50. Search and Rescue Robotics

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In order to summarize the status of rescue robotics, this chapter will cover the basic characteristics of disasters and their impact on robotic design, describe the robots actually used in disasters to date, promising robot designs (e.g., snakes, legged locomotion) and concepts (e.g., robot teams or swarms, sensor networks), methods of evaluation in benchmarks for rescue robotics, and conclude with a discussion of the fundamental problems and open issues facing rescue robotics, and their evolution from an interesting idea to widespread adoption. The Chapter will concentrate on the rescue phase, not recovery, with the understanding that capabilities for rescue can be applied to, and extended for, the recovery phase. The use of robots in the prevention and preparedness phases of disaster management are outside the scope of this chapter.

Rescue robots serve as extensions of responders into a disaster, providing real-time video and other sensory data about the situation. They are an emerging technology, and have not yet been adopted by the international emergency response community. As of 2006, they have been used in only four disasters in the United States (World Trade Center, and hurricanes Katrina, Rita, and Wilma), where they were still viewed as a novelty. However, rescue robots are seeing some use in local incidents. For example, several fire rescue departments in Japan and the United States routinely use small underwater robots for water-based search and recovery, a ground robot has been used for a mine explosion in the United States, and interest in the use of aerial vehicles for wilderness search and rescue is growing. The general lack of adoption is to be expected since the technology is new, and the concept of operations of novel technologies as well as the refinement of the hardware and software coevolution will take time. Rescue robot applications are often similar enough to military operations that the same platforms can be adapted; however, some rescue tasks are significantly different than their military counterpart, some tasks are unique to rescue, and the human–robot interaction for civilian response diverges from military patterns of use.

50.1 Overview

Disaster response is always a race against time, to move as fast as possible to reach all potential survivors and yet move slowly enough to avoid creating additional collapses, damage, or risk to rescuers and victims. The primary motivation is to save lives; robots can assist in meeting this goal either by interacting directly with victims or structures or automating support activities.

50.1.1 Motivation

Historically, the push for rescue robotics started in 1995 as outcomes of the tragic loss of life in the Hanshin–Awajii earthquake in Kobe, Japan, and the bombing of the Murrah federal building in Oklahoma City, United States [50.1]. The advances in robotics and artificial intelligence in the early 1990s supported the moral imperative for roboticists to reach out and help. As a result, research efforts began in individual laboratories. Two mobile robot competitions (the AAAI mobile robot competition in the United States, and the RoboCup rescue league internationally) were started shortly thereafter to engage the scientific community in rescue research.

The 2005 World Disasters report [50.2] suggests just how many lives have been, and will be, impacted by urban disasters. Over 900 000 people were reported killed from 1995 to 2004, with the total amount of disaster-related damage estimated at 738 billion US dollars. Of the victims in urban disasters, only a small fraction may actually survive. Consider from [50.3, 4] that the majority of survivors (80%) of urban disasters are surface victims, that is, the people lying on the surface of the rubble or readily visible. However, only 20% of survivors of urban disasters come from the interior of the rubble, yet the interior is often where the majority of victims are located, providing motivation for robots that can explore deep within collapses. The mortality rate increases and peaks after 48 h, meaning that survivors who are not extricated in the first 48 h after the event are unlikely to survive beyond a few weeks in the hospital.

50.1.2 Rescue Robot Tasks

While the overall motivation for rescue robotics is to save lives, the motivation for specific robot designs and capabilities depends on their potential tasks. The types of tasks that have been proposed for rescue robots are described below.

Search is a concentrated activity in the interior of a structure, in caves or tunnels, or wilderness and aims to find a victim or potential hazards. The motivation for the search task is speed and completeness without increasing risk to victims or rescuers.

Reconnaissance and mapping is broader than search. It provides responders with general situation awareness and creates a reference of the destroyed environment. The goal is speedy coverage of a large area of interest at the appropriate resolution.

Rubble removal can be expedited by robotic machinery or exoskeletons. The motivation is to move heavier rubble faster than could be done manually, but with a smaller footprint than that of a traditional construction crane.

Structural inspection may be either conducted on the interior (e.g., to help rescuers understand the nature of the rubble in order prevent secondary collapses that may further injure survivors) or on the exterior (e.g., to determine whether a structure is safe to enter). Robots provide a means of getting structural sensor payloads closer and in far more favorable viewing angles.

In situ medical assessment and intervention are needed to permit doctors and paramedics to interact verbally with victims, visually inspect the victim or apply diagnostic sensors, or to provide life support by transporting fluids and medication through narrow tubing during the four to ten hours that it usually takes to extricate a victim. The lack of medical intervention was a major problem at the Oklahoma City bombing [50.5].

Medically sensitive extrication and evacuation of casualties may be needed to help provide medical assistance while victims are still in the disaster area, also known as the hot zone. In the case of a chemical, biological, or radiological event, the number of victims is expected to exceed the number that can be carried out by human rescuers in their highly restrictive protective gear; this makes robot carriers attractive. Since medical doctors may not be permitted inside the hot zone, which can extend for kilometers, robot carriers that support telemedicine may be of huge benefit.

Acting as a mobile beacon or repeater to extend wireless communication ranges, enable localization of personnel based on radio signal transmissions by providing more receivers, and to serve as landmarks to allow rescuers to localize themselves.

Serving as a surrogate for a team member, such as a safety officer or a logistics person. In this task, the robot works side-by-side with rescuers, for example, a group breaching rubble deep within the interior of a disaster may have difficulty using a radio to request additional resources because of noise. However, a team member outside of the rubble can see and hear through the robot the state of progress and anticipate needs. The objective is to use robots to speed up and reduce the demands of tasks, even if they are done by humans.

Adaptively shoring unstable rubble to expedite the extrication process. Rubble removal is often hindered by the need to adopt a conservative pace in order to prevent a secondary collapse that might further injure a trapped survivor.

Providing logistics support by automating the transportation of equipment and supplies from storage areas to teams or distribution points within the hot zone.

Some of the above tasks are similar to tasks for military robots, especially search and reconnaissance and mapping, but many are unique or have a different flavor. For example, structural inspection, rubble removal, and adaptively shoring rubble are rescue specific. Tasks such as casualty extraction appear to be similar but are significantly different. Consider that a wounded soldier is unlikely to have a spinal-cord injury and is likely to be in a space large enough for a human to work in, so a robot entering the area and dragging the soldier to safety is appropriate. However, a crushed victim of a building collapse is physically trapped or pinned in a small space, requiring rubble removal, and the victim's spinal cord must be immobilized before extraction; clearly victim extraction in the search-and-rescue domain is more challenging.

50.1.3 Types of Rescue Robots

Rescue robots are needed to help quickly locate, assess, stabilize, and extricate victims who cannot be easily reached. They typically do this by extending the rescuers' ability to see and act. On the ground, small unmanned ground vehicles (UGVs) can enable rescuers to find and interact with trapped victims in voids that are too small or too dangerous for human or canine entry. Large UGVs can accomplish tasks such as removing large rubble faster than humans. In the air, unmanned aerial vehicles (UAVs) robots extend the senses of the responders by providing a bird's eye view of the situation. In the water, unmanned underwater vehicles (UUVs) and surface vehicles (USVs) robots can similarly extend and enhance the rescuers' senses.

Rescue robots can be broadly categorized into types based on *modality* and *size* [50.6], though other taxonomies that mix modality, size, and task have been proposed [50.7]. There are four modalities of robots: *ground*, *aerial*, *underwater*, and *water surface*. The modality impacts on the basic design and capabilities of the robot. Within each modality, rescue robots can be further described as one of three sizes: *man-packable*, *man-portable*, and *maxi*. The size of the robot impacts both on the tasks for which it is suited and how soon after a disaster it might be used. In order to be man-packable, the entire robot system, including the control unit, batteries, and tools, must fit into one or two backpacks. Man-packable robots are more likely to be used immediately after a disaster since they can be carried by responders over debris and up and down ladders into the core of the disaster, while larger equipment must wait for paths to be carved out. The next larger size is man-portable; these are robots that can be carried a short distance by two people or on a small all-terrain vehicle. Man-portable robots can be used as accessibility within the hot zone improves or outside the hot zone for logistics support. Maxi-sized robots require trailers or other special transportation logistics. This inhibits their insertion into the hot zone, unless they are being used on the exterior of the rubble.

