmaceutical approach.

The paper surveys examples of robot usage during the pandemic and classifies them by their deployment and purpose. The main contribution of the paper is a proposed novel holistic framework for applying a set of existing robotized assisting tools toward pandemic mitigation within infectious disease hospitals and analysis of potential ethical problems related to these deployments. We highlight common requirements for robotized tools for infection outbreak zones and major ethical risks that should be considered prior to the deployment. The overview of an infection hospitals' management system should help robot developers to obtain general ideas of infection containment and provide a higher level of their products' applicability. We hope that after further successful deployment and long-term testing of the proposed framework within real hospitals it could become an international standard for infectious disease smart hospitals.

The rest of the paper is organized as follows. Section 2 describes existing disease management techniques. Section 3 overviews successful robotic deployments and classifies them by robot usage purposes. In Section 4 the described robotic deployments are analyzed and classified with respect to their readiness for pandemic mitigation and required training skills of operators. A holistic framework of a robotized infectious disease hospital is described in Section 5. Section 6 deals with ethical issues of the robotic deployments within a smart hospital environment. The discussion and conclusions are presented in Sections 7 and 8 respectively.

2. Modern disease control practices

The organizational structure of medical facilities and construction standards of infectious disease hospitals are quite similar in different countries [31, 32]. An infectious disease hospital is divided into two completely independent parts, which are referred as 'dirty' and 'clean' zones. The clean zone is used by personnel of a hospital on a daily basis and it should not contain any risk of contamination. Therefore, only standard hygiene and safety measures of a regular hospital are required within the clean zone without a necessity of wearing safety suits for personnel. Infected people are located in a dirty zone. The dirty zone ideally has all its communications (including a ventilation system) and infrastructure being separated from the safe zone. The only way to enter the dirty zone and to leave it is to pass through a highly secured sanitary room. A sanitary room is equipped with a broad

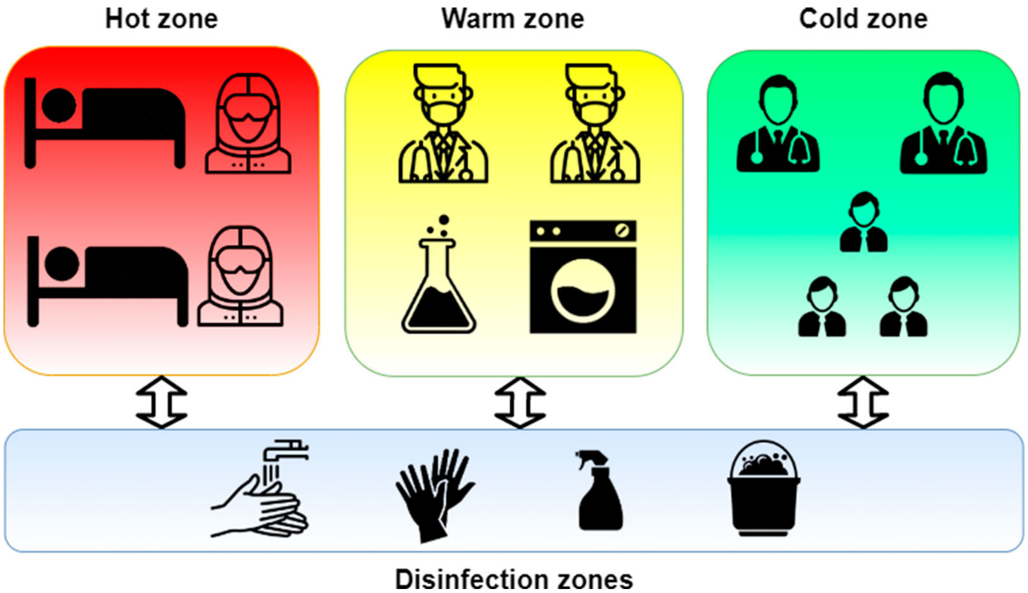


Figure 1. Existing infection epicenter structure.

range of disinfection tools and extra clothes for a change. Every person (doctors, medical staff, technical personnel, etc.) should go through this procedure every time he/she enters and leaves the dirty zone. Sanitary rooms are also designed for potentially infected patient management. All newly arrived patients with probable infection symptoms stay in these rooms until a diagnosis is established. Such restrictions target to contain infectious diseases in bounded space and protect medical personnel. Modern hospital management techniques also distinguish zones with a moderate risk of contamination. These zones do not require such high-level safety measures as the dirty zone, however, they are not completely isolated from potentially infectious subjects [33]. This standard scheme is shown in Figure 1. Other classifications use similar structure referring to the distinct zones as dirty, semi-clean, and clean zones (e.g. in [34, 35]) or A, B, and C zones in WHO classification [36].

A hot zone (an epicenter) is the most dangerous location of a direct contact with infected patients that have confirmed cases of a disease. Commonly, a positive infection test result means an immediate hospitalization, and thus the hot zone is usually located within medical facilities. This zone has strong restrictions aimed at containing the infection strictly inside the zone. During the current pandemic, infected patients with mild symptoms are often isolated at their homes, and in these cases, the hot zone could be extended to a private isolated apartment of an infected patient.

A cold zone (a safe zone) includes places with a low risk of infection. There should be no confirmed cases of infection within the cold zone in order to prevent direct contamination. The location should be thoroughly disinfected in order to avoid indirect disease transmission. The main purpose of this zone is to take measures against the infection diffusion with a minimized impact on everyday life. During the COVID-19 pandemic, individual safety measures in the cold zone are limited to wearing face masks, gloves, and periodical hands' sanitizing.

Warm zones are parts of medical facilities with indirect contact with an infection. This zone includes medical wards, laboratory areas, blood banks, dietary and laundry services, personnel restrooms for short breaks. Safety requirements in this zone are less strict, e.g. full protective suits could be substituted with face masks. However, this zone still has a risk of contamination: an indirect contact with the infection persists during laboratory analyses, clothes changing and laundry, dish cleaning, etc.

