# Chapter 5

# Robotics as an Enabler of Resiliency to Disasters: Promises and Pitfalls

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**Abstract.** The Covid-19 pandemic is a reminder that modern society is still susceptible to multiple types of natural or man-made disasters, which motivates the need to improve resiliency through technological advancement. This article focuses on robotics and the role it can play towards providing resiliency to disasters. The progress in this domain brings the promise of effectively deploying robots in response to life-threatening disasters, which includes highly unstructured setups and hazardous spaces inaccessible or harmful to humans. This article discusses the maturity of robotics technology and explores the needed advances that will allow robots to become more capable and robust in disaster response measures. It also explores how robots can help in making human and natural environments preemptively more resilient without compromising long-term prospects for economic development. Despite its promise, there are also concerns that arise from the deployment of robots. Those discussed relate to safety considerations, privacy infringement, cyber-security, and financial aspects, such as the cost of development and maintenance as well as impact on employment.

**Keywords:** Resiliency · Disasters · Robotics

## 1 Introduction

Human society and activities are often severely disrupted due to high-impact disasters. For instance, the Covid-19 pandemic has significantly affected human daily lives and brought up destabilizing threats to many societal aspects and the economy at a global scale. There is a long list of other disasters in the 21st century that impacted human life, such as terrorist attacks (e.g., the 9/11 events in New York City), earthquakes and tsunamis (e.g., the Indian Ocean tsunami of 2004 and the Haitian Earthquake of 2010, the Japanese Fukushima Daiichi Nuclear Disaster of 2011), as well as recent years of multiple high-impact hurricanes, forest fires and extreme heat waves or droughts. Each of these disasters has caused casualties, infrastructure destruction and significant economic loss [13]. Two billion people were estimated to have been affected by disasters from 2008 to 2017 [15].

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Given the scale of this impact, there is a continuing need for improving the resiliency of human society against disasters, where technology can play a critical role. Here resiliency refers both to preemptive measures and post-disaster responses. As a long-term strategy towards preventing or reducing the probability of a disaster from happening, technology can help fortify infrastructure, supply chains and the natural environment. Similarly, early detection and warning mechanisms, evacuation management tools and efficient deployment of response resources can help with resilience when a disaster can be foreseen. Once a disaster has occurred, appropriate response and containment measures can help a system to recover quickly and minimize losses in the aftermath. Activities that provide resilience range from immediate medical care to long-term clean-up efforts.

Robotics can play a critical role across this spectrum of disaster resilience activities, given significant advancements over the last few decades through more robust mechanisms, faster computational power, improved sensors, access to more data and more efficient algorithms. Today, robots are deployed primarily in industrial and logistics environments, such as assembly lines and warehouses. They are also used in military and space exploration applications, and have some limited presence in domestic and public facility environments, such as homes and hospitals. The annual global sales of robots hit 16.5 billion dollars in 2018 with a historical maximum of 422,000 units installed globally, 55% of which corresponded to service robots for professional use (logistics, inspection and maintenance, medical, agriculture, etc.) [97]. The role of robots in managing public health and infectious diseases was highlighted by the Covid-19 pandemic [122].

This paper examines the ability of robotics to provide persistent resiliency against high-impact disasters both through preemptive measures for fortification and preparation as well as for post-disaster response activities. It focuses on identifying what aspects of robotics technology are mature enough to be already deployable for resiliency. This effort also identifies robotics domains where further investment is needed in order to achieve more comprehensive and robust disaster resilience, without compromising long-term prospects for economic development. This work also examines the challenges and undesirable side-effects that arise from the deployment of robotics technology in this context, together with ideas on potential mitigation efforts of the undesirable side-effects.

### 1.1 Past/Present Robotic Deployments

Robotics has already seen use in responding to and preventing disasters. Perhaps one of the first uses was by the military to diffuse or safely detonate mines (Fig. 1 (b)). Various robots with unique mobility features - such as snake-bots (Fig. 1 (a)) - have been used for search and rescue in the aftermath of geological disasters and extreme storms. Firefighting robots have also been demonstrated (Fig. 1 (c)). Although their potential for impact in this domain is significant, robots have been rather limited in their scope and reliability when pushed to the limits.

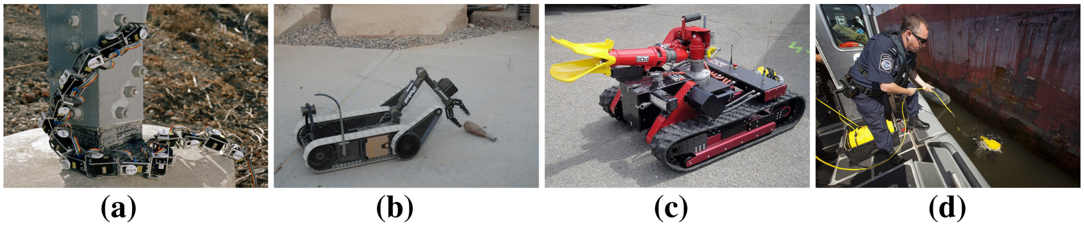

**Fig. 1.** (From Left to Right) (a) A snake-like robot developed by NASA (Image Source: [81] 🄍). Similar designs are deployed for search and rescue after earthquakes. (b) iRobot's PackBot most commonly used to detect and diffuse improvised explosive devices (Image Source: [23] 🄍). (c) A POK Jupiter firefighting robot (Image Source: [94] 🅭🅯🄎). (d) An aquatic robot deployed under a ship to inspect it (Image Source: [34] 🄍).

For instance, in March of 2011 when a tsunami hit Japan's Fukushima-Daiichi nuclear plant, robots were deployed to assess damage and attempt cleanup/repair. Unfortunately, many of the robots did not accomplish their designated tasks due to the challenges of navigating a highly unstructured environment and performing complex manipulation [36]. For similar reasons, there has not been wide deployment of firefighting robots or search and rescue robots to help move debris in addition to navigating through it. Fortunately, recent developments in robotics could push the deployments of robots into a larger variety of environments in order to deal with more disasters.

### 1.2 Examples of Robotics Technology

Robotics encompasses a large variety of systems, which can potentially be deployed to provide resiliency against a wide variety of disasters.

**Autonomous Ground Vehicles (AGV).** AGVs, such as autonomous vehicles, have advanced and are able to self-localize and navigate in structured spaces with minimal human intervention and increasingly in dynamic and unstructured spaces [41,69,95]. Despite this progress, there is still significant effort required for wide, safe deployments.

**Unmanned Aerial Vehicles (UAV).** Aerial robots, such as drones and unmanned helicopters, are capable of autonomously flying and hovering in the air. This allows them to quickly reach areas, which are inaccessible to ground vehicles [19,84,91].

**Autonomous Underwater Vehicles (AUV).** Marine robots, such as automated submarines, are capable of navigating in the water and exploring underwater environments. They are increasingly deployed to monitor the quality of the ocean or search for debris [39,126].

**Robotic Manipulators.** Robotic arms and hands are built for tasks that require manipulating objects, such as picking and placing, reorienting, pushing, changing the form of an object or rearranging multiple objects [61,64].

They have many industrial applications, such as bin picking [40,42] and part-assembly [2,56]. These robots typically have many degrees of freedom (DOF) and are often mounted on a fixed base to ensure high precision.

**Mobile Manipulators.** An extension of the above category, where mobile robots carry manipulators, they combine the advantages of mobility from AGVs/UAVs/AUVs and the manipulation ability of robotic arms and hands. This type of robot is needed for tasks that involve both navigation and manipulation, such as debris removal [27,120].

**Humanoid Robots.** Humanoid robots are designed to have a human-like form that allows them to be easily deployed in spaces made for people. They can perform bi-pedal locomotion over non-flat terrains [3,54], coordinate two arms for manipulation, and more naturally interact with people [59,117].

**Other Bio-inspired Robots.** Other types of bio-inspired robots, such as snake-like robots, are inspired by non-human biological systems [32]. Mimicking their counterparts, they usually have the appropriate size, form and agility for solving tasks in natural environments [71]. They can also form large collectives, such as robot swarms [72,90].

## 1.3 Fundamental Challenges for Robotics Technology

Across all of these types of robots, there is a sequence of fundamental robotics problems that need to be addressed in order to endow the corresponding systems with the ability to solve real-world tasks.

**Robot Mechanisms and Design.** This area encompasses mechanisms and actuators that can: (i) generate sufficiently high and precise forces and torques without significant energy expenditure, (ii) withstand punishing impacts, (iii) be safe for interaction with people, and (iv) be adaptive to different domains. A well-designed robot must withstand the adversity of its environment, such as that of a nuclear plant [83,98] or of the deep ocean [105].

**Sensing and Computer Vision.** Robots need to perceive and understand their surroundings, e.g., autonomous cars need to detect pedestrians and other vehicles typically through visual sensors [65,74,102,106]. Non-visual sensors, such as tactile or proprioception sensors, can also provide useful data about the robot's environment or its own state.

**Simultaneous Localization and Mapping (SLAM).** SLAM is a key technique in robot navigation where robots are exploring unknown environments or where the robot's location is critical in solving a task. SLAM techniques are linked to the underlying sensing technology used, such as monocular vision or LiDAR [31]. SLAM in dynamic environments [124] or for multi-robot systems [129] can be more challenging but is needed in many applications.