50.2 Disaster Characteristics and Impact on Robots

The type of disaster influences the choice of robot platforms and payloads. *Natural disasters* generally span large geographic areas, making a bird's eye view from a UAV invaluable in establishing situation awareness and determining areas or individuals which need immediate evacuation or assistance [50.8]. *Manmade disasters* are geographically concentrated with the most vital aspects of the disaster invisible beneath the rubble. Small ground robots that can enter deep into the interior of the rubble, and large robots, which can help remove rubble, appear to hold the most promise for manmade disasters. Note the focus on the search for victims and on general information gathering. This focus implies that communications plays a major role in the design of search-and-rescue robot systems and the impact of the environment on wireless communications is an important consideration.

Independently of the type of disaster, search and rescue is very demanding both in terms of robotic capabilities and working conditions for the operator [50.9]. The robot is, by definition, operating in a harsh, mobility-challenging environment. The presence of abrasive dust and water, the corrosive effects of wet cement, and the wide range of obstacles in the environment serve to accelerate the wear and tear on a robot [50.6, 10]; therefore, the adage *simple is better* is especially true in rescue robotics. The disaster also places demands on the robot operator that will likely impact performance. Certainly, the operator will be stressed by the time criticality and life-saving urgency of the mission. Other sources of stress include: the operator will not be able to keep the robot in line of sight (which is a more favorable operating regime), perception to the robot is computer-mediated and therefore cognitively fatiguing, and the operator is likely to be sleep-deprived and may be at some personal risk.

50.2.1 Categories and Phases of Disasters

An incident may be *local* or it may be a true *disaster*; a disaster exceeds local resources or expertise and requires specially trained teams from outside the immediate agency to be involved. Disaster operations consist of four phases: *preparedness*, *prevention*, *rescue*, and *recovery*. Preparedness and prevention are *pre-incident activities*, where as rescue and recovery are *post-incident tasks*. Rescue is also distinct from the recovery phase of a disaster operation; recovery seeks to mitigate longer-term threats to life and damage to property and to extract the dead.

Rescue is the broad term applied to activities immediately following a critical incident that directly deal with immediate threats to the survivability of those impacted by the event. This includes locating, assessing the medical condition, stabilization, and extrication of survivors. *Rescue* is often used interchangeably with the term *search and rescue*, which actually refers to the teams and activities that work in the field, whereas rescue is frequently used by the public to connote the larger disaster management activities needed to support the teams and victims. *Search* refers to activities related to finding survivors; while *rescue* refers to the activities related to extricating survivors. In general, the typical process of search and rescue takes two tracks: *strategic* and *tactical*. Strategic operations focus on mission planning and coordination for the entire enterprise, which may involve robots as mobile sensor, communication networks, or logistics support.

Within search and rescue, there are numerous specialties and these specialities may impact on the design or use of a robot. Of these, *urban search and rescue* (abbreviated as US&R or USAR) has been the subject of the majority of work in rescue robotics. Urban search and rescue takes its name from its focus on the aftermath of urban structures collapsing around people. These structures may collapse for natural reasons such as earthquakes, hurricanes, and flooding or they may stem from manmade causes such as structural failures or terrorism. However, there are other types of search and rescue, though these are generally associated with local incidents. *Wilderness search and rescue* tracks people in the outdoors, such as lost hikers or people buried by avalanches. *Water-based search and rescue* deals with situations such as saving victims of floods or high currents (also known as *swift water rescue*) or in the aftermath of traffic accidents where victims are trapped in cars that have plunged into a river or bay.

In order to understand how to apply robotics to disaster response, it is helpful to understand the general pattern of activity, which can be summarized as [50.11, 12]:

1. Responders become aware of the existence of victims. This awareness may be generated by information from family, neighbors, and colleagues, an understanding of demographic patterns (e.g., at night, apartment buildings will be heavily occupied, while during a work day, office buildings will be occupied), or by a systematic search.
2. The response command staff attempt to understand the disaster site. They investigate the site for conditions such as hazardous materials, the risk posed to the rescuers themselves, any pending threats to trapped victims, and resource restrictions such as barriers to transporting resources to the site, nearby

usable equipment and materials that can be exploited, and any other barriers to a timely rescue.
3. The command staff plans the operations.
4. Search and reconnaissance teams are sent to map the situation and assess environmental conditions. Accurate estimates of the need for emergency medical intervention are highly desirable in order to optimize allocation of medication personnel in the field and to prepare ambulances and hospitals. (In the case of the Kobe earthquake, this stage took the longest time [50.11].)
5. Excavation of rubble to extract victims begins. Note that removal of rubble in search and rescue differs from construction removal of rubble, because the safety of the victims is the top priority.
6. Responders gain access to victims and apply emergency medicine in situ.
7. Victims are transferred to hospitals.
8. Field teams report activities periodically, usually at the end of the shift, and the command staff modifies or replan accordingly.

Robots are particularly needed for *tactical search and rescue*, which covers how the field teams actually find, support, and extract survivors. Tactical search and rescue typically begins independently of strategic planning [50.13]. As discussed in [50.12], the first responders on the scene, policemen and firemen, as well as civilians immediately assist with extracting survivors. Regional search-and-rescue teams are deployed and arrive within a few hours, while strategic operations are only beginning to be set up. Based on the condition of the structure and the size of voids, rescuers may enter the rubble, typically using a right-wall-following algorithm. In order to locate inaccessible victims not visible on the surface of rubble, rescuers working in teams of two typically bring in canine teams to smell for the presence of survivors, or use pole-mounted search cameras. Search cameras and boroscopes can usually extend visibility into the rubble by several meters, depending on the irregularity and turns in the voids. If a team has any indication of a survivor, another team is called over to verify the finding. If the finding is verified, and the victim is presumed to be alive, extrication begins. Rescue teams work systematically through a structure and mark each void as to when it was searched and what the findings were.

50.2.2 Natural Disasters

Natural disasters, such as earthquakes, tsunamis, hurricanes and typhoons, volcanoes, avalanches, landslides, and floods, present many challenges for rescue robots. Natural disasters are usually geographically distributed, perhaps affecting a 200 km or more radius around the epicenter of the event. The sheer size of the affected area presents many challenges to the emergency response. The primary impact of natural disasters is on residences, light commercial buildings, sea walls and canals, and transportation and communications infrastructure. This means rescuers have thousands of structures to check quickly for survivors, but those structures will be fairly small and amenable to manual and canine search. Besides the sheer volume of structures to check, communication disruptions prevent rescuers from getting timely information as to the state of transportation access and the general needs of an area. However, designing robots to meet these challenges is important because natural disasters provide the most hope of a large number of survivors. Uninjured survivors may simply be stranded and can survive for up to 72 h.

As described in [50.8], responders are often left with no choice but to break up into small teams and begin searching in the largest centers of population with rescue on a *first-come first-served* basis. Because of the lack of pervasive communications, these teams and squads must work independently and typically with no real-time access to information being gathered by governmental agencies. Survivors may have hidden themselves in closets or in the attic, and therefore be difficult to detect. The risks to rescuers include live or suddenly re-energized electric lines, gas leaks, contamination from sewage, and victims who may try to protect themselves from perceived looters.