Entering or leaving any of these zones should be controlled and should include activities, which are targeted to prevent a possible infection spread: hand sanitizing and overall skin hygiene, clothes changing, tools disinfection, and other measures to prevent the infection transfer via objects from the epicenter.

3. Robotic deployment examples

This section presents a number of selective existing robotics solutions that could be employed or are already employed (in a point-wise manner) for COVID-19 pandemic care. The paper proposes a holistic framework for pandemic mitigation, and the presented in this section examples form pieces of a puzzle that should be brought together in a legally and ethically acceptable, and responsible way.

3.1. Indoor cleaning and disinfection

Cleaning and disinfection procedures are obligatory in all modern hospitals and critical for infectious disease hospitals. These include personnel hygienic procedures (such as hand washing [37]) and keeping surfaces clean, disinfecting medical tools [38] and proper medical waste management [39].

A number of solutions for indoor cleaning and disinfection are already provided by researchers and commercial companies. UVD robot and LightStrike robot [40–42] could perform local Ultraviolet (UV) indoor disinfection using hard UV radiation that is dangerous for human personnel. Their use increases disinfection quality and efficiency, reduces the risk of contamination for hospital staff, and shortens disinfection time comparatively to manual cleaning.

Classical dust cleaning [43] and window cleaning [44] robots reduce contamination risks, yet their efficiency is a question of hardware capabilities, coverage algorithms, and software flexibility, and their speed would highly likely be behind a human, especially for geometrically complicated surfaces. Robots could help in delivering sanitizer tools (e.g. [45, 46]) and 'forcing' visitors and patients to use sanitizers by a rather pragmatic reminding and execution tracking that apply computer vision-based algorithms [47, 48]. In most cases, such proactive assistance approach might work more efficiently than a standard hospital concept of placing sanitizers in crowded indoor locations and at building entrances together with a human nurse, whose functions are to remind and control sanitation and body temperature of all passing-by people. However, such proactive assistance may raise ethical issues, which are discussed in Section 6.

3.2. Basic medical support

Infected people in hospitals need continuous medical care. They should be examined daily to control their health status, including body temperature, blood pressure, and other physical and psychological parameters. Medical care includes various activities performed by medical staff continuously: medical supplies collection, tools disinfection, food delivery, cleaning, medical devices control, etc. [49, 50]. Everyday tracking requires close contact of medical personnel with infection carriers and potentially infected people, and robots could significantly decrease these contacts' intensity [45, 51, 52].

3.3. Remote presence

Robots are used as mobile 'avatars' for the remote presence of doctors, which allows safe for doctors remote checkups of patients and allows working with multiple patients in a short period of time. Robots of this type are often used in commercial and educational organizations [53, 54], which makes it easy to adapt them for medical purposes in case of infection outbreaks.

3.4. In-hospital delivery

Typically, hospitals are featured with a greater need for cargo delivery. Each drug, piece of food, or garbage should be collected and transported to a particular waste disposal location [39]. This takes personnel time but does not require special skills. Therefore, such tasks could be delegated to robots. Delivery robots may carry more goods than a human and do not need continuous operator guidance. Moreover, robots have less need to leave hot zones, therefore, such an approach simplifies keeping a cold zone safe. In cases when a robot moves through several types of zones, it is easy to automatically disinfect a robot using available disinfection tools [55, 56].

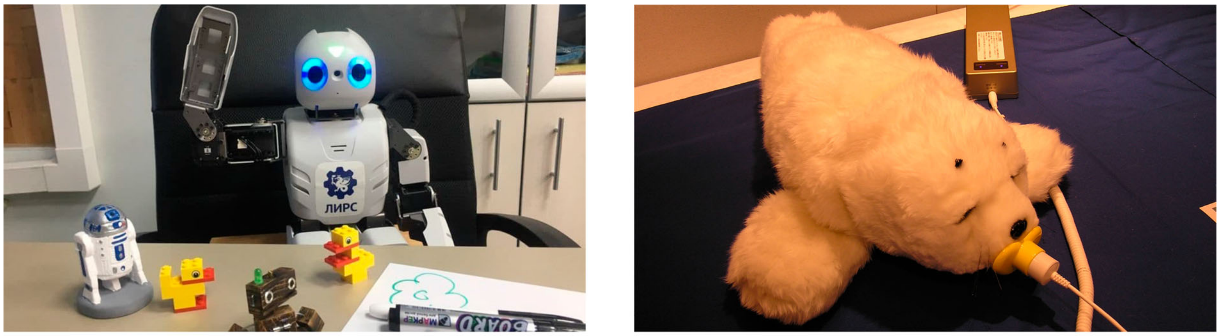
3.5. Psychological aid

Massive vaccination is the most robust way to prevent an infectious disease spread, followed by its further localizing and treating [57]. Therefore, right after a vaccine is synthesized and tested, population vaccination starts. It includes massive interaction and, generally is hard to automate, especially in cases of young age patients, children and babies. However, robotics could ease a vaccination procedure providing psychological aid and entertainment for young patients. This is highly actual for children vaccination and robot could be used to create a comforting environment, e.g. robots Darwin, NAO [58, 59], Paro [60], AIBO [61], NeCoRo [62], and ERIC [63] were already reported as successful tools for this purpose (Darwin and Paro are demonstrated in Figure 2).

Another important way of psychological aid is providing socialization tools for people staying in isolation on a hospital treatment or at home. In these tough conditions with no social contacts, people often rely on their pets, which could be the best solution for home-based isolation, but is impossible for hospitals [64]. Robotic pets, including those mentioned in the previous paragraph, are the way to meet this psychological need for people with no possibility to acquire a pet [65–67].