**Telerobotics.** Though full autonomy is desirable, telerobotics, i.e., the remote operation or semi-autonomous control of robots, is sufficient and often easier to achieve for many tasks but introduces its own cognitive load challenges. Telepresence [115] and telemedicine [62] are example high-demand tasks that relate to disaster events [29].

**Motion Control and Planning.** An autonomous robot has to determine how to navigate, locomote in or manipulate its environment. Intelligent planning involves often safe obstacle avoidance [87,114] and determining feasible [67] and optimized [58,99] sequences of actions [51,103] to solve a target task. Control involves the safe and effective execution of the corresponding actions as a fast, online response to sensory input.

**Learning.** Robots can improve their performance given prior experience and data. Machine learning approaches can be used to improve components of a robot, such as perception or planning, or for end-to-end learning of navigation [121] and manipulation behaviors [63], and transfer learning to bridge the simulation to reality gap (sim2real) [38].

**Multi-robot Systems.** Many applications require more than one robot [21,75]. Coordinating teams of robots poses non-trivial challenges both in terms of efficiency [125] and safety [24], such as ensuring the robots avoid collisions among themselves while fulfilling the tasks more effectively as more resources are used.

**Human-robot Interaction (HRI).** Robots need to interact with people in tasks such as emergency evacuation [127] or collaborative assembly [44]. In addition, robots need to be able to understand human task specification. Similarly, people should not feel threatened and surprised by robots' actions [60].

## 2 Robotics as an Enabler of Resiliency

Robotics technology can help in resiliency against disasters in two distinct ways: (1) via taking measures for averting disasters or preparing a system to better deal with them once they occur (**preemptive measures**) and (2) via responding to disasters and minimizing their impact through technological resiliency (**post-disaster responses**). Figure 2 indicates the 9 Technology Readiness Levels

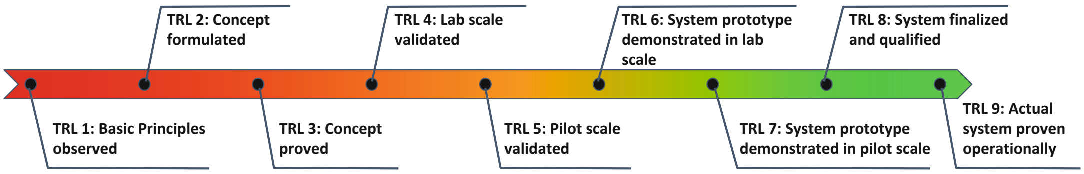

**Fig. 2.** The Technology Readiness Level (TRL) arrow above indicates the 9 levels of technology readiness. The higher the number, the more mature the technology is. Red phases are early stages of the technology (TRL 1–3); orange phases are transitional stages where the technology is validated conceptually and in small scale (TRL 4–6), and green phases are operational stages where the technology is validated in the industry, and is ready to be used in real applications (TRL 7–9). (Color figure online)

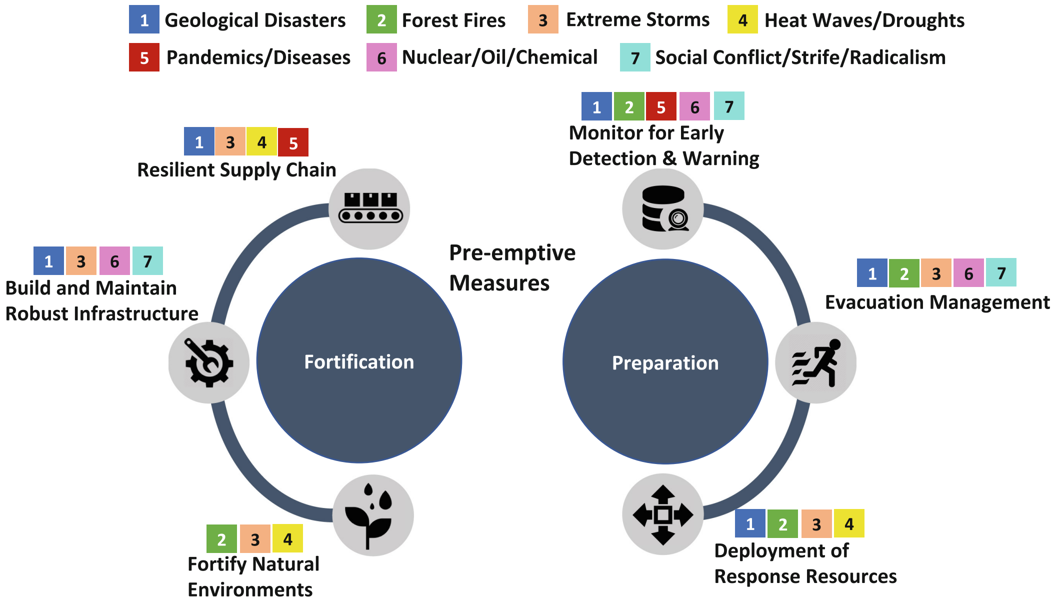

**Fig. 3.** Robotics can enable the above "preemptive measures" for resiliency. This paper splits preemptive measures into two categories: (1) Fortification and (2) Preparation (dark blue circles), each with its own sub-categories (grey circles). The number-indexed icons with associated colors indicate types of disasters. They appear next to preemptive measures that are more relevant to them. (Color figure online)

according to NASA [12], which provide a metric for estimating the maturity of technology. This paper adopts this metric in the context of evaluating robotics technology to enable resiliency against disasters. For each category below, the paper provides our TRL scores as the evaluation at the end of each discussion.

### 2.1 Robotics for Preemptive Measures

This paper summarizes in Fig. 3 the resiliency activities related to preemptive measures, which reduce the chance of accidents or machine failures and help with disaster preparation. Preemptive measures are further categorized into those long-term "Fortification" measures and short-term "Preparation" measures.

**Resilient Supply Chain (Fortification).** An important factor to make a community less vulnerable to disasters is to ensure an operational manufacturing and logistics chain to deliver essential supplies (e.g., first-aid, food, medicine, disinfectants, etc.). The sudden occurrence of a disaster can create a shortage of essential supplies in the proximity of an affected area. Robot manipulators can be used both in production and distribution of supplies, especially those not typically produced in high quantities in ordinary times. For instance, during the Covid-19 pandemic there was a need to convert factory floors towards producing simple hygiene and protection products. Britain's Wales-based Royal Mint produced plastic visors, one every 10 s, to meet the public need, and Minnesota-based Protolabs moved to making parts for Covid-19 test kits using 3D printing;

they were able to produce over 10,000 parts on short notice [79]. Automation technology is needed that allows production lines to be adapted on demand to such drastic changes in supply needs. Given the increasing demand for 3D fabrication, further research is needed in the area of robotic spatial extrusion, an alternative to traditional layer-based 3D printing [46].

On the distribution side of supply chain, automated warehouses have become increasingly popular as they reduce dependence on manual labor [1,7]. Various types of robots can perform diverse tasks including picking, moving, and sorting. This often requires the use of multiple AGVs in the same workspace [50], such as robots that lift shelves of goods and transfer them to human pickers without colliding with each other [47]. In addition, increasing focus in the area of object rearrangement [100] is yielding more efficient methods of performing packing tasks, such as preparing packages for delivery.

*TRL* 7–9: Robotics technology for manufacturing and distribution of supplies is becoming increasingly mature. 3D printing is increasingly used in production, but maturity varies on materials - e.g. 9 for plastics but 7 for metals. Effective adaptability to changing demand requires additional investment.

**Build and Maintain Robust Infrastructure (Fortification).** Robots, such as drones and ground vehicles, can be deployed to monitor the health of critical infrastructure. Such surveillance tasks, together with frequent maintenance, that can also be partly automated through robotics, could drastically reduce failures in factories, power-plants, oil rigs or civic infrastructure. Building more secure and safe new facilities is also highly desirable. Nevertheless, constructing such high-profile facilities is both costly and time-consuming. Part of the cost involves manual labor and associated safety measures during construction as well as the requirements for high precision. Leveraging automation could reduce the associated costs as well as injury risks for workers that may arise from interaction with manually controlled heavy machinery (drills, excavators, and cranes). Mobile manipulators can be envisioned as construction and maintenance robots, which navigate sites as well as lift and assemble heavy materials. One approach to handling these heavy load tasks is to utilize the existing machinery and connect it to a computer with advanced software. Companies like Built Robotics [4] integrate artificial intelligence (AI) systems into off-the-shelf equipment, making them operate autonomously. While the prospect of deploying fully autonomous construction robots on a large scale is a future vision, telerobotics [108] and exoskeletons can be deployed more heavily to ensure high efficiency and to lower the risk of injuries.

*TRL* 4–6: for teleoperation and surveillance tasks; 1–3: for autonomy and construction/maintenance.

**Fortify Natural Environments (Fortification).** It is important to consider when and where to alter the natural environment in order to reduce the possibility of a disaster. For example, clearing away trees from power lines can reduce the chance of a power outage before a storm. Similarly, clearing out buffer zones in forests can reduce the spread of disastrous fires. Fortifying a water supply network can help agriculture to better manage resources in the case of a drought. While these tasks are routinely performed by humans today, they are both risky and expensive to perform at a large scale. There has been limited use of robots in these domains, however, given the difficulty of deploying robots in such highly unstructured setups. At the same time, there are research efforts on robots that interact with the natural environment without much human intervention. For example, European researchers are working on a mobile manipulator called TrimBot [104] which can trim vegetation. The underlying technology focusing on gardening is an example of how robots can be deployed in forestry-fortification tasks. There are many challenges, however, in hardening such technology; these lie in the integration of several key components: computer vision to understand complex natural environments, 3D mapping techniques for navigation, and manipulation to remove dead plants, trim dry leaves, and plant new trees. So far, forest fire prevention humanoid robots are limited to the design phase [33].