50.2.3 Suitable Robot Technologies for Natural Disasters

Natural disasters present unique opportunities and problems for robots. The major missions are to provide situational awareness of the distribution and degree of need of survivors (e.g., who needs immediate evacuation, who can remain in place longer), identification of routes of entry for responders, and assessment of conditions that may present a further immediate threat to life [50.8, 14]. These missions generally require coverage of large areas with information ideally provided immediately to the team of responders. As such, these types of missions favor the use of UAVs, particularly man-portable and man-packable models that can be launched as needed from small clearings and provide real-time video directly to the responders. Rotary-wing UAVs are useful even in densely forested rural areas to enable the assessment of rural areas and road damage. Both types of vehicles may be flown at night, but this would be subject to local airspace regulations.

It is important to remember that disasters often have a water-related component. Most of the world's population lives near a bay or river and relies on bridges and sea walls. USVs are expected to be of more benefit than UUVs in inspecting this infrastructure for several reasons [50.15]. They can be launched from a distance, and because they provide a view above and below the water line of bridges, sea walls, docks, etc. UUVs are difficult to control in swift water and may become easily trapped by debris in the aftermath of flooding or a cyclonic event.

As a whole, ground robots may not be as immediately useful as UAVs and USVs for natural disasters [50.8, 16]. Ground robots are handicapped by the number of dwellings and light commercial buildings that must be explored at least as rapidly as a human team, compounded by the need to often break down a door or window in order to insert the robot. It is unlikely that ground robots will be able to compete with canines and their ability to smell the presence of survivors without having to break and enter intact dwellings.

50.2.4 Manmade Disasters

In comparison to natural disasters, manmade disasters (such as a terrorist bombing or serious accident) occur in a small area. The challenge is often not how to see the entire external extent of the damage, but rather to see what is not visible: the interior of the rubble, the location and condition of survivors, and the state of potentially dangerous utilities (e.g., electricity, gas lines) [50.6, 17]. The communications and power infrastructure usually exist within a 10 km range and cell phones generally work outside of the collapsed area. Voids in the rubble may be irregular in shape and vertical in orientation. Wireless communications in the interior of the rubble is unpredictable, and generally nonexistent due to the large amount of steel within commercial structures, but the combination of irregular voids and sharp rubble do not favor the use of fiber optic cables. Visibility is difficult as there is no lighting and everything may be covered with layers of gray dust, further hampering recognition of victims, potential hazards, or accurate mapping. The interiors may be wet or contain standing water due to water lines, sewers, and sprinkler systems. Survivors are more likely to be in dire need of medical attention.

50.2.5 Suitable Robot Technologies for Manmade Disasters

The attractiveness of robots for manmade disasters stems from their potential to extend the senses of the responders into the interior of the rubble or through hazardous materials. UGVs are expected to be essential for building collapses, attacks such as the 1995 sarin release in the Tokyo subway, and responses to radiological disasters such as Chernobyl and Three Mile Island, while UAVs are key for mapping external plumes and spills of toxic chemicals. UGVs are expected to be the dominant modality for victim rescue in a building collapse, though other modalities might help with long-term recovery. This strongly suggests that UGVs should be waterproof or at least highly water resistant, since the interior of the rubble is likely to have some water present from the sprinkler and sewage systems. The small size and irregular shape of voids in the rubble also suggests that UAVs, no matter how small, will be unlikely to have enough space to fly in and navigate the interior.

50.3 Robots Actually Used at Disasters

While many types of robots have been proposed for search and rescue, only a few have actually participated in a rescue or been allowed to operate on site after a disaster for testing purposes; all of these have been teleoperated. Six of the seven disasters that have employed robots have occurred in the United States, with one in Japan (Table 50.1). The majority of deployments have fortunately been by scientists at the Center for Robot-Assisted Search and Rescue (United States) or the International Rescue System Institute (Japan), providing crucial information about robot design, concepts of operation, and human–robot interaction. In terms of ground robots, small tracked platforms dominate but there have been promising results with a snake robot fielded at the Niigati Chuetsu earthquake, as described below. Man-portable and man-packable fixed- and rotary-wing aerial platforms also have been useful at disasters. Many state National Guards in the United States own the Predator UAV. Unmanned surface vehicles have been used once with good results. Small UUVs such as the VideoRay

Table 50.1 Tables showing the modalities and sizes of robots deployed to actual disasters or used for experimentation at the disaster site

Disaster Deployment		UAV	UGV	USV
2001	World Trade Center, New York, USF		Man-packable Man-portable	
2005	La Conchita, California mudslides, USF		Man-packable	
2005	Hurricane Katrina, USA	Man-packable fixed wing Man-packable rotary wing	Man-packable	
2005	Hurricane Rita, USA	Maxi fixed-wing		
2005	Hurricane Wilma, USA	Maxi fixed-wing		
2006	Sago Mine, West Virginia, USA		Maxi	
Post-Disaster Experimentation		**UAV**	**UGV**	**USV**
2001	World Trade Center, New York, USF		Man-packable Man-portable	
2004	Niigati Chuetsu Earthquake	Man-portable snake		
2005	Hurricane Wilma, USA	Man-portable fixed-wing		Maxi
2005	Hurricane Katrina, USA	Man-packable rotary-wing		

are commonly used internationally to help find bodies after a car accident or drowning. Only three agencies are known to own ground rescue robots, the Tokyo Fire Department in Japan, the New Jersey Task Force 1 State Urban Search and Rescue team in the United States, and the United States Mine Safety and Health Administration. There is no known disaster where a robot actually found a survivor, though robots have generally received high marks for completing their search missions and finding remains.

50.3.1 2001 World Trade Center, United States

Unmanned ground vehicles were used at the World Trade Center 9/11 disaster in New York City, United States [50.10]. The disaster occurred on 11 September 2001 with terrorists crashing planes into the twin towers, which subsequently collapsed. Another building in the complex was sheared in half, and a fourth building burned down. Close to 3000 people and firefighters were killed immediately. A massive search-and-rescue response was conducted in the hope of finding trapped survivors in stairwells and basements covered under the pancaked debris of 110 storeys of collapsed steel structure.

Three species of small UGVs (Inuktun micro-VGTV, Inuktun micro-Tracks, and Foster-Miller Solem) were used initially to actively explore the rubble of the twin towers, Tower One and Tower Two, plus the partially demolished Tower Four. Later the Foster-Miller Talon was also used to inspect the building foundations. The UGVs were all affiliated with the DARPA Tactical Mobile Robots program, and were fielded under the direction of the Center for Robot-Assisted Search and Rescue (CRASAR) in conjunction with the state of New York State Emergency Management department and the New York Department of Design and Construction. Seventeen species of robots were available, but only the most portable, ruggedized, and user-friendly were actually selected for use by the responders.

The first robots arrived on scene by 16:00 on 11 September 2001 and tethered robots were put into service around midnight. Robots were used through to 2 October 2001, when the last robot broke. The robots and operators were deployed with several Federal Emergency Management Agency teams, especially Indiana Task Force One, through until 21 September 2001. The robots were used to explore voids with less than 1 m diameter that a person or dog could not enter or voids less than 2 m diameter that were still on fire. The robots found approximately 10 sets of remains in rubble 7–20 m below the surface but no survivors. Only one robot was lost, a Solem, which lost wireless communications, stopped in place, and the safety rope broke during retrieval; note that the density of the rubble significantly interfered with wireless networks. Later in September, as rescue became improbable, larger man-portable Foster-Miller Talon robots began to be used to explore the stability of the basement, especially the slurry wall. The slurry wall was a foundation shared by many other buildings in that part of New York and damage could create further structural difficulties. The

New York (City) Department of Design of Construction actually breached holes in likely locations of the perimeter of the basement in order to insert the larger robots.

The lessons learned fall into two categories: *design of robots* and *human–robot interaction*. These are summarized below, following [50.10]. Robot platforms will be operating in narrow, vertical spaces that pose communications interference. Each robot will need a safety rope and, if wireless, the wireless system should be replaced with a communications (fiber-optic) tether sturdy enough to act as a safety rope. Robots should be invertible, since the confined spaces often do not permit sufficient room for self-righting, and with sufficient waterproofing to permit decontamination and to operate in water, rain, and snow. The minimum payload is a color camera and two-way audio, while an operator control unit should contain record and playback video capabilities. Thermal imaging was not of use at the World Trade Center due to the overall heat in the voids, but is generally desirable.