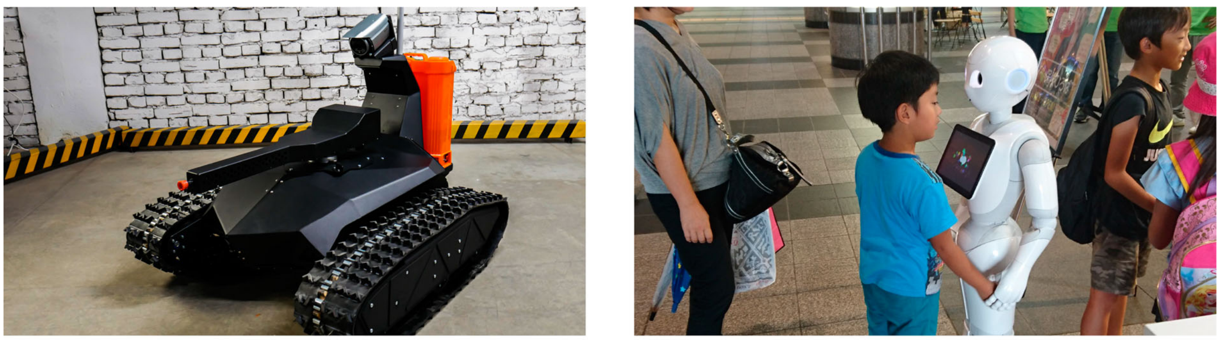
3.6. Large-scale disinfection

Disease diffusion containing includes large-scale disinfection measures outside of medical facilities. Such procedures performed manually require significant human resources while treating large spaces of streets, parks,



(a) (b)

Figure 2. Robots providing psychological aid: (a) Darwin OP2 supporting children during medical procedures; (b) Paro robot for psychological and socializing aid in isolation.



(a) (b)

Figure 3. (a) Mobile robot Scorpion for indoor and outdoor disinfection (image courtesy of Promobot company); (b) Pepper robot serving customers in a shop, Amu Plaza shopping center, Kitakyushu, Japan.

and inside of industrial buildings [68, 69]. In addition, a disinfection process is generally dangerous for personnel in cases when it lasts for a long time. To cope with these problems, mobile robots could be employed (Figure 3(a)).

3.7. Isolation tools

A disease outbreak region is usually declared as a region with restricted internal and external migration and traffic. These measures are intended to limit human contacts and decrease infection spreading speed. Therefore, security forces (police or military) require tools (e.g. UAVs and UGVs) to control a strict execution of imposed measures. Another way to provide isolation is to prevent unnecessary human contacts in regular places such as shops by employing shop assistant robots [70] as shown in Figure 3(b).

3.8. Population screening

Crowded places are sources of additional dangers during a pandemic, which cause a further rapid spread of disease. Therefore, when avoiding high people density is impossible, they should be continuously monitored in order to detect and track potential carriers. Such population screening is obligatory when large gatherings are unavoidable, for example, in vitally important industries or elections. Robots perfectly suit such massive screening tasks as they could send statistics directly to task force databases (shown in Figure 4).

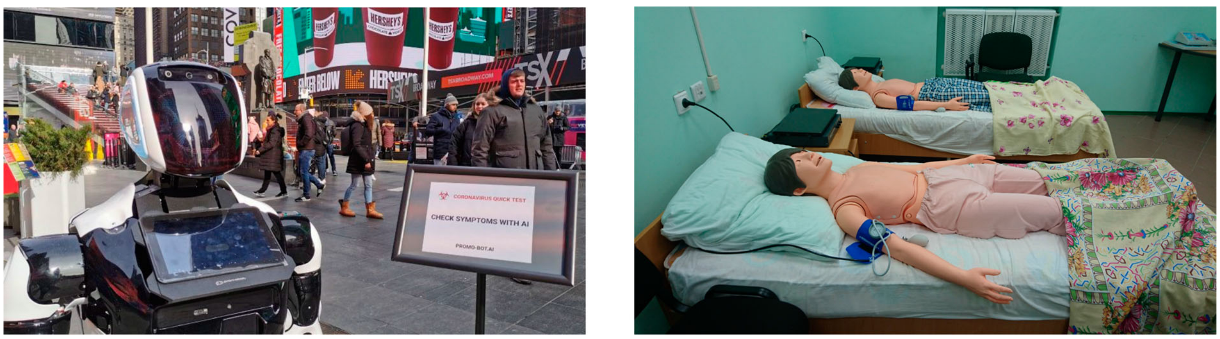
3.9. Education on disease and basic medical training

Education is an important and resource-saving way to decrease infection victims' figures. Proper informing about disease danger and first aid measures could save many lives in healthcare system overload conditions. Robots always attract people attention and might be very effective in information dissemination as it was on Times Square in New York (see Figure 5(a)).

In severe pandemic situations, a lot of volunteers are required in medical facilities in addition to regular staff in order to help with patient management. Typically, these are medical students or non-trained volunteers. They should be ready to perform generic medical manipulations, which do not require long term education, and

(a) (b)

Figure 4. Population screening robots located at crowded places (images courtesy of Promobot company): (a) Promobot Thermocontrol and (b) Promobot Diagnostician.



(a) (b)

Figure 5. (a) Promobot robot (image courtesy of Promobot company) informing about COVID-19 symptoms [72]; (b) A robotic patient during a nursing practice at Kazan State Medical University.

their training quality could be improved using special humanoid robots [71] (e.g. Figure 5(b)), which allow learning basic medical care manipulations with no risk to human life or health.

3.10. Medical testing

Medical staff working with infection testing samples is highly vulnerable to indirect contamination. Each testing includes several preliminary steps that prepare a sample for analysis. A preliminary stage consists of mechanical and chemical operations with samples; the operations are the same for each sample. Robotized testing laboratories are designed to automate these repetitive operations and process tens of samples simultaneously [73]. Such systems do not produce final results of testings, however, they dramatically reduce time and a risk of a medical personnel contamination [74].