*TRL* 1–3: for nature fortifying robots.

**Monitor for Early Detection and Warning (Preparation).** Early detection and monitoring can be effective for minimizing losses in many disasters. For instance, knowing early that a fire started and is growing can speed up evacuation and counter-measures before the disaster gets out of hand. In addition, predicting the duration and magnitude of potential disasters can better inform as to if and where further attention is needed. Furthermore, the detection of warning signals including "behavior pattern recognition" [88] is critical to combat terrorist attacks. Thanks to advances in machine learning and data mining, predictive models of disasters can be obtained through the analysis of data from previous events. Collecting data, however, could be burdensome and even impossible in disaster-prone areas which are not naturally accessible. In these cases, robots can help to both gather data and provide immediate alert of potential disasters through real-time monitoring. Liquid Robotics launched an autonomous Wave Glider robot, a marine robot outfitted with a hydrophone, time-lapse camera, and satellite uplink to communicate with a sensor package on the ocean floor [66]. It looks for changes in water pressure and magnetic fields that indicate whether a tsunami has formed. The concept of fire-detecting robots is also on the horizon as Insight Robotics is developing an early wildfire detection system that combines a high-precision, pan-tilt robot with thermal imaging sensors and advanced vision technology [8]. Given its ability to collect temperature data, it is now being considered for measuring body temperature in the mass screening of fever candidates. It can reduce human labor and lower the risk of testing staff being exposed to infected people in the Covid-19 pandemic.

*TRL* 4–6: Some of the technologies are currently at the level of minimum viable products (MVP).

**Evacuation Management (Preparation).** Some unfortunate tragedies due to disasters occur during the evacuation process. For example, in response to the possibility of hurricane Rita hitting Texas in 2005, over 100 people died during the evacuation because heavy traffic caused people to get stuck in traffic jams during a heat wave [11]. Better communicating and guiding an evacuation can help people be more resilient in escaping disasters that are not preventable. There are two main areas where robotics can help: one is deployment of more intelligent or driver-less vehicles (AGVs) and the other is effective means of human-robot interaction during emergencies.

Introducing driverless cars is predicted to significantly lower chaos caused by panic during an evacuation [28]. Automated cars are emotionless when facing dense crowding and traffic disturbances, and are capable of taking more responsive actions while maintaining high accuracy. Before reaching the wide-spread adoption of autonomous vehicles, drones and other types of mobile robots can be used to communicate information to human drivers. Inside buildings, evacuees tend to follow the crowd to find an exit, which can cause gridlock and potentially trampling. Recent work [82] proposes effective evacuation strategies for humanoid robots to positively take advantage of and influence "follow the crowd" behavior. The idea is to assign mobile shepherding robots that lead evacuees to a particular exit and stationary handoff robots that use gestures or verbal commands to direct the evacuees to another robot. This type of human-robot and robot-robot interaction shows promise in improving effectiveness of future evacuations.

*TRL* 4–6: for autonomous driving technology; 1–3: for evacuation-guiding robots.

**Deployment of Response Resources (Preparation).** Managing response resources in disaster-prone regions ahead of time is an effective way to alleviate the negative impact of a disaster. This can be achieved by building better transport networks for both people and supplies. Robots are able to distribute response resources both in a shorter period of time and more rationally than humans can. In the event of a drought, for instance, aerial robots and UAVs like drones can take prompt action and deliver water to where it is most needed. In general, due to high precision, such robots could be used to more efficiently water crops [5]. In fact, in drought-stricken California, farmers are using drones as drip systems that save them 40–50% on the water that they previously used [6]. The water savings by these intelligent systems help farmers survive through heat waves and droughts. A future direction to take would be to improve the sensing and vision of the drones (e.g., using infrared cameras) to analyze the coloration of plants and accurately identify the regions in lack of water.

*TRL* 7: Although drones are viable, there is room for improvement in terms of sensing and vision.

## 2.2 Robotics for Post-disaster Response

This paper summarizes in Fig. 4 the resiliency activities related to post-disaster responses, which minimize loss of life and reduce the recovery time, i.e., time required to rebuild damaged infrastructure and biotopes after a disaster has taken place. Post-disaster responses are further categorized into those responses focused on “Infrastructure and Nature” and “People”.

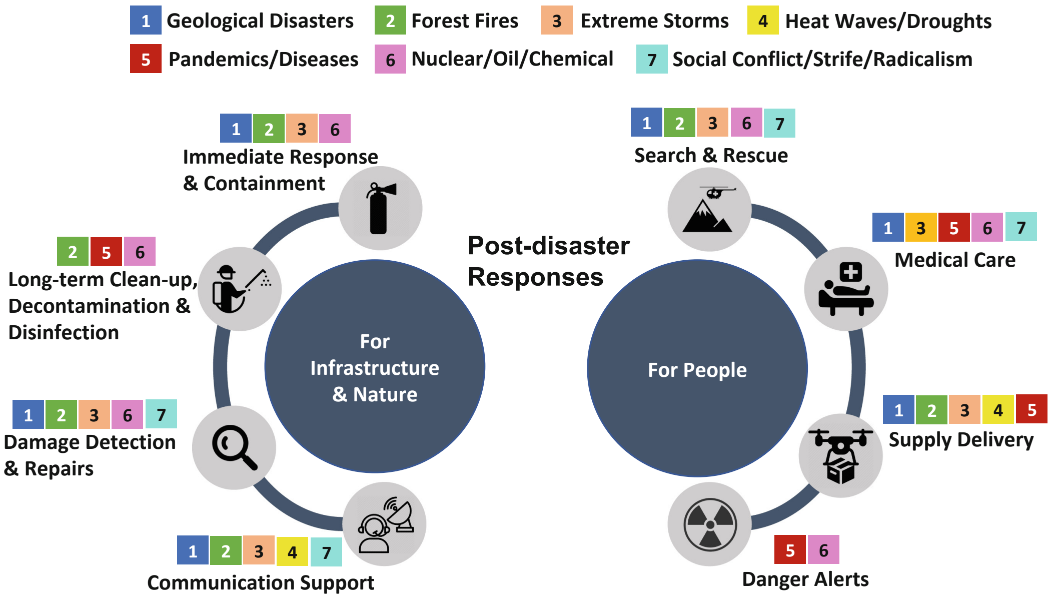

**Fig. 4.** Robotics can enable the above “post-disaster” responses for resiliency. This paper splits post-disaster measures into two categories: (1) For People and (2) For Infrastructure and Nature (dark blue circles), each with its own sub-categories (grey circles). The number-indexed icons with associated colors indicate types of disasters. They appear next to preemptive measures that are more relevant to them. (Color figure online)

**Search and Rescue (People).** Timely search and rescue work is essential for victims in geological disasters, nuclear/chemical accidents, and terrorist attacks. A major challenge in search and rescue work arises from navigating adverse and dangerous environments. Rescue teams could face debris from fallen buildings after earthquakes, dense vegetation in forests, and high levels of radiation in contaminated nuclear plants. Robots have the advantage of being less vulnerable and more expendable but they are generally less mobile. Researchers are pushing robot mobility by exploring different mechanisms of motion. For instance, bio-inspired spider-like and snake-like robots are being developed to search and rescue people trapped in the places which are hard for rescue teams to see or reach. In addition to mechanical design advances, rescue robots perform SLAM to effectively localize themselves [113] and multi-robot coordination [73]. Future emphasis will be put on coordinating robots to maximize search coverage. For instance, drones can be dispatched to survey large areas such as entire cities or forests [128].

*TRL* 5–7: UAVs are currently more mobile but limited by sensor range and bio-inspired robots are still in relatively early stages of control.

**Medical Care (People).** Fast and effective medical care can save lives in the aftermath of a disaster and can help prevent bio-disasters. A common challenge for the medical community during disasters is the sudden influx of patients. Perhaps more lacking than space and equipment are the medical staff themselves. Telerobotics could be used by offsite staff to quickly look at and possibly treat patients before a doctor becomes available onsite. There are telepresence robots on the market already such as the Double telepresence robot [76]. Even for diagnosis, though, such robots currently lack maneuverability of cameras and any bio-medical imaging sensors. Care is also needed for protecting medical staff from infectious diseases. Teleoperated robots lower the risk of medical worker infection by limiting their exposure. Furthermore, robots that could sanitize rooms and medical equipment regularly without the need of an operator could speed up pre/post patient prep. Already during the Ebola epidemic, germ zapping robots were deployed in hospitals to decontaminate a room by blasting ultraviolet light into it [78]. For such robots, designing optimal coverage paths is an ongoing focus of research [45,57].

*TRL* 6–7: Telerobotics are advanced but not yet proven in mission critical settings.