50.3.2 2005 La Conchita Mudslide, United States

Ground robots were used unsuccessfully at the La Conchita mudslide [50.18]. On 10 January 2005, at the small town of La Conchita outside of Los Angeles, a sudden mudslide destroyed 18 houses, killed ten people and left searchers looking for six people missing for several days (the missing persons were out of the state on vacation). While this was not a mass disaster, it did extend beyond a local incident and engaged regional and national response teams.

CRASAR responded with an American Standard Robotics VGTV Extreme, a waterproof upgrade of the polymorphic Inuktun micro-VGTV used extensively at the World Trade Center. The robots were used twice and failed within two minutes and four minutes, respectively. The obvious reason for the failure in both cases was poor mobility. The robot was initially directed to search a crushed house where a canine team had indicated the possibility of a victim. The robot entered the house via a narrow gap between the foundation and flooring, but immediately failed when a root in the wet soil became lodged in the left track and it came off. In the second run, the robot was inserted into the intact second story of a house damaged on the lower floor to test a vertical entry. The robot detracked once again, this time due to the compliance of the thick shag carpeting. Though a poor track design (originally intended for movement on smooth ventilation ductwork) was the ultimate cause of failures, the severity of the design flaw was undetected by both the manufacturer and CRASAR due to the lack of adequate testing under realistic conditions.

The lessons learned for robotics from this disaster were that ground mobility remains a major challenge and that adequate testing is important. Open track designs appear to be unsuitable for rescue; they are too susceptible to detracking and vulnerable to debris becoming wedged in the tracks. Testing in diverse soil and interior terrain conditions is important, adding emphasis to the need for adequate standards.

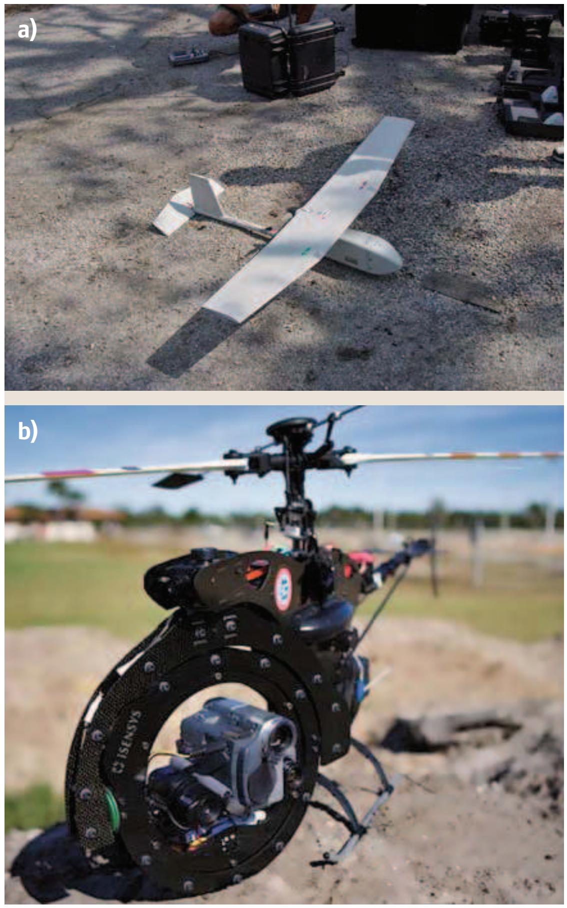

Fig. 50.1a,b Man-packable UAVs used to search portions of Mississippi during the hurricane Katrina response: **(a)** an anonymous fixed-wing UAV and **(b)** an iSENSYS IP3 rotary-wing UAV (courtesy of CRASAR)

50.3.3 2005 Hurricanes Katrina, Rita and Wilma, United States

State and military unmanned aerial vehicles were used in the aftermath of several hurricanes in the United States, along with a ground robot. In 2005, the southern Gulf Coast of the United States was battered by a series of hurricanes from June through November. Hurricane Katrina was the worst hurricane in the history of the United States. It made its primary landfall near New Orleans on 29 August 2005, devastating the states of Louisiana and Mississippi and portions of Alabama, impacting an area of 200 km^2, costing nearly 2000 lives, and leaving behind 80 billion US dollars in damage. Hurricanes Rita and Wilma were less extensive and damaged parts of Texas, Louisiana, and Florida.

The 2005 hurricane season saw the first use of UAVs for a large-scale disaster [50.16]. During the hurricane Katrina response, two UAVs were used by CRASAR in Mississippi as part of the Florida State Emergency Response Team to search rural regions cut off by flooding and downed trees. The UAVs are shown in Fig. 50.1: a battery-powered fixed-wing and a battery-powered rotary-wing (a Like90 T-Rex miniature helicopter modified for stability in high winds) UAVs. An internal-combustion Silver Fox was used later in the week over New Orleans by the Department of Defense to help identify which areas were still in need of assistance. All systems were under 2 m in their characteristic dimension, easily dismantled and transportable, and flew below regulated airspace, with procedures spontaneously developed to ensure safety and avoid collisions with manned aircraft. The UAVs were tasked for surveying, providing information directly to the responders rather than waiting for the data from unmanned helicopter flights to be processed and then manually transported to the responders in the field. In hurricanes Rita and Wilma, the Texas and Florida state National Guards flew much larger Predator UAVs in regulated airspace to provide timely information to strategic decision makers. The Predator class of UAVs are physically larger, require more people to operate, and a large take-off and landing zone, and must be coordinated with airspace operators since they operate at the same altitudes as manned aircraft.

An American Standard Robotics VGTV Extreme robot, the same model that failed at La Conchita, was used by Florida Task Force 3 State Urban Search and Rescue Team to successfully investigate the first floor of an apartment building in Biloxi, Mississippi, which was unsafe for human entry. The team did not have a canine and was unsure if a trapped victim would be able to shout in reply to an audio challenge, so the decision was made to deploy the robot. Unlike La Conchita, the area of operation was favorable and the interior was smooth linoleum. The robot showed that no one was trapped inside.

The lessons learned during the 2005 USA hurricane season were primarily related to how large, geographically distributed disasters influence the choice of robot modality and how they can be used. The disasters highlighted the need for miniature aerial vehicles which could provide tactical teams with viewpoints of 1–10 km on demand or viewpoints that had not been possible before (e.g., from a miniature helicopter) [50.19]. Autonomous waypoint navigation of fixed-wing platforms was available but was not used; instead responders were much more interested in actively directing the UAVs. This suggests that the ultimate control regime will not be full autonomy but rather enabling a responder to use the robot as if it were an extension of their person.

50.3.4 2006 Sago Mine Disaster, United States

A maxi-class ground robot was used at the Sago Mine disaster in the United States. On 2 January 2006, a mine explosion in Sago, West Virginia killed 12 miners and severely injured another. It took two days to reach the victims, who were approximately 3 km from the surface; the primary obstacle was not physical debris but the need to operate in an environment saturated with carbon monoxide and methane. The Sago Mine disaster is considered a disaster, despite the relatively small number of people trapped in a confined area, because rescue teams and equipment had to be deployed from other states and from the Mine Safety and Health Administration (MSHA).

A large Remotec ANDROS Wolverine robot was deployed by the Mine Safety and Health Administration. The Wolverine class of robot is primarily designed for bomb-squad applications, where its slow speed and heavy weight (over 500 kg) is not a disadvantage. The robot had been previously modified with an enclosure rendering it intrinsically inert in the presence of explosive gases and a fiber-optic communications tether added to improve communications. Even with its slow speed and limited agility, the robot has the advantage of being able to enter a mine faster than a person in a contained suit and also being less likely to create an explosion. Unfortunately, the robot, nicknamed V2, was only able to

Fig. 50.2 The V2 robot used at the 2006 Sago Mine Disaster (courtesy of the US Mine Health and Safety Administration)

penetrate about 700 m into the mine before getting stuck on rails.