3.11. Cargo delivery

Multiple commercial companies (e.g. Amazon [75] and Yandex [76]) develop autonomous delivery robots to reduce delivery costs [77]. During a pandemic such robots (e.g. in Figure 6(a)) allow preventing undesirable contacts between people and supplying citizens during lockdowns. Moreover, these robots do not require customization, adaptation, or special maintenance except careful disinfection after each delivery. The disinfection could be manual or automatic [45, 78].

3.12. Factory automation and in-place manufacturing

In-place printing [79] in nowadays is a use of personal 3D printers (e.g. [80]) to create required tools and spare parts closer to end users. We extend *in-place printing* term by defining *in-place manufacturing* as a set of manufacturing methods that require low-cost tools and inexpensive materials, which are affordable to techno enthusiasts that attempt – as a part of their hobby – adapting technologies to locally improve their own life [81]. In-place manufacturing could be more flexible and provide faster service when fast adaption and a small batch of products are required [82]. Moreover, during a pandemic with its multiple restrictions and production chains' disruptions, responsible techno enthusiasts are expected to

(a) (b)

Figure 6. (a) Autonomous outdoor delivery robot Avrora Unior [83]; (b) Oxygen valves for respirators [84] (courtesy of Cristian Fracassi).

extend their hobbies to serve the urgent needs of the local community in disease mitigation.

Massive and obligatory quarantine measures change the way industrial enterprises are functioning. Some factories, including food, energy, and medical industries, should continue their work despite pandemic spread since their production is essential for disease control and social service to population [85]. While many modern mass-production industries already had automated a large portion of their production processes [86], others could improve their efficiency by combining existing production technologies with an in-place manufacturing approach [87]. The current pandemic clearly demonstrated a relevance of open-source 3D spare parts for medical devices [84] and accessories for medical personnel [88] (Figure 6(b)). In-place manufacturing could take over such tasks as the production of small-size batches of non-standard parts for local community needs. These measures could decrease unprofitable restructuring and adjustments of industrial enterprises and a need for human personnel on factories, thus limiting unnecessary contacts [89].

4. Adaption for a pandemic and required training classifications

The examples provided in the previous sections form a general picture of robotic tools that are already employed in combating infection. Examples' analysis allowed us to determine patterns of deployments and common properties of robots that are required in pandemic conditions. We suggest two optional classifications, which could serve as guidance for robot designers to better estimate requirements and possible use cases of a particular robot in a pandemic scenario, to improve robots' efficiency and increase deployment speed.

4.1. Adaption level

Robots that could be used in a pandemic scenario split into two groups by their original purpose: *initially constructed* for medical facilities (or purposes) and those, which could be *adapted* for pandemic conditions' use. Table 1 presents this classification.

The first column presents types of robots that were constructed specially for medical purposes and thus do not require further adaptation for a pandemic mitigation related use.

Hardware and software setup of indoor disinfection robots allow performing strictly standardized disinfection procedures and protocols using UV or disinfection chemicals. An individual health screening robot is a mobile or a stationary device that measures, analyzes, and records a particular health parameter (e.g. a body temperature or a blood pressure) of a patient or visitor. Tool disinfection robots and specialized robots

Table 1. Robots classified by initial purpose and adaption possibilities for a pandemic mitigation.

	Adaption level	
Initially constructed for medical purposes	Minimal changes	Significant changes
Indoor disinfection robots	Indoor and outdoor cleaning robots	Robotic manipulators
Individual health screening robots	Indoor and outdoor delivery robots	Outdoor disinfection robots
Tool disinfection robots	Population monitoring UGVs and UAVs	Funeral robots
Specialized laboratory robots	Informational robots	
Basic medical training robots	3D-printers	
Psychological aid robots		
Remote presence systems		
Automated testing systems		

for laboratory research (e.g. analysis of blood samples) reduce the amount of repetitive simple tasks for highly trained personnel and allow them to concentrate on tasks that require more skills and intelligence. Basic medical training robots are used in a cold zone, do not directly contact infected patients or samples, and therefore do not require any additional adjustments for pandemic conditions. Psychological aid robots and remote presence systems only require to undergo additional disinfection after each use in a hot zone.

The second column contains types of robots that were initially constructed for non-medical purposes but could be adapted for pandemic mitigation without significant hardware adjustments. Regular indoor and outdoor cleaning robots might require only to replace sanitizing chemicals and their tanks, and slightly update algorithms, software, and threshold values to consider the difference between regular daily life and pandemic limitations (e.g. the danger level of new chemicals, disinfection schedule). Indoor and outdoor delivery robots require to improve the security and cleanness of containers for transferred objects, to adjust navigation algorithms with regard to pandemic recommendations (e.g. social distance and secure delivery's extraction), and to undergo additional cleaning and disinfection upon return.

Population monitoring UGVs and UAVs are to be equipped with additional sensors that could take non-contact measurements, which correspond to a particular disease feature, and their software should be adjusted in order to analyze and report collected data to disease control centers.

In turn, simple informational robots require only new software modules, which could advise passing by people on disease symptoms and individual safety measures, and a scheduled (preferably automatic) disinfection procedure. More complicated informational robots could combine basic announcer function with individual health screening and population monitoring. For example, they could detect and track a disease carrier, and these would require additional sensors and connectivity.

Finally, 3D-printers require only new CAD models and materials.