**Supply Delivery (People).** First-aid essentials for earthquake victims, food for people left stranded by storms, fire extinguishers for rangers fighting forests fires, and high-quality masks for medical staff fighting viruses are in desperate need. Such situations pose challenges of limited accessibility to remote or isolated regions and high demand exceeding the capacity for timely delivery. After the outbreak of Covid-19, the demand for doorstep delivery dramatically increased while couriers tried to minimize risk of exposure. Intelligent delivery systems can be used to deliver goods to the door without human involvement. Logistics company DoorDash has started providing food delivery with minimal human interaction by using Starship Technologies' ground robots [109]. UAVs have also been notably explored by Amazon for more general package delivery [85]. UAVs have the added benefit of avoiding traffic but are limited by the weight of goods they can carry. An interesting direction is to design an efficient truck-drone or truck-robot system where the truck aims for long-distance delivery [92] and then the drone/mobile robots arm for last-mile delivery [101] to meet high demand.

*TRL* 6: Fundamental technology is mature but policies for public operation need further research/testing.

**Danger Alerts (People).** Besides rescuing or curing those who fall victim to a disaster, it is also critical to prevent those who survive from falling victim to the aftermath and lasting effects. For instance, to prevent disaster escalation, warning signs and protective barriers can deter or prevent people from further danger. Workers setting up such barriers might expose themselves to the hazardous environment and the affected region or facility might be too large to cover all entry points. Robots can tackle unfavorable working conditions and their behavior is reproducible, thus allowing for more scalable solutions. Small mobile robots with sensors can be dispatched on site to guard certain areas [43], detecting and warning people from approaching danger. Humanoid robots for this task would be more effective at getting peoples' attention [123] but UAVs would be more practical for covering larger areas quickly.

*TRL* 3: How robots interact with people and alert to surrounding dangers still requires fundamental human-robot interaction (HRI) research.

**Immediate Response and Containment (Infrastructure and Nature).** Immediate actions are needed to reduce the damage from/to the environment and infrastructure after a disaster. Robots are good at immediate response and containment due to durable hardware and fast computational ability. For instance, high-speed helicopters can pour heavy water or sand buckets over fires which are beyond the reach of firefighters. Moreover, a fleet of UAVs that periodically survey a forest to detect wildfires could respond instantly to a smaller fire whereas people typically won't notice until much later [20]. Similar style automation could be used for snow clearance vehicles [68]. The quickened response to clearing snow could greatly improve traffic flow during the winter and minimize road closures.

*TRL* 7: Semi-automated machines that are deployed in large scale but full autonomy is a work-in-progress.

**Long-term Clean Up, Decontamination and Disinfection (Infrastructure and Nature).** Though quick action can minimize problems before they get worse, if a disaster does get out of control (such as a forest fire or a nuclear/oil/chemical accident) it can leave behind an unfavorable environment which needs long-term efforts to clean up. As robots are less vulnerable to adverse conditions, they are increasingly used for this type of work. However, disaster cleanup requires specialized mobile manipulators depending on the scenario. For instance, STR-1 robots have been placed on the roof of nuclear plants to clean up destroyed reactors and debris, which mitigated the aftermath of the nuclear leak of the Chernobyl reactor containment walls [55]. Timely clean-up efforts are also important for oil spills as water can spread toxins quickly depending on currents and winds. MIT has been developing a fleet of marine robots called Seaswarm [107] which are designed to clean up oil spills quickly and relatively cheaply. In terms of virus disinfection, remote-controlled ground robots are also used in China to disinfect neighborhoods daily amid the Covid-19 outbreak to ensure a safer environment for residents [48]. The future focus is more on whether they can be in full autonomy and make decisions without human intervention.

*TRL* 6–9: Special purpose cleaning robots have been deployed but their effectiveness and level of autonomy vary.

**Damage Detection and Repairs (Infrastructure and Nature).** Quick detection of damage to infrastructure can prevent further destruction in a potential aftershock. Such detection needs high accuracy and undisturbed reasoning, which are the advantages of robots over humans. In addition to navigation challenges, robots performing detection tasks are faced with perception and vision challenges in actually identifying/sensing issues. During the nuclear leak in Fukushima, Japan, the Japanese investigation team dispatched a robot manipulator equipped with dedicate sensors and gauges to identify the main source of the nuclear leak and detect if the danger had been eliminated [25]. There is also active research on designing mobile robots equipped with 2D laser scanners [119] to detect road surface damage; this is especially important after an earthquake or a volcanic eruption occurs. Monitoring technology can also be used to detect weak links in heavy machinery, factories, and power grids. One such technique is motion amplification, currently deployed by RDI Technologies, which helps detect faulty machine behavior by visually exaggerating small vibrations through image processing [10]. It remains a challenge on the mechanism design of such robots so that they can be placed into small regions without the risk of damaging the equipment on the robots.

*TRL* 7–8: Machines are pretty good at identifying damage or possible weak points but distributing them efficiently to survey infrastructure has plenty of room for improvement.

**Communication Support (Infrastructure and Nature).** When a disaster such as a geological disaster or a forest fire occurs in a remote area, the ability to maintain communication is very important in order to properly respond to the disaster and keep people safe. One key task is to gather accurate disaster information on site for leaders to make wise decisions. Due to limited human access to those regions, ground vehicles (AGVs) and aerial robots (UAVs) can be used to coordinate with each other to gather information [77,84]. Robots can not only get disaster information on site for the needs of rescue teams, but also successfully gather those for the needs of victims on site. This requires that robots have excellent sensing and analytical tools to locate victims [93], so as to provide guidance for rescue. The deployment of these robots requires many advanced techniques including SLAM [110].

Another important task is to provide backup for existing human communication channels (e.g. phone and internet). If a storm knocks out power in a region and is expected to become even more dangerous, people might not realize the need to evacuate before it is too late. Deploying drones to either provide temporary wireless networks [70] or even dropping warning pamphlets at peoples' doorsteps could prevent people from getting trapped in such situations. Furthermore, the same temporary communication networks could be used for search and rescue teams [86] to improve reliability of government facilities so as to provide extra security in case of a national security incident.

*TRL* 6: SLAM techniques have been broadly used. However, multi-robot interaction is still challenging especially as the number of robots increases and when centralized communication is not available.

### 2.3 Summary of Robotics Technology for Resiliency Activities

Table 1 summarizes which robotics technology (column 1) applies to which resiliency activities discussed in Sects. 2.1 and 2.2 (column 2) and the types

**Table 1.** The table summarizes which robotics technology (column 1) applies to which resilience activities (column 2) and the types of robots involved (column 3) in using the robot technology for the resilience activities.

| Robotics Technology | For Resiliency Activities | Types of Robots |
|---|---|---|
| Additive Manufacturing | Resilient Supply Chain | Robotic Manipulators |
| Logistics Robots | Resilient Supply Chain<br>Supply Delivery | Autonomous Ground Vehicles (AGV)<br>Unmanned Aerial Vehicles (UAV)<br>Robotic Manipulators |
| Construction/Infrastructure Robotics | Build and Maintain Robust Infrastructure<br>Immediate Response and Containment | Mobile Manipulators<br>Unmanned Aerial Vehicles (UAV) |
| Forestry Robotics | Fortify Natural Environments | Mobile Manipulators |
| Data Collection and Hazard Detection | Monitor for Early Detection and Warning<br>Danger Alerts<br>Damage Detection and Repairs | Autonomous Ground Vehicles (AGV)<br>Autonomous Underwater Vehicles (AUV) |
| Driverless Cars | Evacuation Management<br>Deployment of Response Resources | Autonomous Ground Vehicles (AGV) |
| Human-robot Coordination | Evacuation Management<br>Danger Alerts | Humanoid Robot |
| Drones | Deployment of Response Resources<br>Search and Rescue<br>Supply Delivery<br>Communication Support | Unmanned Aerial Vehicles (UAV) |
| Rescue Robots | Search and Rescue<br>Communication Support | Autonomous Ground Vehicles (AGV)<br>Bio-inspired Robots |
| Medical Robots | Medical Care | Robotic Manipulators<br>Humanoid Robots<br>Bio-inspired Robots |
| Disinfectant Robots | Medical Care<br>Immediate Response and Containment<br>Long-term Clean up, Decontamination and Disinfection | Autonomous Ground Vehicles (AGV)<br>Autonomous Underwater Vehicles (AUV)<br>Mobile Manipulators |

of robots introduced in Sect. 1.1 involved (column 3). There are many types of robotics technologies, at varying levels of maturity, that can aid in both preemptive measures and post-disaster responses to strengthen resiliency against disasters. Broadly speaking, the robotics technologies that rely on simpler movement modalities (autonomous vehicles, warehouse robots, drones) are more mature and even deployed towards some of the useful resiliency activities. Such technologies would gain more benefit from better sensor hardware/software and distributed communication methods. The less mature robotics technologies are predominantly those that deal with more complex movement modalities (bio-inspired movement, unstructured environments), dexterous manipulation tasks (assembly, rearrangement), and human interaction. Such technologies still need fundamental research and experiments involving new algorithmic and hardware ideas before becoming practical for deployment in disaster resiliency tasks.

When considering strategies for disaster resilience, it is important to know which technologies are available now, which can be pushed to work soon, and which should be developed in the long term for future use. This information alone, however, is not enough to fully make decisions on which resilience actions to take. It is important to also consider the negative consequences that can result from the use of robotics technology whether by intentional abuse or negligent misuse, which is the topic of the next section.