The lessons learned from the use of a UGV at the Sago Mine disaster highlighted again the need for better mobility, communications, and navigational autonomy. It illustrated the need for robots to enter areas that are unsafe for humans, but also that simply *wrapping* a robot with an explosion proof enclosure is a stopgap measure; a new class of robots for operating in explosive environments is necessary. Communications remains difficult, and the fiber-optic tether is a vulnerable component. While the fiber-optic tether was not severed during the disaster deployment, it had been damaged in prior tests and reopenings of mines. The ability to maintain reliable wireless communications with more agile robots remains a top priority in underground rescue. Navigation via teleoperation is a known challenge and often distracts the operator from larger search and assessment issues.

50.3.5 Post-Disaster Experimentation

In many cases, the real hope of rescue has passed before robotics equipment can be requested and deployed. Fortunately, forward-thinking response personnel may allow roboticists to work in the disaster zone (hot zone) during the later stages of the rescue or the recovery. In these deployments, the robots were not actually used for rescue operations but rather for experimentation, allowing the response community to evaluate and comment on rescue robot progress as well as rescuers to collect valuable data. Operations in post-disaster conditions are much more realistic than the best test beds.

At the 2001 World Trade Center disaster, CRASAR teleoperated an iRobot Packbot and a SPAWAR Urbot in a collaterally damaged building and parking garage near the main disaster site [50.10]. While the robots worked largely as expected, one surprise was the negative impact of water and dust on stair climbing and general mobility. The water from the sprinkler systems and the dust made surfaces very slippery.

In 2004, the International Rescue System Institute (IRS) inserted a serpentine robot into a house damaged during the Niigata Chuetsu earthquake (Fig. 50.3). This was the first snake robot used at a disaster site and showed the promise of biomimetic alternatives to tracked platforms. The first quake occurred on 23 October 2004, and was the largest to have hit Japan since the Hanshin Awaji earthquake in 1995. Thirty-nine people were reported to have died and massive damage was done to the transportation infrastructure. The robot, a variant of the Soryu III robot developed in collaboration between the Tokyo Institute of Technology and IRS, is 1.2 m long and weighs 10 kg, with a turning radius of 0.41 m, and a maximum speed of 0.37 m/s. The IRS Soryu carried a charge-coupled device (CCD) camera, an infrared camera (FLIR), and two-way audio as well as proprioceptive sensors. The robot was controlled through a tether that also served as a safety rope. In addition, the Soryu can support a CO_2 sensor that can detect human breathing, navigation sensors such as a laser range finder, and localization sensors, though it does not appear that this was tested. The testing in the debris concentrated on mobility.

Three days after hurricane Wilma in 2005, CRASAR deployed both a modified Like90 T-Rex and a man-portable, experimental unmanned surface vehicle (USV) to inspect seawall and bridge damage at Marco Island,

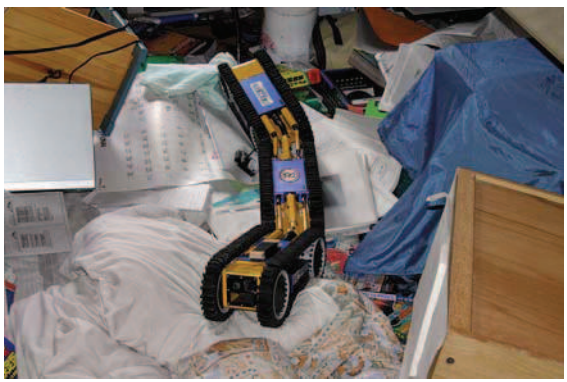

Fig. 50.3 IRS Soryu robot searching a house destroyed by the Niigata Chuetsu earthquake (courtesy IRS)

Fig. 50.4 Unmanned surface vehicle exploring the bridge to Marco Island, Florida (courtesy of CRASAR)

Fig. 50.5 A small UUV used for underwater inspection (courtesy of CRASAR)

Florida [50.15]. The USV, shown in Fig. 50.4, carried a DIDSON acoustic camera, capable of penetrating through turbid waters and mud, as well as a camera above the surface. The UAV was used independently to investigate damage topside, but was very helpful to the USV crew in establishing where the USV was in relationship to piers and pilings; this strongly indicates the need for UAV–USV teams. The use of the USV near and underneath large structures hampered wireless communications and Global Positioning System (GPS) signals, posing additional demands.

Three months after hurricane Katrina in 2005, CRASAR used a small rotary-wing UAV, an iSENYS IP3, to document the structural damage to multistory commercial buildings along the Gulf Coast impacted by hurricane Katrina [50.16, 19]. The eight days of intense flying, which duplicated emergency response missions, showed that three people are needed to operate a UAV safely close to urban structures: a pilot, a mission specialist to run the payload and take pictures, and a flight director to serve as safety officer and maintain overall situation awareness. The post-hurricane-Katrina effort confirmed the concept of operations from hurricane Wilma, where a mission consists of a short flight (five to eight minutes) on each face of the building, allowing the pilot and flight director to keep the vehicle in line of sight. This concept of operations fosters safety and reduces cognitive fatigue for the pilot. Although it is likely that teleoperated line-of-sight in the United States will be mandated, the close proximity to the building (1–3 m) indicates the need for semiautonomy, especially guarded notion, to assist the pilot and prevent collisions.

50.3.6 Search and Recovery

While ground and aerial rescue robots are new, very small underwater robot cameras such as that shown in Fig. 50.5 have been routinely used by law enforcement and fire rescue teams for over a decade to find submerged cars that have gone into the water. These operations are generally considered search and recovery, rather than rescue, because the victims have drowned and are beyond revival by the time the specialized equipment can arrive. The UUVs are miniature torpedo-like devices with cameras teleoperated by a person on the surface. The problems facing UUVs are sensing through the turbidity of the water and control of devices in strong currents that prevent them from being used in swift water.

50.4 Promising Robots and Concepts

Search and rescue is a demanding application and it is reasonable to expect that new types of robots will evolve to meet the challenge. Numerous speculative designs for unmanned ground and aerial vehicles have been proposed, and representatives that have been tested are described below. While approaches to search and rescue have mainly been presented in terms of single-robot activities, teams of robots proffer interesting future scenarios where teams of robots swarm and cooperate to accomplish their mission. Robots need not look like robots in order to be useful for search and rescue; unattended ground sensors, blimps, kites, and smart shores using the principles of robotics and artificial intelligence are poised to make a difference in the near future. In addition, basic research in legged robots (Chap. 16), wheeled robots (Chap. 17), micro/nanorobots (Chap. 18), multiple-robot systems (Chap. 41), networked robots (Chap. 42), general underwater robots (Chap. 44), and aerial vehicles (Chap. 45) are expected to yield more concepts for rescue robotics.

50.4.1 Alternative Ground Rescue Robot Designs

Polymorphic tracked vehicles represent the state of the practice of ground rescue robots. These tracked vehicles have been primarily used for navigation and sensing missions, ignoring missions that require manipulation. Wheeled platforms are severely limited by the roughness of the terrain and the need to overcome obstacles, steps, ramps, but combination wheeled and tracked vehicles are commercially available. Small tracked robots with manipulators have been developed for bomb-squad activities and appear well suited for transfer to rescue applications. In addition, many alternatives to tracks have been proposed. Of these, serpentine (or *snake*) robots and legged vehicles appear the most promising. Jumping or rolling robots have been proposed to cope with rough terrains, but their effectiveness still needs to be demonstrated.