The third column contains the types of robots that were initially constructed for non-medical purposes but could be adapted for pandemic mitigation after significant hardware and software adjustments. Robotic manipulators could be adapted to perform a broad variety of activities, including food preparation and packing, dishwashing, laundry, waste collection, patient probe gathering, and vaccination. Even though there already exist robotic solutions for most of these tasks, they all should be significantly adjusted to consider strict requirements of pandemic protocols, in a safe and secure manner with an extended autonomy level, which allows performing without human intervention in hot and warm zones of a medical facility. Outdoor disinfection robots and funeral robots are a new R&D field that came to life due to the current pandemic. For example, while previous funeral robot solutions concentrated only on human-robot interaction (e.g. with a robot in a role of a priest [90] or as an automated cemetery that had been inspired by production processes [91]) the recent pandemic demonstrated that the death-care industry was not ready for such high mortality rate [92]. Therefore new automated approaches in preparation for a burial ceremony, transporting, and respectful burial of infectious corpses are required in order to avoid further spread of the infection while performing these activities in a traditional manner.

As our analysis demonstrated, robots that were initially constructed for medical purposes are more specialized, have a limited number of functions, and take medical requirements into account by design. Specialized medical robots have very high effectiveness and efficiency, and their integration into an existing medical institution workflow is easy. However, their effectiveness and ease of deployment increase the price, therefore, many medical facilities, especially in developing countries, could not afford such robots.

Adapted robots have several obvious disadvantages, such as difficulties in their sanitizing and disinfection (e.g. humanoid robots or psychological aid robots with a sensitive to liquids cover, like Paro, Figure 2), operator training requirements (e.g. teleoperated UAVs), or necessity of additional sensors' integration, which require additional power sources or a redesign of a robot. Yet, since they are manufactured in relatively large numbers and usually have intuitive user interfaces, a large-scale robotic deployment process could be rapid and at more reasonable costs. Good examples of such large-scale successful robotic deployments are UAV [93] and UGV [94, 95] based delivery systems.

4.2. Required training level

Another classification considers robot users. Since robots have a broad variety in their purpose, functionality, and price, different robots require different levels of professional skills and specialized training. Thus, robots are differentiated by a level of specialized skills required to use each particular robot, and we distinguish *no training*, *minimum training*, and *specialized training* groups.

4.2.1. No training required

The lowest level implies that a robot is designed for a wide range of users. Commonly, this category includes robots that are constructed for commercial purposes, e.g. goods delivery robots or remote presence systems. These type of robots have common properties that ensure reliability and ease of use:

- High specialization. They are designed to perform a particular task and it is almost impossible to change their functions without crucial changes in their hardware, which limits adaption possibilities.
- Limited interaction with a user. User-robot interactions are strictly constrained and well-scripted. For example, a delivery robot does not have an interface that allows going beyond its straightforward behavioral algorithm.
- Intuitive and well-designed interfaces provide a comfortable user experience for a broad range of customers.

4.2.2. Minimum training required

The next level of requirements is when a robot user must go through short-term training, which allows them to use the robot properly. Yet, this training does not require technical education or background. Usually, these types of robots are dangerous in case of improper use. For example, UV disinfection, outdoor disinfection, and teleoperated robots require some interaction with a user. If the user misuses the robot, it may severely harm other people or infrastructure in its vicinity. Such robots have some safety mechanisms, however, these measures do not block all potentially harmful actions.

4.2.3. Specialized training required

Most complicated robots could be used only by specially trained personnel, sometimes, this means even a special certification process, technical education, programming, and basic hardware maintenance skills. This group includes highly flexible and high powered devices such as UAVs and robotic manipulators. They require obligatory safety training for users as any mistakes could lead to lethal injury cases. Robots of this category are generally the most flexible and, after proper reprogramming and hardware adjustments, could be used for many purposes. This flexibility leads to sophisticated control schemes and high requirements for users' skills.

5. Robotic deployment framework in medical facilities

In this section, we present a novel integral robotic deployment framework in medical facilities, which follows the standard modern approach of the three disease control zones that was described in Section 2. The proposed framework brings together all pieces of a puzzle with stand-alone robotic solutions (Section 3) and their extensions (Section 4). This section, together with the ethical considerations discussion (Section 6), is the main novel contribution of the paper.

Robots designed to operate with infection carriers in medical facilities should comply with the following requirements:

Ease of cleaning. Robots' housings should have simple shapes that are easy to access for cleaning. Housing materials should be resistant to aggressive cleaning substances and UV radiation.

Improved safety. Personnel and patients are under permanent stress, therefore not only the own actions of a robot must be safe, but unexpected and unpredictable behaviors of surrounding humans should be considered while analyzing safety issues. Each potentially harmful operation (e.g. UV radiation turning on) must have a double-check system to prevent accidents; additional safety measures may include a remote teleoperator control of switching on and off.

Simplified and adapted user interfaces. Medical staff in a hot zone is equipped with glasses, protective suits, and gloves. All these measures increase their safety level, however, decrease their viewing angle, reaction speed, hearing abilities, and fingers' motor skills. Therefore, robots must have simple and relatively large indicators of their state, well-balanced timeouts before potentially harmful operations, and adapted for gloved hands interface.

High operational readiness. Robots should have simple switching on/off procedures and fast self-checking systems. To provide robots' continuous work, they should have easily interchangeable batteries, indicators of expendable materials exhaustion, spare parts availability, etc. These features keep robots ready and safe for immediate action on demand.

Next, we describe the three zones of a robotized infectious hospital, the way humans and robots interact within these zones and move between the zones. Figure 7 demonstrates a high level abstraction of the proposed approach.