## 3 Pitfalls of Robotics Deployment for Disaster Resiliency

While robots enable resiliency to disasters, their deployment can also result in side effects if not executed properly. This section brings up such potential undesirable consequences resulting from either intentional or negligent application of robotics technology and suggests general policies and broad guidelines to mitigate the negative impact. The proposed guidelines in this section reflect the opinions of the authors, and not necessarily of any cited works. In fact, we want to stress that as technology itself is developing, careful consideration and further socio-technological research is needed to inform practical policies for the deployment of specific types of robotics technology. Figure 5 summarizes potential undesirable consequences.

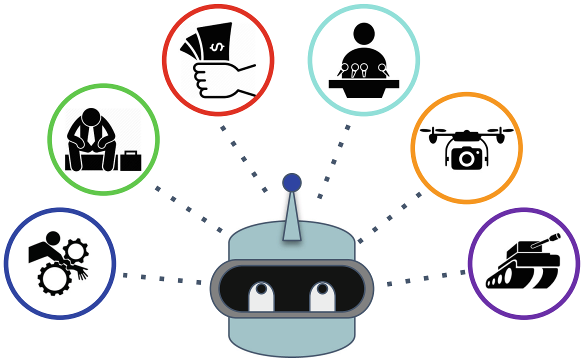

**Fig. 5.** Potential undesirable consequences from the deployment of robotics technology as a resiliency strategy include but are not limited to (from left to right circles): (1) Safety Concerns; (2) Impact on Employment; (3) Size of Investment; (4) Unbalanced Expectations and Reactions; (5) Privacy Infringement and Cyber Security; (6) Undesirable Uses of the Same Technology.

**Robotics Safety Concerns.** Industrial robots are generally precise, powerful and fast. Therefore they are deployed in assembly lines and warehouses to achieve high efficiency and throughput. These good features, however, are also sources of potential danger for humans that are in proximity to or interact with robots. The fast and unpredictable motion of a robot manipulator leaves little time for an operator to respond and thus can cause permanent injury or even death. In 2015, a worker at a Volkswagen plant was grabbed by a robot arm and smashed into a metal plate [37], which is just one of approximately 40 robot-related occupational accidents reported since 1988 [9]. Such accidents may even happen more frequently during a disaster where supply chains and autonomous delivery are in high demand. Workers and robot operators are asked to take longer shifts to meet manufacturing and distribution demand. Fatigue increases the risks of unsafe robot operation, and can delay human reaction to malfunctioning robots. Furthermore, the number of robotic failure modes in more unstructured setups, such as in natural environments or for post-disaster responses, can be significantly higher, and human supervision is needed. In the domain of surgical robots where robots are expected to perform super-accurate minimal invasive surgeries, a study reported that at least 144 deaths and more than 1000 injuries are linked to robotic malfunction during surgery over a 14-year period in the US [14]. If surgical robots are going to see increased use during disasters where doctors are in short supply, technical difficulties and complications need to be addressed.

*Mitigation Strategies*:

1. Regardless of demand, established safety protocols and warning systems [30] for traditional rigid robot manipulators must be enforced at all times. This typically includes the physical separation between traditional robotic manipulators and human workers/operators.
2. Safety concerns motivate the transition from traditional to collaborative robots, which are safer to operate in close proximity to human workers. Such robots have compliant mechanisms that allow them to safely stop when unexpected collisions are detected.
3. Safety protocols need to be defined for the operation of robots in unstructured domains. Safety training, not just for robot operators, but also for other people in the vicinity of robots, is needed and should not be overlooked even before time-critical deployments.
4. Robot exoskeletons have been increasingly used to provide protection and endurance for workers so as to reduce failure from handling machines. Side effects from body contact with robot exoskeletons, such as excessive pressure or tension, are not well known and should be examined further.
5. Human operators of robots require sufficient breaks and task variety in their daily shift so as to maximize alertness during robot supervision.

**Impact on Employment.** Technology displacing human laborers has been a constantly re-emerging concern. In the long term, advancement in technology can increase job opportunities, in the short term, however, sudden deployment of technology without concern for people can cause waves of unemployment. It has been argued that about 1.7 million manufacturing jobs world-wide have been lost to robots since 2000 [16]. Tangentially, unemployment can further increase in the event of a disaster; many jobs were lost at the peak of the Covid-19 pandemic [96] as companies were reducing in-person interaction or due to lost revenue. Though such unemployment is mainly due to the pandemic, not robot deployment, arguments can be made that job replacement is likely to continue with the objective of minimizing human contact and saving labor cost. This trend has already spread from manufacturing industry to healthcare; more robots have been used in hospitals to disinfect areas, measure patients' temperatures and deliver medicine. They can do it without getting anyone else (both care providers and the patients) infected [49]. The robots are also increasingly deployed in restaurants and may reshape the industry after the pandemic. At the end of the day, if a machine costs less to maintain than the wages for an "equivalent" number of workers, then companies will be incentivized not to rehire people.

*Mitigation Strategies*:

1. The machines deployed in factories and warehouses need monitoring and maintenance work. Training existing workers to operate and repair the robots can effectively reduce job loss while increasing safety and resiliency. Though robots can replace human laborers, new human tasks can be defined that involve the operation and coordination of the corresponding tools. Other jobs will arise from the need to understand and explain accidents involving robots.
2. Skilled workers are far more valuable than unskilled workers. Thus, making higher education and vocational training more accessible would reduce unemployment from automation as well as benefit society more broadly [89].
3. More potential administrative jobs are also created as robotic applications introduce new considerations, especially those related to regulatory and safety compliance.

**Size of Investment.** Despite technology's positive economic benefits, it may require a very significant initial investment to make technology practical. For instance, the rapid advance in computing power and cognitive systems is contingent on significant improvement of materials. To give an example, an American supplier of Applied Materials is experimenting with Cobalt as the alternative to Tungsten and Copper in transistors but is held back by the much higher cost of Cobalt [26]. High cost also lies in software engineering and algorithmic innovations as programmers are in high demand and paid high salaries while research funding focuses on the long term. Systems architecture is similarly costly as cleverer development takes a lot of design, prototyping, and testing time [35]. In terms of disaster resilience, the cost invested in resiliency technology can potentially be significant relative to the losses from an infrequent disaster. Consider the task of recovering black boxes and fuselage/debris [80] after air crashes. Currently such efforts can exceed $35 million in cost. Since airplane crashes happen infrequently there is less immediate need to develop an autonomous black-box recovery system if manual human effort or simpler teleoperation methods already work. Instead, there is motivation to focus research and funding towards developing robotic systems that improve plane manufacture, construction, and operation in order to minimize damage during crashes and to avoid crashes altogether.

*Mitigation Strategies*:

1. Design robots to be used for multiple purposes. For instance, a robot which can extinguish emergent fires during a disaster can be used as a gardening robot when it doesn't fight fires.

2. Many robots are designed to work for long periods without being powered off. To mitigate the energy cost, natural energy resources such as solar energy could be used. For marine robots, the cost of operation can be minimized by installing equipment that can collect and harness wave and wind energy.
3. Though different robots have different functionality and work in different fields, some of the mechanism design like the joints, controllers and motors can be standardized. Modularizing common robotic components can save cost in design, manufacture, and repair.

**Unbalanced Expectations and Reactions.** The effectiveness of robotic-related products can be easily exaggerated to obtain overly optimistic expectations from the public in the surge of interest in artificial intelligence. For instance, a lot of resources have been invested in the development and promotion of self-driving cars with the promise of decreasing car accidents and inner-city traffic. Several car companies bragged that self-driving cars will be widely deployed in the year 2020 with Level 5 (a.k.a full) autonomy [22]. Nevertheless, self-driving cars still have yet to overcome some hard challenges, such as sensing accuracy, collision avoidance under dynamically-changing environments, and generalization to different weather conditions [52]. Such overly zealous praise of incremental successes can make people become overly optimistic and careless when the technology is used in atypical situations and behaves unexpectedly. For instance, the Tesla accident in 2015 [118] and Uber accident in 2018 [111] shared one common factor that the driver was inattentive during the period of the accident (either kept hands off the wheel or was on the phone). Such recklessness is not entirely the fault of the driver as they were misled into putting too much trust in an autonomous system which had nowhere near 100% success rate. These incidents spiked public concern and consequently many companies suspended their road testing and recalled their cars. Only 16% of respondents to a recent survey [17] felt comfortable allowing autonomous driving without the option of human control. Unfortunately, this new public distrust is also too extreme. Just because driverless technology isn't good enough yet doesn't mean it can't be developed further. If such public distrust lingers when the technology does become ready it could delay the deployment of disaster resilience techniques - such as using autonomous cars for faster evacuation - and ultimately cost more lives.

*Mitigation Strategies*:

1. Companies and research organizations should provide more realistic plans and properly inform customers of the exact maturity level of high-tech products so as not to form unreasonable expectations or biases.
2. Users of high-tech products, or drivers for instance, should receive training which involves abnormal situations and operation under emergency scenarios in addition to regular use, to fully understand the applicability of a product.
3. In the case of autonomous cars, some regulations can be considered such as drivers having to take periodic tests (like fire drills) in order to renew a certification for operating driverless cars.