Robots with manipulators (such as that seen in Fig. 50.6) extend the capabilities of ground vehicles by allowing the robot to sample the environment, interact with survivors, move light obscurations (manipulators typically cannot lift heavy objects), and add unique camera viewpoints. Operators of the Foster–Miller Talon robot at the World Trade Center disaster used the camera mounted on the robot arm to peer over railings and inspect the basement substructure below. Manipulator arms are often used as camera masts, allowing the operator to see more of the environment, examine the surfaces of desks, tables and counters, and to see if a robot is stuck or disabled. However, adding a manipulator comes at a cost. The manipulator extends the volume of the robot, impacting on navigation; the arm is often at risk of being damaged in confined spaces by being hit on overhanging rubble. Manipulators also add to the control and mechanical complexity of the robot.

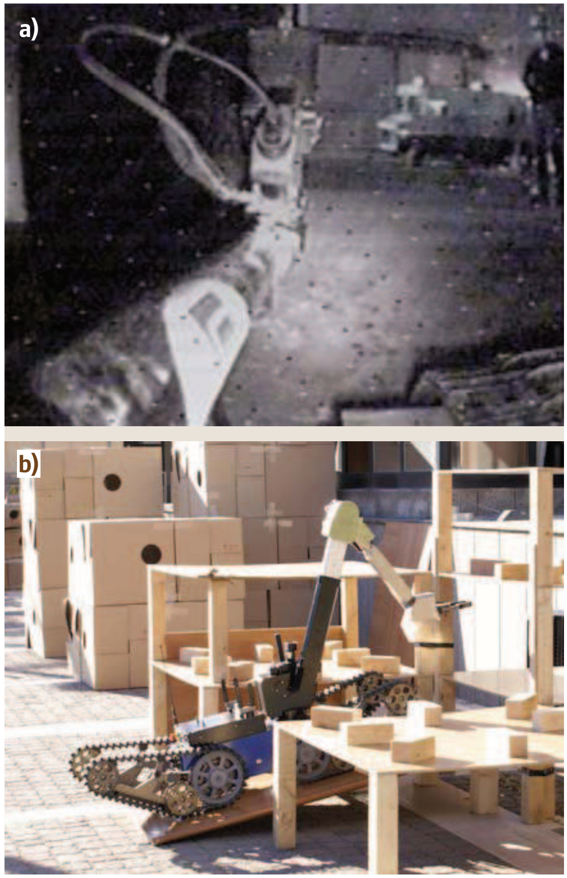

Fig. 50.6a,b Examples of tracked robots with manipulator arms that have been used for disasters or rescue competitions. **(a)** View from Foster–Miller Talon at the WTC of its arm (courtesy of CRASAR) and **(b)** telemAX by Telerob at the Rescue Robotics Camp (courtesy of R. Sheh)

Free serpentine robots such as the Soryu III used at the rubble at the Niigata–Chuetsu earthquake provide a fundamentally different style of mobility, while *fixed-based* snakes can be used in tandem with a more traditional platform as a highly flexible sensor manipulator [50.20]. Examples of both types of snake robots are shown in Fig. 50.3 and Fig. 50.7. Serpentine robots are more correctly known as hyperredundant mechanisms [50.21]. Free snakes propel themselves either by direct propulsion, making direct contact with the ground, or undulation, wriggling the internal degrees of freedom of the robot. Snake robots present some of the most demanding challenges for roboticists [50.22]. In order to be truly deployable, much work is needed in design and actuation, as well as control. Autonomous gaits need to

Fig. 50.7 A CMU fixed-base snake being tested at a facility in California (courtesy H. Choset)

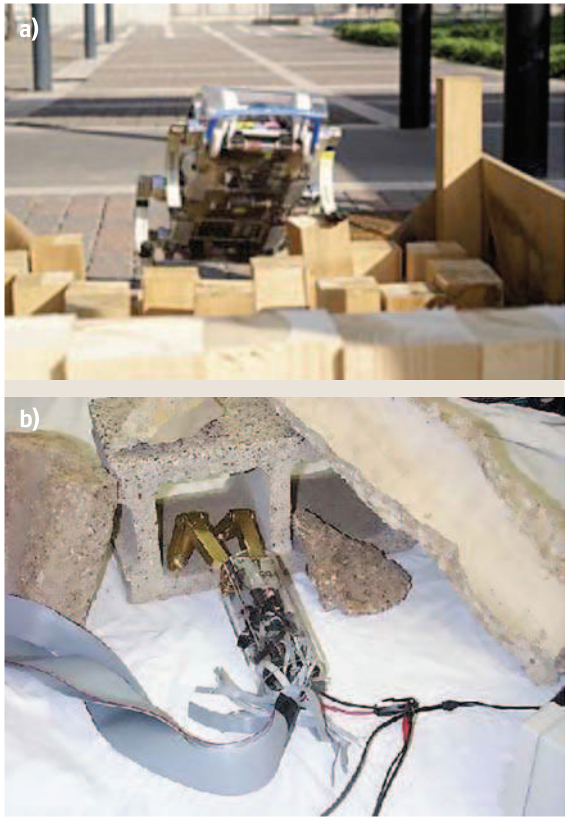

Fig. 50.8a,b Examples of legged and crawler robots. **(a)** Hexapod (legged) robot from the RHex project traversing a portion of the NIST test bed (courtesy of R. Sheh) and **(b)** Terminatorbot being tested in rescue test bed (courtesy of R. Voyles)

be developed in conjunction with a sensor skin that will let a snake move in confined spaces out of the line of sight of an operator.

In order to overcome the difficulties posed by unknown terrain, legged robots and crawler robots have been proposed. In addition, some types of crawler robots can climb walls and reach locations that would otherwise be very hard to reach. Legs are interesting because they exploit biomimetic principles. The RHex hexapod robot [50.23], proposed for search and rescue among other potential applications, is shown in Fig. 50.8 climbing random step fields. The legs on RHex are curved and rotate, yet duplicate the spring-like capabilities of insect legs. They illustrate how biologically inspired forms of locomotion do not have to look like animal legs to achieve the same effect. RHex has favorable mobility properties but the slapping motion of the legs may stir up large amounts of dust in interior building collapses and interfere with sensing. Crawler robots such as the Terminatorbot [50.24] use their arms or legs to pull themselves through the rubble. The Terminatorbot is designed to withdraw itself into a cylinder that can be inserted through one of the small boreholes commonly drilled by responders to get through walls, then open up and begin moving. Other types of crawlers include lizard- or gecko-like robots that adhere to walls; these types are promising but have not been tested for the dusty, wet, and irregular conditions found in disasters.

50.4.2 Aerial Rescue Robots

Aerial rescue robots represent the most advanced robotics technology in use, and new concepts continue to emerge. Aerial vehicles can be further subdivided into *fixed wing* (a.k.a. plane-like), *rotary wing* (helicopters), *lighter-than-air* (blimp), and *tethered* (kite) platforms. Fixed-wing UAVs typically travel long distances and can circle points of interest, while rotary-wing platforms can hover and require a small area to launch and land. Lighter-than-air vehicles may be tethered, similar to a kite. Underwater vehicles may also be subdivided into tethered and untethered platforms.

Large unmanned helicopters, such as the Yamaha R-Max, continue to be adapted for commercial rescue-and-recovery missions, including carrying heavy payloads capable of estimating the amount of rubble and debris generated by a disaster. Small fixed-wing platforms for tactical military use may have great benefit to the response community. Novel ideas include a plane the size of a person's hand that can fly indoors and planes with foldable wings, making it easier for responders to carry them. Novel rotary-wing designs are also being proposed. Quadrotor helicopters appear far more stable and easier to pilot; a design that balanced the larger size of a quadrotor with an appropriate payload could make UAVs more assessable to non-pilots. Another exciting direction is hybrid platforms that can change from fixed-wing operations, covering large distances, to rotary-wing operations, flying near or inside buildings [50.25]. However, UAVs are drawing the attention of agencies that control airspace and may become heavily regulated in the future.