Sanitizing procedures for robots are as obligatory as for humans. A variety of these procedures is limited for people and commonly include manual disinfecting with various liquids and change of clothes. Robots, in turn, could be easily sanitized automatically using UV radiation and sanitizing liquid sprays, which increases their value as devices with quick and unmanned maintenance. There are two types of robot disinfection zones in the proposed framework. An intensive disinfection zone (IDZ) between the red zone and the warm zone provides a UV radiation procedure, followed by few rounds of sanitizing liquid spraying and regular cleaning. A mild disinfection

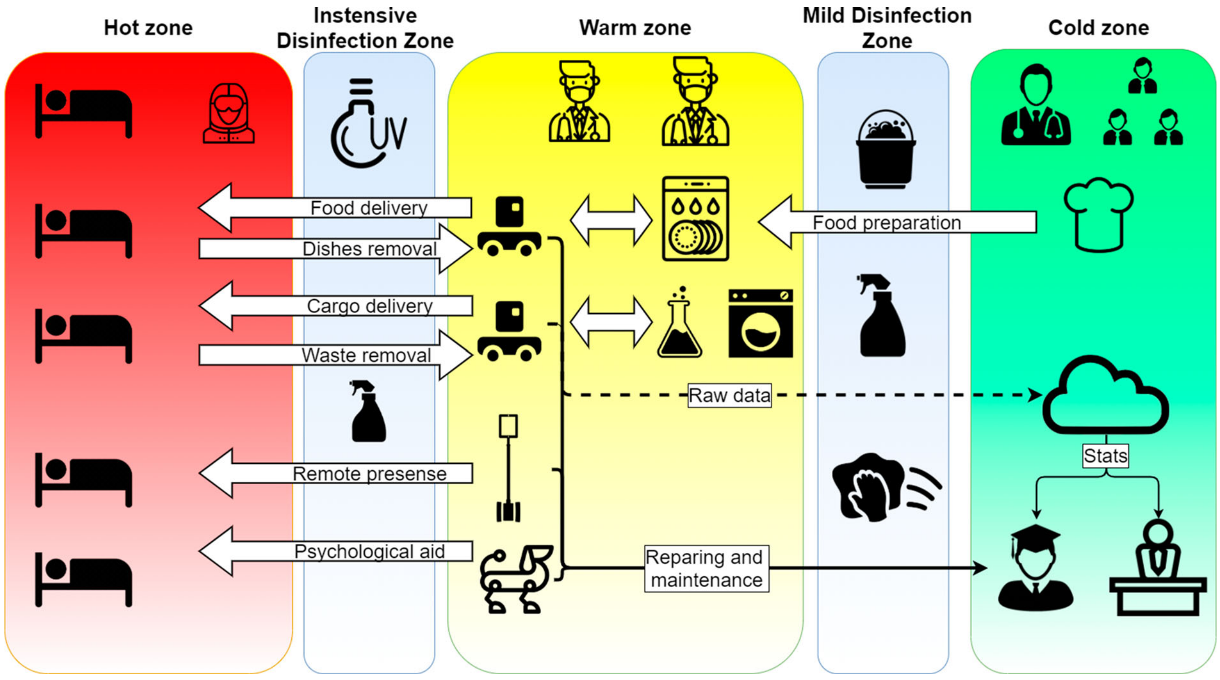


Figure 7. Proposed robotic deployment framework.

zone (MDZ) between the warm zone and the cold zone provides only a single round of sanitizing liquid spraying and regular cleaning.

It is worth mentioning that all activities and human-robot interactions (HRI) follow strict protocols that should be created based on human-human interaction protocols for an infectious hospital. The development of these protocols and their modeling in ROS Gazebo environment [96] is a part of our ongoing work [97].

5.1. Hot zone

Operations in a hot zone imply a high contamination risk for human personnel. Robots are immune to infections, therefore, their usage in the hot zone is preferred to human-provided services. However, robots still carry an infection on their housing surfaces and actuation mechanisms and could spread it via other objects that are carried by the robots between the zones.

Robots enter the hot zone only if required. A request should be expressed explicitly using a predefined schedule or using a direct command from hospital staff or patients. All available to staff or patients commands are defined by corresponding HRI protocols. Since we are dealing with an infectious hospital, each patient within the hot zone is a carrier of a disease or a potential carrier placed under monitoring. Ideally, this requires keeping a single patient within a room, and all deliveries and HRI communications are performed in a setting of a single robot – a single human. While most of the tasks within the hot zone could be delegated to robots, some tasks still require a human medical staff presence. In these cases medical personnel should enter the hot zone in protection suits and the robots should be aware of a possibility to meet the human personnel occasionally and thus require sensor-based reactive mechanisms that allow dynamic obstacles avoidance and interaction.

Operations scheduling should be used for robots performing everyday actions, including:

Food delivery. In the warm zone, a delivery robot undergoes sanitation procedures (with regard to a food sanitation protocol), and an individual secured food container is placed into the robot. Next, the robot passes through an inter-zone disinfection block IDZ, where UV and other types of disinfection are automatically executed. After the delivery, the robot passes IDZ again and returns to the warm zone in order to proceed with the delivery to the next patient, to recharge its battery, or to go through technical maintenance. One of the ways to speed up the delivery process is to serve food containers to multiple patients without returning to the warm zone, but only with a short-time visit of the IDZ in-between. Food deliveries are scheduled with regard to a hospital day plan. Additional food deliveries (e.g. snacks or drinking water) are performed on a patient request via an application on an individual smartphone.

Cargo delivery. This includes delivery of pharmaceuticals and personal items, which could be scheduled or initiated by an individual request. The delivery procedure follows the same flow as for the food delivery.

Dish removal. A robot enters the hot zone via IDZ, collects dishes (that might contain food leftovers), passes again through IDZ, delivers dishes to an organic waste center where they are cleaned from the waste, and next loads them into a dishwasher. To speed up the dish removal procedure in a large hospital it is possible to construct a conveyor belt that takes care of removing organic waste and loading dishwashers. This simplifies the dish removal robot construction and functional but requires infrastructural changes and additional manipulators to sort waste and load dishes.