**Privacy Infringement and Cyber Security.** As highlighted in Sect. 2, drones are an effective resiliency technology for delivering essential supplies or extending short term communication to remote or suddenly inaccessible areas in the event of a disaster. Improper use of drones, however, can result in massive invasion of privacy if used for unsolicited surveillance of private residents (e.g., taking pictures of the outside or possibly inside of someone's place of residence). Correlating such gathered data to a potential customer could lead to targeted advertisement at an unprecedented level; thus, companies are certainly motivated to break privacy if unregulated. Furthermore, drones, whether military or commercial, can be hacked even if they are well regulated.

*Mitigation Strategies*:

1. Better regulation or law enforcement should be formulated to ensure the safe use of drones [18]. For instance, limiting the range of sensors which commercial drones are allowed to be built with could prevent certain data from being collected in the first place.
2. In addition, recipients of drone deliveries should have the right to obtain the pictures/data taken or collected from the drone during delivery and the ability to ask for their deletion.

In terms of cyber security, an attack on a communication platform facilitating both rescue teams and victims as discussed in Sect. 2 would undermine the disaster responses and even escalate problems. Using state-of-art encryption algorithms is becoming standardized but negligent system design and human gullibility are still common weak points that hackers exploit, which may result in a factory accident, a building collapse and a misleading public transportation system. One prediction is that by 2040 more crimes will be committed by machines than by humans [116].

*Mitigation Strategies*:

1. Regular scanning and penetration tests should be performed more frequently and used to inform and strictly enforce proper protocols (both in software and for people).
2. One effective way to protect critical machinery such as cars and nuclear reactors from cyber attacks is to have physically inherent safety mechanisms; such as lacking a physical link to a wide area network (WAN).
3. In order to reduce crimes through robots, critical robotic services (e.g., ridesharing, product delivery, military use) should be registered and monitored by a third party.

**Undesirable Uses of the Same Technology.** Military interests and contracts are a large source of funding for robotics research. It was reported that global spending on military robotics grew from about \$2.4 billion in 2000 to \$7.5 billion in 2015 and is projected to reach \$16.5 billion by 2025. Not coincidentally, 26% of the new robotics companies formed from 2012 are focused on military applications [112], mostly involving autonomous drones. Though military robots are increasingly deployed in the context of national defense and disaster responses, the improper use of such robots can cause significant negative consequences. For instance, if a natural disaster occurs at the border of two countries in conflict, a military robot may mistake victims in need of rescue as potential invaders to defend against. Such misuse could escalate political tension between the two countries and lead to retaliation.

*Mitigation Strategies*:

1. In addition to mechanical design and control strategies to improve robots' abilities to handle harsh environments, moral responsibilities should also be assigned to intelligent robots. As pointed out in [53], military robots should be designed with some moral framework in mind. For instance, a robot could be designed with the ability to reason about and prevent unwanted behaviors commanded by its operators.
2. To mitigate security concerns, mission critical robots need to be designed with some level of transparency in mind. Some software and hardware components should be publicly available so that external security audits can be frequently conducted and so that any vulnerabilities can be fixed more quickly by a larger invested community.

## 4 Discussion

Robotics technology has many applications towards strengthening disaster resilience including preventative measures, reactionary measures, and methods to mitigate the impact of the aftermath of disasters. The state-of-art in robotics manipulation and perception needs technological advancement in order to more effectively provide post-disaster resiliency given the unstructured nature of the challenge. Meanwhile many preemptive resiliency measures involving efficient resources in manufacturing or distribution are already seeing real deployment due to advancements in autonomous mobility. Additional capabilities can be achieved across resiliency activities by further exploring human-robot interaction and employing more advanced locomotion modes inspired by animals. There are also potential downsides and concerns to consider in the application of robots in these domains; these include safety, employment, cost, trust imbalance, privacy, abuse, and negligence.

As robotics is an interdisciplinary subject involving research efforts from multiple domains, the deployment of robotics also calls for a convergence of approaches based on science, technology, sociology, and ethics. Improvement through both technological and social means is necessary to ensure effective and proper use of robotics technology.

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## References

1. Amazon Robotics. https://www.amazonrobotics.com/#/
2. Assembly Robots. https://www.robots.com/applications/robotic-assembly
3. BostonDynamics: ATLAS. https://www.bostondynamics.com/atlas
4. Built Robotics. https://www.builtrobotics.com/
5. DroneDeploy: Drones in Agriculture, Then and Now. https://medium.com/aerial-acuity/drones-in-agriculture-then-and-now-ebde3df01667
6. Euronews: Farmers use drones to fight drought. https://www.euronews.com/2016/09/12/farmers-use-drones-to-fight-drought
7. GeekPlus Robotics. https://www.geekplus.com/
8. Insight Robotics. https://www.insightrobotics.com/en/
9. Occupational Safety and Health Administration: Robot-related Accident. https://www.osha.gov/
10. RDI Technologies. https://rditechnologies.com/
11. Wiki: Hurricane Rita. https://en.wikipedia.org/wiki/Hurricane_Rita
12. Wiki: Technology readiness level. https://en.wikipedia.org/wiki/Technology_readiness_level
13. World Disasters Timeline. http://www.mapreport.com/disasters.html
14. BBC News: Robotic surgery linked to 144 deaths in the US (2015). https://www.bbc.com/news/technology-33609495
15. Two Billion People Hit by Natural Disasters in the Past Decade (2018). https://www.securitymagazine.com/articles/89535-two-billion-people-hit-by-natural-disasters-in-the-past-decade
16. Robots' to replace up to 20 million factory jobs' by 2030 (2019). https://www.bbc.com/news/business-48760799
17. Self-Driving Cars-facts and Figures (2020). https://www.driverlessguru.com/self-driving-cars-facts-and-figures
18. (ACLU), A.C.L.U.: Protecting privacy from aerial surveillance: Recommendations for government use of drone aircraft (2011). https://www.aclu.org/files/assets/protectingprivacyfromaerialsurveillance.pdf
19. Afghah, F., Razi, A., Chakareski, J., Ashdown, J.: Wildfire monitoring in remote areas using autonomous unmanned aerial vehicles. In: IEEE INFOCOM 2019-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp. 835–840. IEEE (2019)
20. Afzaal, H., Zafar, N.A.: Robot-based forest fire detection and extinguishing model. In: 2016 2nd International Conference on Robotics and Artificial Intelligence (ICRAI), pp. 112–117. IEEE (2016)
21. Ahmadi, M., Stone, P.: A multi-robot system for continuous area sweeping tasks. In: Proceedings 2006 IEEE International Conference on Robotics and Automation. ICRA 2006, pp. 1724–1729. IEEE (2006)
22. Anderson, M.: Surprise! 2020 Is Not the Year for Self-Driving Cars (2020). https://spectrum.ieee.org/transportation/self-driving/surprise-2020-is-not-the-year-for-selfdriving-cars
23. Army, T.U.: iRobot PackBot (2009). https://commons.wikimedia.org/wiki/File:Flickr_-_The_U.S._Army_-_iRobot_PackBot.jpg
24. Bao, D.Q., Zelinka, I.: Obstacle avoidance for swarm robot based on self-organizing migrating algorithm. Procedia Comput. Sci. **150**, 425–432 (2019)
25. Becker, R.: Robot squeezes suspected nuclear fuel debris in Fukushima reactor (2019). https://www.theverge.com/2019/2/15/18225233/robot-nuclear-fuel-debris-fukushima-reactor-japan

26. Bhagavatula, S.: Robots are getting expensive (2019). https://medium.com/datadriveninvestor/automation-is-getting-expensive-1a4656b1bd9a
27. Bischoff, R., Huggenberger, U., Prassler, E.: Kuka youbot-a mobile manipulator for research and education. In: 2011 IEEE International Conference on Robotics and Automation, pp. 1–4. IEEE (2011)
28. Bliss, L.: Could Self-Driving Cars Speed Hurricane Evacuations? (2016). https://www.theatlantic.com/technology/archive/2016/10/self-driving-cars-evacuations/504131/
29. Burke, R.V., et al.: Using robotic telecommunications to triage pediatric disaster victims. J. Pediatr. Surg. **47**(1), 221–224 (2012)
30. Burmeister, S., Holz, M.: Warning method and robot system, US Patent 9,908,244, March 6 2018
31. Chen, X., Zhang, H., Lu, H., Xiao, J., Qiu, Q., Li, Y.: Robust slam system based on monocular vision and lidar for robotic urban search and rescue. In: 2017 IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR), pp. 41–47. IEEE (2017)
32. Coyle, S., Majidi, C., LeDuc, P., Hsia, K.J.: Bio-inspired soft robotics: material selection, actuation, and design. Extrem. Mech. Lett. **22**, 51–59 (2018)
33. Crozier, S.: Forest Fire "Clear Cut" Robot (2008). https://www.yankodesign.com/2008/04/24/forest-fire-clear-cut-robot/
34. Customs, U., Protection, B.: CBP Officers deploy underwater robot below a ship (2012). https://commons.wikimedia.org/wiki/File:CBP_Officers_deploy_underwater_robot_below_a_ship_(8405583933).jpg
35. Deierling, K.: The End of Moore's Law and the Return of Cleverness (2019). https://blog.mellanox.com/2019/08/the-end-of-moores-law-and-the-return-of-cleverness
36. D'Monte, L.: 5 Robots That May Rescue You From Natural Disasters (2015). https://www.govtech.com/em/safety/5-Robots-That-May-Rescue-You-From-Natural-Disasters.html
37. Dockterman, E.: Robot Kills Man at Volkswagen Plant (2015). https://time.com/3944181/robot-kills-man-volkswagen-plant/
38. Doersch, C., Zisserman, A.: Sim2real transfer learning for 3D human pose estimation: motion to the rescue. In: Advances in Neural Information Processing Systems, pp. 12949–12961 (2019)
39. Dunbabin, M., Grinham, A., Udy, J.: An autonomous surface vehicle for water quality monitoring. In: Australasian Conference on Robotics and Automation (ACRA), pp. 2–4. Citeseer (2009)
40. Ellekilde, L.P., Petersen, H.G.: Motion planning efficient trajectories for industrial bin-picking. Int. J. Robot. Res. **32**(9–10), 991–1004 (2013)
41. Ess, A., Schindler, K., Leibe, B., Van Gool, L.: Object detection and tracking for autonomous navigation in dynamic environments. Int. J. Robot. Res. **29**(14), 1707–1725 (2010)
42. Fallon, P.J.: Acoustical/optical bin picking system, US Patent 4,985,846, January 15 1991
43. Feng, S.W., Yu, J.: Optimally guarding perimeters and regions with mobile range sensors. arXiv preprint arXiv:2002.08477 (2020)
44. Foster, M.E., By, T., Rickert, M., Knoll, A.: Human-robot dialogue for joint construction tasks. In: Proceedings of the 8th International Conference on Multimodal Interfaces, pp. 68–71 (2006)
45. Galceran, E., Carreras, M.: A survey on coverage path planning for robotics. Robot. Auton. Syst. **61**(12), 1258–1276 (2013)