50.4.3 Unique Concepts of Operations

Current rescue robot scenarios have typically complemented or enhanced human capabilities, but within a fairly conventional, single-robot framework. New concepts of operations for exploiting rescue robots are being continuously identified. At this time, the major themes are *multi-robot teams* or *swarms*, robots forming or extending *communications and sensor networks*, *smart tools*, and *roboticized animals*. Past experience has shown that current ground robots are not appropriate for multi-robot team operations; relatively few voids occur that current robots could explore and these may be in different sectors assigned to different teams, so the idea of an operator managing 10 or more robots each actively investigating the rubble is speculative for now.

Teams of robots that cooperate with each other or work on the same objective have already been demonstrated for rescue activities. Homogeneous teams have been entered at the RoboCup rescue competition [50.26]. After hurricane Wilma, a UAV and USV team accomplished together what a single USV could not [50.15]. The small Inuktun robots used at the World Trade Center were actually intended to be the daughters (or joeys) of a marsupial (kangaroo) team, where a larger ground robot would deposit the smaller robots into voids [50.27]. (In reality, responders carried and inserted the robots.) Aerial vehicles that drop intelligent sensors and motes is another type of heterogeneous team. One of the most intriguing types of teams is swarms. Researchers such as [50.28] have discussed the possibility of using cost-effective, insect-sized robots to penetrate deep within a pancake building collapse and then signal the presence of a victim. Such teams can make use of collective intelligent behaviors from simple animal models that are far more complex than the behavior exhibited by the individuals. Consequently, robot teams can be composed of a large number of simple devices, thus yielding greater robustness to failure and distributed information gathering. One of the key features of swarm approaches is that they can scale up easily. The insect swarm scenario leaves hard problems like control, sensing payloads, localization of the victim, and communications to the imagination, but is certainly a worthy concept. However, some of the search algorithms used by insects may be adapted to single robots, for example win-shift win-stay sampling exhibited by bees may be useful for search [50.29].

Robots, stationary and mobile, can facilitate the establishment of communications and sensor networks. As repeaters for mobile ad hoc networks, robots on the land, sea, and air can extend the range and throughput of wireless networks [50.30]. Aerial vehicles are particularly attractive as they can provide larger relay ranges while providing a bird's eye view of the disaster. However, a UAV does not always have to move: a tethered blimp or kite can support a sophisticated payload with no maintenance or support for days [50.31, 32].

Another concept is that of *smart* tools, particularly lifts that can help stabilize collapsed structures during extrication [50.33, 34]. Extrication is one of the most time-consuming activities in rescue. Rescuers must proceed cautiously when removing rubble in order to prevent secondary collapses or slides that would further injure the survivors. Experiments suggest that roboticized lifts or shoring mechanisms would be able to sense and respond fast enough to small movements in the rubble to adaptively maintain stability. [50.34]

The trend towards miniaturization of sensors and wireless communications has led some researchers to propose having search dogs carry roboticized cameras (dog-cams) or wiring rats with controllers. Attaching cameras to search dogs has been explored for several years and such a system was used at the World Trade Center. The concept does not compete with robots, as robots are used to enter places canines cannot. The canine team handlers have generally objected to dog-cams because the cameras and communications gear interfere with the dog's mobility, pose the hazard of snagging, and the dog cannot be readily commanded to stop at points of interest beyond the line-of-sight of the handler (dogs use visual cues as commands, more than audio). However, there is less objection to placing nodes in a rat's brain to stimulate and drive the rat into a void while carrying a camera or other sensors [50.35]. The motivation for a robot rat stems in part from the rat's mobility and relative low value. While the technical feasibility of a robot rat may be within reason, assuming advances in wireless communications, the response community has been lukewarm towards the idea [50.36]. Unlike rates, robots can be kept in storage for years and can penetrate through pockets of fire or areas with no oxygen. A robot rat has all of the limitations of dog, including the problem of a handler becoming too emotionally attached, and is likely to scare a trapped survivor just as much as the other rats that swarm a disaster. The conventional wisdom is that, if the sensors, wireless, and power systems can be miniaturized and operate reliably enough to control a rat deep within rubble, those systems will enable responders and robots to work without the rats.

50.5 Evaluation and Benchmarks

There are a variety of methods for evaluating a rescue robot or the larger mixed human–robot system. *Simulations*, either through computer simulations or physical test beds duplicate some key component of a disaster or a disaster on a smaller scale, are common. Simulations provide availability and repeatability. *Demonstrations* at physical test beds, such as training sites for responders or through the RoboCup rescue competition, have been the primary source of feedback about rescue robots. Demonstrations can provide feedback on the performance of a robot under known conditions and to a lesser extent about the mixed-team performance. Demonstrations are often not repeatable but do offer a higher degree of physical fidelity with expected disaster settings than can be achieved through computer simulation. Simulations can be used for statistically significant experimentation, however, the need to control the number of variables in an experiment often leads to a form of reductionism, where a hypothesis is tested but under such artificial conditions as to undermine the value of the experiments. *Technology insertions* into actual disasters provide valuable information, though that information is not repeatable, and the ground truth is often unknown and generally relies on the skill of the observers.

In order to evaluate a rescue robot or mixed human–robot team, there must be metrics and measurement methods. Unfortunately, rescue robotics is such a new field of endeavor that metrics and methods are still currently under development. The scope of the evaluation influences the choice of metrics and methods. Rescue robots can be evaluated within at least four different categories:

1. the physical attributes of the robot, which can be further broken down by subsystem
2. the human operator performance
3. the performance of the humans and robots together as a mixed team
4. the impact of the robot team on the survivors or non-team members

At this early stage in the development of rescue robots, metrics and methods are being proposed for physical, operator, and team performance [50.37].

Metrics and methods are used by technologists to measure progress towards a useful product while standards represent that product's minimum capabilities and attributes and enables consumers (in this case, the response community) to purchase worthwhile systems. Standards rely on metrics and methods for measuring compliance, though these may sometimes be different from those used by researchers and developers. The US government National Institute of Standards and Technology (NIST) is leading the effort to standardize rescue robots for adoption by US responders. This effort is being conducted through ASTM and thus, even though it is largely driven by the US, will likely result in an international standard that may be adopted by other countries. NIST has considerable experience in testing rescue robotics, beginning with the creation in the late 1990s of a portable standard test bed for search and rescue for use by the RoboCup rescue and AAAI mobile robot competitions.

50.5.1 Computer Simulations for Rescue Robotics

Computer simulations provide a low-cost mechanism to explore the larger behavior or a robot or system. Generally, computer simulations provide high fidelity for testing software execution, but their physical fidelity depends on the physics engine. Simulating sensors and the complex environments produced by a disaster is difficult and is rarely accurate enough to test perceptual algorithms. At the time of writing, two readily available computer simulations exist for exploring the strategic and tactical applications of rescue robots within the RoboCup rescue framework [50.38], the *RoboCup rescue simulation project* [50.39] and *USARSim* [50.40]. These simulations are well understood, accepted, open-source, and free; as such, they should be useful for most researchers or practitioners interested in ground-based rescue robotics.

The RoboCup rescue simulation project is used in the RoboCup rescue simulation league to study agent-based approaches to strategic planning for the disaster response. The simulator assumes a strong centralized response capability that is not necessarily the case for all countries or regions; the United States, for example, relies on a highly distributed organization that obviates many centralized coordination schemes. Although the simulation is focused on strategic decision making, particularly dynamic resource allocation, it does support the examination of how robot resources might be allocated during a disaster and how data from a robot might be propagated through a system. It permits the simulation of monitoring of disaster damage from reports by humans, distributed sensors, and robots and can simulate complex interactions such as telemedicine.

USARSim is a computer simulation developed by the University of Pittsburgh for physical robot simulation in disaster situations [50.40]. The simulation replicates the NIST standard test bed for search and rescue and permits efficient prototyping and testing of robot design and most aspects of control software. It uses Unreal game engine for handling physics and graphics, and virtual robots have capability of sensing (image, laser range finder, etc.) and actuation (wheel, motor, etc.) with data processing (image recognition, SLAM, etc.) in artificial environments. In 2006, the RoboCup rescue competition created a simulation league using this environment.