Waste removal. This includes removal of all other types of waste, which could be scheduled or initiated by an individual request. A waste removal procedure follows the same flow as the dish removal procedure, but on the waste reception end in the warm zone, there should be a waste sorting system that takes care of delivery. The waste removal could be extended to bedclothes change, laundry, and other activities, which require to collect some object(s) from a patient and deliver it to a predefined location for further processing.

Corpse removal. This is one of the most mentally complicated tasks for human personnel that could be delegated to robots. It includes death verification of a patient, contagiousness analysis of remains, a corpse loading, and transferring to a corpse storage room for further processing with regard to standard protocols for each particular type of infection.

Remote presence. This task has three options: health monitoring, professional medical consulting, and individual use. A monitoring robot monitors patient health and should have a set of corresponding onboard sensors that allow taking required body measurements, which might include contact (e.g. take a blood sample or measure blood pressure) or non-contact (e.g. measure body temperature or visually analyze skin lesion) based measurements. Professional consulting and individual remote presence robots perform the same activities of remote human-human communication and the same robot model (with a large screen and good quality onboard camera) could be used for both. Yet, if extended professional consulting capabilities are required, a teleoperated adjustable magnification zoom camera and a high-quality microphone array might be integrated in addition to basic remote presence hardware. Professional consulting is performed by a doctor and could be scheduled, decided after analyzing a patient's recent data collected by a health monitoring robot, or arranged on demand of a patient. An individual remote presence robot gives a patient opportunities to communicate with family members and friends. Its use should be scheduled in advance and limited, similarly to visiting hours in regular hospitals, yet it should consider an opportunity of a limited number of emergent on-demand calls as well. The remote presence robots should undergo disinfection procedures in the IDZ after each use.

Psychological aid. When possible, these robots might have various shapes and functionalities because they serve as intelligent heartwarming toys that temporarily substitute interaction with pets and other people, and therefore it would be beneficial if a patient could have a choice and a variety. After each use, psychological aid robots should undergo disinfection procedures in the IDZ, followed by manual inspection and cleaning.

5.2. Warm zone

Most daily activities that support hospital functioning are performed within the warm zone. Part of these activities could be automated with a help of robots (e.g. dishwashing, laundry) and part are performed manually (e.g. food packaging and sorting, load/unload of delivery robots, lab research, and sample analysis). Yet, as robotics technologies keep developing, with time more tasks could be further automated.

This zone has less contamination risk, however, it is still preferable to follow all the requirements for robots in the hot zone. People in the warm zone use breath protective masks and gloves with a lower level of safety, which allows to equip warm zone robots with high-quality sensor screens and touch panels.

A warm zone is a default place for robots to wait for actions. Here robots undergo an inspection, basic maintenance, and additional manual cleaning if required. The zone should include battery charging stations and storage for charged batteries. In addition, this zone is the main place for robots to synchronize with a central server of a hospital in scheduling and data upload/download procedures. Such centralized structure allows to control robots and collect all required data in a single place. Collected data are processed using AI methods [23, 98] to make predictions and generate recommendations for hospital management. Centralized monitoring is the way for hospital management to increase the effectiveness of robotic deployment, increasing the number of robots used actively and uncovering the causes of idling or misused robots. Robots could travel between the warm zone and the cold zone applying basic disinfection procedures within the MDZ.

5.3. Cold zone

The cold zone includes various hospital services that are not related to direct contact with patients, e.g. food cooking, drug preparation, and sorting, medical personnel resting rooms, etc. It hosts data servers and hospital management offices that are an integral part of the proposed robotic deployment.

The cold zone has minimum constraints for in-zone robots since they do not contact infected persons and do not imply special properties. This category includes most of the existing commercial robotic systems adapted to perform supportive tasks for infection mitigation, e.g. manipulators for heavy deliveries unloading and professional 3D-printers for spare parts. The cold zone is used by robot technicians for repairing and maintenance procedures.

6. Ethical considerations

Researchers highlight a wide range of safety and ethical problems that should be considered prior to robotic deployments. At the time of HRI protocols development researchers should answer complicated questions of moral choices and robots' behavior in cases when mental harm or physical harm to a human is highly possible, unavoidable, or even necessary (e.g. surgery robots). This issue is especially important for medical robots [5, 99, 100] and autopilots [101]. Two main reasons for high attention to these kinds of robots are as follows:

- High level of autonomy. All autopilots and some types of medical robots are designed to act with a minimum level of human intervention. Since an autonomous behavior is their key property, the behavior must be flexible enough to properly react in different situations.
- High cost of an error. Both types of robots replace humans in situations where a high responsibility level is required. Improper reactions easily could become lethal for a patient (for medical robots) or for passengers of the vehicle and surrounding vehicles, and pedestrians (autopilot).

Modern robots that are suitable for the proposed infectious disease hospital framework and other tasks of pandemic mitigation (described in Section 4) have a narrow scope of application, limited autonomy capabilities, limited locomotion speed, and, in many cases, a rather strictly standardized operational environment. Therefore, most problems of highly autonomous robots are irrelevant for them [102, 103]. However, they meet other ethical problems that must be considered to provide proper robotic deployments. The deployment risks could have a technical, psychological, social, or combined nature [104]. This section presents important issues that must be considered prior to a robotic deployment as early as at a stage of HRI protocol development.

Safety: Robots must be safe for human beings during their regular use cases and in emergency cases. Regular use safety means that all professional activities, which were embedded into a robot at design and programming stages, should be safe and should prevent improper use of the robot. This requires an intuitive user interface, predictable for an unprepared lay user interaction algorithms, double-check mechanisms (potentially with a human teleoperator in a loop) for potentially harmful actions, and an integrated self-check safety system of the robot. For example, robots with potentially harmful actuators must be examined intensively and have safety self-blocking mechanisms that are triggered as a function of a potential workspace collision with a human; UV and large-scale disinfection robots should have a teleoperator in a loop and could have additional IoT-integrated security mechanisms that allow monitoring cameras of adjacent locations and predict an unexpected human appearance within a dangerous zone.