46. Garrett, C.R., Huang, Y., Lozano-Pérez, T., Mueller, C.T.: Scalable and probabilistically complete planning for robotic spatial extrusion. arXiv preprint arXiv:2002.02360 (2020)
47. Gonzalez, C.: Changing the Future of Warehouses with Amazon Robots (2017). https://www.machinedesign.com/mechanical-motion-systems/article/21835788/changing-the-future-of-warehouses-with-amazon-robots
48. González-Jiménez, H.: Can robots help us overcome the coronavirus health crisis and lockdown? (2020). https://theconversation.com/can-robots-help-us-overcome-the-coronavirus-health-crisis-and-lockdown-134161
49. Gow, G.: COVID-19 and unemployment: the robots are coming (2020). https://www.forbes.com/sites/glenngow/2020/07/07/covid-19-and-unemployment-the-robots-are-coming/?sh=225497141fab
50. Han, S.D., Yu, J.: DDM: fast near-optimal multi-robot path planning using diversified-path and optimal sub-problem solution database heuristics. IEEE Robot. Autom. Lett. **5**(2), 1350–1357 (2020)
51. Hanheide, M., et al.: Robot task planning and explanation in open and uncertain worlds. Artif. Intell. **247**, 119–150 (2017)
52. Hecht, J.: Self-driving vehicles: many challenges remain for autonomous navigation (2020). https://www.laserfocusworld.com/test-measurement/article/14169619/selfdriving-vehicles-many-challenges-remain-for-autonomous-navigation
53. Hellström, T.: On the moral responsibility of military robots. Ethics Inf. Technol. **15**(2), 99–107 (2013)
54. Hereid, A., Cousineau, E.A., Hubicki, C.M., Ames, A.D.: 3D dynamic walking with underactuated humanoid robots: a direct collocation framework for optimizing hybrid zero dynamics. In: 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 1447–1454. IEEE (2016)
55. Husseini, T.: From Cherno-bots to Iron Man suits: the development of nuclear waste robotics. https://www.power-technology.com/features/cleaning-up-nuclear-waste-robotics/
56. Islam, F., Salzman, O., Agraval, A., Likhachev, M.: Provably constant-time planning and re-planning for real-time grasping objects off a conveyor. arXiv preprint arXiv:2003.08517 (2020)
57. Kapoutsis, A.C., Chatzichristofis, S.A., Kosmatopoulos, E.B.: DARP: divide areas algorithm for optimal multi-robot coverage path planning. J. Intell. Robot. Syst. **86**(3–4), 663–680 (2017)
58. Karaman, S., Frazzoli, E.: Incremental sampling-based algorithms for optimal motion planning. Robot. Sci. Syst. VI **104**(2), 267–274 (2010)
59. Kerzel, M., Strahl, E., Magg, S., Navarro-Guerrero, N., Heinrich, S., Wermter, S.: Nico–neuro-inspired companion: a developmental humanoid robot platform for multimodal interaction. In: 2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), pp. 113–120. IEEE (2017)
60. Khalid, M.A.B., Shome, R., Stone, C.M.K.B.M.: That and there: judging the intent of pointing actions with robotic arms (2019)
61. King, J.E., Haustein, J.A., Srinivasa, S.S., Asfour, T.: Nonprehensile whole arm rearrangement planning on physics manifolds. In: 2015 IEEE International Conference on Robotics and Automation (ICRA), pp. 2508–2515. IEEE (2015)
62. Koceska, N., Koceski, S., Beomonte Zobel, P., Trajkovik, V., Garcia, N.: A telemedicine robot system for assisted and independent living. Sensors **19**(4), 834 (2019)

63. Kroemer, O., Niekum, S., Konidaris, G.: A review of robot learning for manipulation: challenges, representations, and algorithms. arXiv preprint arXiv:1907.03146 (2019)
64. Krontiris, A., Bekris, K.E.: Efficiently solving general rearrangement tasks: a fast extension primitive for an incremental sampling-based planner. In: 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 3924–3931. IEEE (2016)
65. Kulik, S.D., Shtanko, A.N.: Experiments with neural net object detection system YOLO on small training datasets for intelligent robotics. In: Misyurin, S.Y., Arakelian, V., Avetisyan, A.I. (eds.) Advanced Technologies in Robotics and Intelligent Systems. MMS, vol. 80, pp. 157–162. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-33491-8_19
66. LaMonica, M.: Ocean-faring Robot Cashes in on Offshore Oil and Gas (2013). https://www.technologyreview.com/2013/03/20/253500/ocean-faring-robot-cashes-in-on-offshore-oil-and-gas/
67. Lavalle, S.M.: Sampling-based motion planning (2006)
68. Lavine, K.: Take3: Left Hand Robotics creates snow-clearing robot (Video) (2018). https://www.bizjournals.com/denver/news/2018/01/02/take3-left-hand-robotics-creates-snow-clearing.html
69. Levinson, J., Thrun, S.: Robust vehicle localization in urban environments using probabilistic maps. In: 2010 IEEE International Conference on Robotics and Automation, pp. 4372–4378. IEEE (2010)
70. Li, X., Guo, D., Yin, H., Wei, G.: Drone-assisted public safety wireless broadband network. In: 2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), pp. 323–328. IEEE (2015)
71. Lopez-Arreguin, A., Montenegro, S.: Towards bio-inspired robots for underground and surface exploration in planetary environments: an overview and novel developments inspired in sand-swimmers. Heliyon **6**(6), e04148 (2020)
72. Lu, Q., Fricke, G.M., Tsuno, T., Moses, M.E.: A bio-inspired transportation network for scalable swarm foraging. In: 2020 IEEE International Conference on Robotics and Automation (ICRA), pp. 6120–6126. IEEE (2020)
73. Luo, C., Espinosa, A.P., Pranantha, D., De Gloria, A.: Multi-robot search and rescue team. In: 2011 IEEE International Symposium on Safety, Security, and Rescue Robotics, pp. 296–301. IEEE (2011)
74. Mandloi, A., Jaisingh, H.R., Hazarika, S.M.: Perception based navigation for autonomous ground vehicles. In: Deka, B., Maji, P., Mitra, S., Bhattacharyya, D.K., Bora, P.K., Pal, S.K. (eds.) PReMI 2019. LNCS, vol. 11942, pp. 369–376. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-34872-4_41
75. Manjanna, S., Li, A.Q., Smith, R.N., Rekleitis, I., Dudek, G.: Heterogeneous multi-robot system for exploration and strategic water sampling. In: 2018 IEEE International Conference on Robotics and Automation (ICRA), pp. 1–8. IEEE (2018)
76. Margaret Rouse, I.W.: Telepresence robot. https://searchenterpriseai.techtarget.com/definition/telepresence-robot
77. Meguro, J.I., Ishikawa, K., Hasizume, T., Takiguchi, J.I., Noda, I., Hatayama, M.: Disaster information collection into geographic information system using rescue robots. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3514–3520. IEEE (2006)
78. Michael Martinez, P.V., Hannah, J.: CNN: germ-zapping robot Gigi sets its sights on Ebola (2014). https://www.cnn.com/2014/10/16/us/germ-zapping-robot-ebola/index.html

79. Miller, N.: How factories change production to quickly fight coronavirus (2020). https://www.bbc.com/worklife/article/20200413-how-factories-change-production-to-quickly-fight-coronavirus
80. Mohney, G.: Long Search for Missing Plane Could Cost ‘Hundreds of Millions of Dollars’ (2014). https://abcnews.go.com/International/long-search-missing-plane-cost-hundreds-millions-dollars/story?id=22899690
81. NASA: Snakebot (2000). https://www.nasa.gov/centers/ames/news/releases/2000/00images/snakebot/snakebot.html
82. Nayyar, M., Wagner, A.R.: Effective robot evacuation strategies in emergencies. In: 2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), pp. 1–6. IEEE (2019)
83. Noha, S.Y., et al.: Design of a 2dofs pantograph leg mechanism for rapid response robot platform in nuclear power plant facilities (2020)
84. Onosato, M., et al.: Disaster information gathering aerial robot systems. In: Rescue Robotics, pp. 33–55. Springer (2009). https://doi.org/10.1007/978-1-84882-474-4_3
85. Palmer, A.: Amazon wins FAA approval for Prime Air drone delivery fleet (2020). https://www.cnbc.com/2020/08/31/amazon-prime-now-drone-delivery-fleet-gets-faa-approval.html
86. Pan, Q., Lowe, D.: Search and rescue robot team RF communication via power cable transmission line-a proposal. In: 2007 International Symposium on Signals, Systems and Electronics, pp. 287–290. IEEE (2007)
87. Panagou, D.: Motion planning and collision avoidance using navigation vector fields. In: 2014 IEEE International Conference on Robotics and Automation (ICRA), pp. 2513–2518. IEEE (2014)
88. Paraskevas, A., Arendell, B.: A strategic framework for terrorism prevention and mitigation in tourism destinations. Tourism Manag. **28**(6), 1560–1573 (2007)
89. Paul, M.: Don’t Fear the Robots: Why Automation Doesn’t Mean the End of Work (2018). https://rooseveltinstitute.org/publications/dont-fear-the-robots-automation-doesnt-mean-the-end-of-work/
90. Pierson, A., Schwager, M.: Bio-inspired non-cooperative multi-robot herding. In: ICRA, pp. 1843–1849. Citeseer (2015)
91. Quaritsch, M., Kuschnig, R., Hellwagner, H., Rinner, B., Adria, A., Klagenfurt, U.: Fast aerial image acquisition and mosaicking for emergency response operations by collaborative UAVs. In: ISCRAM (2011)
92. Ramirez, V.B.: Waymo Just Started Testing Its Driverless Trucks in Texas (2020). https://singularityhub.com/2020/08/27/waymo-just-started-testing-its-driverless-trucks-in-texas/
93. Reich, J., Sklar, E.: Robot-sensor networks for search and rescue. In: IEEE International Workshop on Safety, Security and Rescue Robotics, vol. 22 (2006)
94. Reise, R.: POK Jupiter firefighting robot (2019). https://commons.wikimedia.org/wiki/File:POK_Jupiter_firefighting_robot_(3).jpg
95. Sadigh, D., Sastry, S., Seshia, S.A., Dragan, A.D.: Planning for autonomous cars that leverage effects on human actions. In: Robotics: Science and Systems, vol. 2. Ann Arbor (2016)
96. Semuels, A.: Millions of Americans Have Lost Jobs in the Pandemic – and Robots and AI are Replacing them Faster than Ever (2020). https://time.com/5876604/machines-jobs-coronavirus
97. Shaw, K.: World Robotics Report: Global Sales of Robots Hit $16.5B in 2018 (2019). https://www.roboticsbusinessreview.com/research/world-robotics-report-global-sales-of-robots-hit-16-5b-in-2018/

98. Shi, S., Wu, H., Song, Y., Handroos, H.: Mechanical design and error prediction of a flexible manipulator system applied in nuclear fusion environment. Ind. Robot: Int. J. **44**(6), 711–719 (2017)
99. Shome, R., Nakhimovich, D., Bekris, K.E.: Pushing the boundaries of asymptotic optimality in integrated task and motion planning. In: The 14th International Workshop on the Algorithmic Foundations of Robotics (2020)
100. Shome, R., et al.: Towards robust product packing with a minimalistic end-effector. In: 2019 International Conference on Robotics and Automation (ICRA), pp. 9007–9013. IEEE (2019)
101. Simoni, M.D., Kutanoglu, E., Claudel, C.G.: Optimization and analysis of a robot-assisted last mile delivery system. Transp. Res. Part E: Logistics Transp. Rev. **142**, 102049 (2020)
102. Ruiz-del Solar, J., Loncomilla, P., Soto, N.: A survey on deep learning methods for robot vision. arXiv preprint arXiv:1803.10862 (2018)
103. Srivastava, S., Fang, E., Riano, L., Chitnis, R., Russell, S., Abbeel, P.: Combined task and motion planning through an extensible planner-independent interface layer. In: 2014 IEEE International Conference on Robotics and Automation (ICRA), pp. 639–646. IEEE (2014)
104. Strisciuglio, N., et al.: Trimbot 2020: an outdoor robot for automatic gardening. In: ISR 2018 50th International Symposium on Robotics, pp. 1–6. VDE (2018)
105. Stuart, H., Wang, S., Khatib, O., Cutkosky, M.R.: The ocean one hands: an adaptive design for robust marine manipulation. Int. J. Robot. Res. **36**(2), 150–166 (2017)
106. Sun, P., et al.: Scalability in perception for autonomous driving: Waymo open dataset. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pp. 2446–2454 (2020)
107. Sutter, J.D.: MIT unveils swimming, oil-cleaning robots (2010). http://edition.cnn.com/2010/TECH/innovation/08/26/mit.oil.robot/index.html
108. Tanimoto, T., Shinohara, K., Yoshinada, H.: Research on effective teleoperation of construction machinery fusing manual and automatic operation. ROBOMECH J. **4**(1), 14 (2017)
109. Team, R.O.M.: Food Delivery Robots Take to the Streets (2019). https://www.robotics.org/blog-article.cfm/Food-Delivery-Robots-Take-to-the-Streets/212
110. Tuna, G., Gulez, K., Gungor, V.C.: Communication related design considerations of WSN-aided multi-robot slam. In: 2011 IEEE International Conference on Mechatronics, pp. 493–498. IEEE (2011)
111. Wakabayashi, D.: Self-Driving Uber Car Kills Pedestrian in Arizona, Where Robots Roam (2018). https://www.nytimes.com/2018/03/19/technology/uber-driverless-fatality.html
112. Walker, J.: Military Robotics Innovation - Comparing the US to Other Major Powers (2019). https://emerj.com/ai-sector-overviews/military-robotics-innovation/
113. Wang, H., Zhang, C., Song, Y., Pang, B.: Master-followed multiple robots cooperation slam adapted to search and rescue environment. Int. J. Control. Autom. Syst. **16**(6), 2593–2608 (2018)
114. Wang, R., Mitash, C., Lu, S., Boehm, D., Bekris, K.E.: Safe and effective picking paths in clutter given discrete distributions of object poses. arXiv preprint arXiv:2008.04465 (2020)
115. Wang, Y., Jordan, C.S., Hanrahan, K., Sanchez, D.S., Pinter, M.: Telepresence robot with a camera boom, US Patent 8,996,165, March 31 2015

116. Winder, D.: Is the future of cyber crime a nightmare scenario (2016). https://www.raconteur.net/is-future-cyber-crime-a-nightmare-scenario/
117. Wood, L.J., Zaraki, A., Walters, M.L., Novanda, O., Robins, B., Dautenhahn, K.: The iterative development of the humanoid robot kaspar: an assistive robot for children with autism. In: International Conference on Social Robotics, pp. 53–63. Springer (2017). https://doi.org/10.1007/978-3-319-70022-9_6
118. Yadron, D., Tynan, D.: Tesla driver dies in first fatal crash while using autopilot mode (2016). https://www.theguardian.com/technology/2016/jun/30/tesla-autopilot-death-self-driving-car-elon-musk
119. Yamada, T., Ito, T., Ohya, A.: Detection of road surface damage using mobile robot equipped with 2D laser scanner. In: Proceedings of the 2013 IEEE/SICE International Symposium on System Integration, pp. 250–256. IEEE (2013)
120. Yamamoto, T., Terada, K., Ochiai, A., Saito, F., Asahara, Y., Murase, K.: Development of human support robot as the research platform of a domestic mobile manipulator. ROBOMECH J. **6**(1), 4 (2019)
121. Yan, C., Xiang, X., Wang, C.: Towards real-time path planning through deep reinforcement learning for a UAV in dynamic environments. J. Intell. Robot. Syst. 1–13 (2019)
122. Yang, G.Z., et al.: Combating Covid-19–the role of robotics in managing public health and infectious diseases (2020)
123. Yatsuda, A., Haramaki, T., Nishino, H.: A robot gesture framework for watching and alerting the elderly. In: International Conference on Network-Based Information Systems, pp. 132–143. Springer (2018). https://doi.org/10.1007/978-3-319-98530-5_12
124. Yu, C., et al.: Ds-slam: A semantic visual slam towards dynamic environments. In: 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 1168–1174. IEEE (2018)
125. Yu, J., LaValle, S.M.: Optimal multirobot path planning on graphs: complete algorithms and effective heuristics. IEEE Trans. Robot. **32**(5), 1163–1177 (2016)
126. Yuh, J., Marani, G., Blidberg, D.R.: Applications of marine robotic vehicles. Intell. Serv. Robot. **4**(4), 221 (2011)
127. Zhang, S., Guo, Y.: Distributed multi-robot evacuation incorporating human behavior. Asian J. Control **17**(1), 34–44 (2015)
128. Zheng, X., Jain, S., Koenig, S., Kempe, D.: Multi-robot forest coverage. In: 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3852–3857. IEEE (2005)
129. Zhou, X.S., Roumeliotis, S.I.: Multi-robot slam with unknown initial correspondence: the robot rendezvous case. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1785–1792. IEEE (2006)