Privacy: Robots implicitly store a huge amount of personal data, including names, voices, images and videos, medical history, and other private information. Collected data could be sent for further AI-based [26] or manual analysis and backed up. However, personal data must be elaborately protected in a way that no data leakage or unauthorized access of any third-party, including the robot's manufacturer, could be possible. The privacy issue is relevant to any robot, however, developers of psychological aid and remote presence systems should pay increased attention to guarantee data storage and data transfer security. In particular, crowd screening and security systems that could be used for monitoring and surveillance also have a clear risk of privacy violations. Following legal requirements (e.g. in Europe [105]), monitoring data must be anonymized prior to a further analysis, but this process is difficult to verify and control in practice.

Social deprivation:

Typically, people require everyday social interactions. These interactions could be limited and non-personal, however, loneliness suppresses people and decreases the efficiency of any medical interventions and rehabilitation. Moreover, compulsory social deprivation could be addressed as cruelty [106]. Therefore, robots use could implicitly harm people as humans do not accept them as fully valid members of the society. This problem is hard to completely avoid at the current level of social development since robots are designed to replace human personnel. However, service robots could be designed to be more user-friendly and human-like while taking a precaution of avoiding the Uncanny Valley effect [107].

Law enforcement: Robots are very advanced tools with multiple sensors, actuators, and different movement capabilities. However, they are still tools and thus must be used legally, their users must obey the laws of a hosting country. For example, UAV based monitoring requires special flight permission in most countries; indoor and outdoor disinfection should strictly follow local sanitation rules; 3D-printed parts should not violate intellectual property; personal data should not be shared with third-party organizations; HRI dialogues should avoid vocabulary that could hint on some racial, sexual, religious or individual habitual discrimination, etc. At the same time, robots should be equipped with emergency switches that allow transferring a full teleoperation mode control over a robot to local security forces (police, army, militia, federal military reserve forces, etc.) and government (federal and local administration) on their demand.

Unemployment: Unemployment risk is considered as one of the major problems in process of active robots usage. Robots could be more effective and require less special conditions than people, leading to losing jobs and decreasing employment rate, especially for low skilled jobs.

Bulling: For a vast majority of people, robots are relatively new tools. Human curiosity, fear, or misunderstanding leads to robots' bulling [108], which is more typical for children and young people. Users could intentionally cover robot sensors, create obstacles in the robot's way, etc. Therefore, robots should be ready for such behavior and react properly.

Table 2 corresponds to types of robots that could be applied in pandemic mitigation. Ticks in the table emphasize guaranteed ethical problems of various types that may appear during robots' normal operation. '?' symbol hints at potential ethical problems that could appear in a cause of an occasional or intentional misuse and therefore should be carefully considered by robot manufacturers. The table serves as a starting point for further multidisciplinary research that should precisely define functionality, construction, appearance, and behavior for each type of pandemic mitigation robot viewed through the prism of ethical requirements.

7. Discussion

This paper focused mainly on the role of robotics in a pharmaceutical (medical) approach of fighting pandemics and only a few robotic solutions of non-pharmaceutical approach were mentioned, e.g. outdoor population screening and information spreading robots. Integrating together robotics, AI, big data and IoT technologies within pharmaceutical and non-pharmaceutical interventions has a huge potential, e.g. in enforce compliance [109, 110], surveillance [111, 112], limitation of misinformation and disinformation circulation [113, 114], disease diagnostics [115, 116] and pandemic spread prediction [117, 118]. Yet such use of technologies for pandemic mitigation should be carefully examined from positions of ethics, safety, and security as an accidental or intentional misuse [119–121] as well as malicious actions of hackers [122, 123] could endanger not just a single user of a group of users but might present a serious danger for the national security of an entire country or even cause long-term negative consequences for the entire human race. Moreover, it is not enough to provide just philosophical and technical discussions, but these solutions have to be carefully modeled and tested in simulations prior to their transfer into the real world.

8. Conclusions

Robots are modern tools that allow improving the efficiency of infection mitigation. The paper considered existing methodologies in disease control and proposed a new integrated framework for applying a set of existing robotized assisting tools toward pandemic mitigation. Existing robotic solutions were analyzed and a systematic description of desired robot properties based on their application area and target users was presented. We discussed ethical aspects of robotized assistants performing particular roles within the proposed framework and analyzed their privacy, social deprivation, law enforcement, unemployment, bulling, and safety features with respect to target groups of their users and human employees

Table 2. Types of robots for pandemic mitigation viewed through the prism of ethical requirements.

Robots	Safety	Privacy	Social deprivation	Law enforcement	Unemployment	Bulling
Cleaning and disinfection	✓				✓	?
Basic medical support	✓	✓	✓		✓	?
Remote presence		✓				
In-hospital delivery		?	✓		✓	?
Psychological aid		✓	✓			✓
Isolation tools	✓	✓		✓		✓
Population screening		✓		✓		✓
Large-scale disinfection	✓					
Education on disease			✓			✓
Cargo delivery	✓	?	✓		✓	✓
In-place manufacturing				✓		

Note: A tick corresponds to a guaranteed ethical problem. '?' symbol hints on a potential ethical problem.

that could be replaced by these solutions. The proposed holistic architecture of an automated infectious disease hospital could help to develop robots with high practical applicability and allows to define their functions precisely. Our ongoing work is concentrated on further study of challenges and complexity of the proposed framework, integrating IoT and big data techniques into the framework, development of protocols for human-robot, robot-robot, and robot-infrastructure interactions that will extend the proposed holistic architecture, and their modeling in ROS Gazebo environment in order to move further toward a practical application of the proposed approach.

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