50.5.2 Physical Test Beds

Physical test beds provide a more realistic venue than a computer simulation for evaluating rescue robots, but may not be available to researchers, too expensive to use or to travel to, or not adequately capture some key aspect of a disaster. Physical test beds generally fall into two categories: *test beds developed for the fire rescue community* or the *NIST standard test bed for search and rescue*.

Fire rescue training test beds occur throughout the world and are used to train human firefighters and rescue specialists. Some facilities are also used to train canine teams. These test beds are constructed from construction and sewer debris, can introduce smoke and some simulants, and pose challenging mobility conditions, but vary in terms of fidelity. In many test beds, the density of the debris does not contain the actual amount of metals in a real collapse. This can lead to optimistic reports of success of sensors and wireless communication devices. The test beds, being designed for human training, do not replicate the conditions under which a ground robot would be used. The terrain is generally on the exterior of the rubble and does not exercise the robot in confined

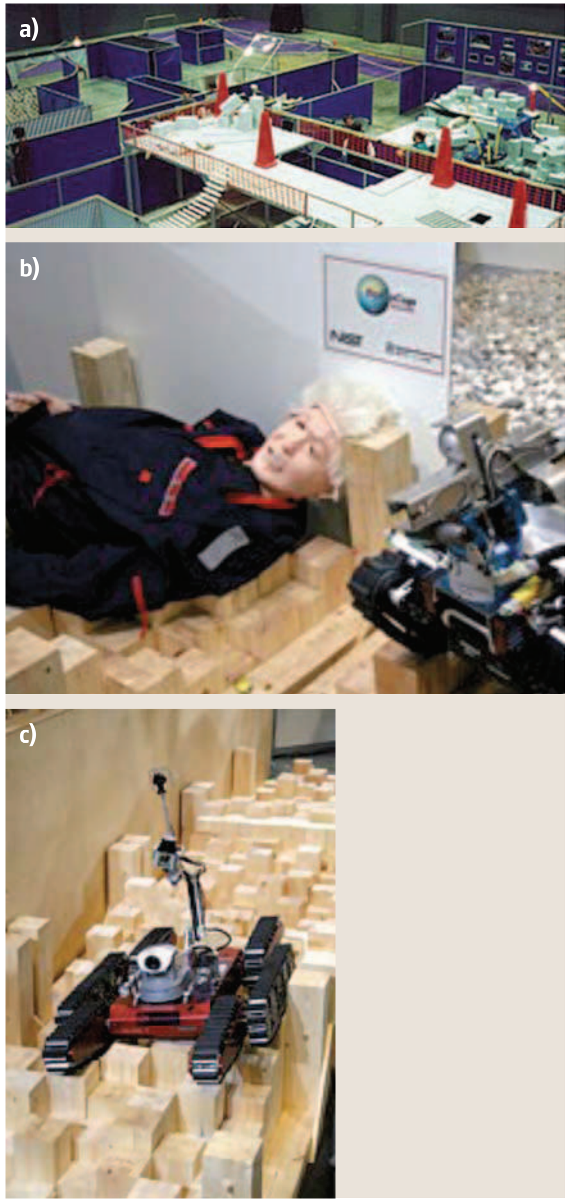

Fig. 50.9a–c View of the NIST standard test bed for search and rescue used by RoboCup Rescue. **(a)** View of overall test bed, **(b)** dummy representing a victim, and **(c)** a step field challenging robot mobility (courtesy NIST)

or vertical spaces. Depending on the size of the facility, the test bed may or may not be suitable for evaluating UAVs. An example of a fire training test bed appeared earlier in Fig. 50.7b.

Perhaps the most influential physical simulation for researchers is the RoboCup rescue physical league which uses the NIST standard test bed for search and rescue, shown in Fig. 50.9. This competition started in 2001 [50.41] and has more than 40 team entries every year from all over the world. The RoboCup rescue physical league scores robot performance in terms of mobility, mapping, situation awareness, sensing, shared autonomy, etc. A robot or robot team competes in one of three arenas which simulate disaster situations at the annual RoboCup world competition. The mission of the robot teams is to collect victim information (existence, state, and location) by sensor fusion of vital signals (heat, shape, color, motion, sound, CO_2, etc.) and report a map of victims in disaster space so that responders can efficiently arrive at the victim for rescue. In addition to the arenas, the competition and test bed contain individual skill test stations, for example, in order to test mobility, robots must traverse a random step field made of wood. The test bed was designed to be portable and reasonably inexpensive and several locations around the world have set up duplicates. As a result of the constraints of cost and portability, the test bed is not fully representative of actual disaster physical conditions and does not test the operating conditions for the human teams.

50.5.3 Standards Activity

Standards for rescue robots and systems are being generated at the time of writing. The E54.08 subcommittee on operational equipment within the E54 Homeland Security application committee of ASTM International started developing an urban search and rescue (USAR) robot performance standard with the National Institute of Standards and Technology (NIST) as a US Department of Homeland Security (DHS) program from 2005 to 2010. It plans to cover sensing, mobility, navigation, planning, integration, and operator control in order to ensure that the robots can meet operational requirements under the extreme conditions of rescue. The standards will consist of performance measures that encompass basic functionality, adequacy and appropriateness for the task, interoperability, efficiency, and sustainability. The components of the robot systems include platforms, sensors, operator interfaces, software, computational models and analyses, communication, and information. Development of requirements, guidelines, performance metrics, test methods, certification, reassessment, and training procedures is planned.

50.6 Fundamental Problems and Open Issues

Rescue robotics is clearly a challenging field with many open issues. This section discusses the challenges by subsystem (mobility, communications, control, sensors, power), then the general human–robot interaction (HRI) challenges, and finally the remaining problems in evaluation. In addition to these specific areas discussed below, there are three cross-cutting challenges that should be mentioned: how to reduce mission times; how to localize, map, and integrate data from the robots into the larger geographic information systems used by strategic decision makers; and how to improve the overall reliability of rescue robots.

One of the most pressing challenges that cut across all subsystems is how to make rescue robot operations more efficient in order to find more survivors or provide more timely information to responders. Since rescue robots typically perform missions that humans cannot do, it is hard to compare performance directly. However, it may be useful to consider how robot operations can be made more efficient in terms of pre-mission preparation (e.g., how long does it take to set up the robot system), mission execution, and post-mission activities (e.g., how long does it take to change batteries, decontaminate, inspect for wear, or perform minor repairs, etc.). Efficient mission execution remains the subject of much research, particularly investigations into how to speed up navigation through rubble or damaged areas with faster robots or autonomy. Studies have consistently shown that ground robots operating in the interior of collapsed buildings are physically moving only 51% of the time and that only 44% of the operator's activities are directly related to navigation [50.42]. Therefore speeding up mission activities such as building situation awareness and recognition may be as important to any type of rescue mission as speeding up navigation.

Rescue robots are tasked with missions where geographical information would help responders. For example, for ground robots, finding the presence of a survivor in rubble is helpful, but knowing the location of the survivor is better, and knowing the path of the robot and the condition or type of rubble along the path even more helpful to extrication. Unfortunately, ground and surface vehicles are generally tasked in areas where structures prevent reliable GPS reception and underwater vehicles cannot receive GPS signals. Fixed-wing aerial vehicles, such as those used after hurricane Katrina, Rita, and Wilma, generally come with software that permits path mapping in GPS coordinates that can be displayed on maps, as well as determining the GPS location of any object in the camera view. Improvements to ground and surface vehicle mapping are expected to be a function of sensor miniaturization. As seen in Chap. 38, significant progress has been made in three-dimensional (3-D) simultaneous localization and mapping using range sensors larger than fieldable rescue robots.

Reliability of rescue robotics is obviously important, as robots which frequently break or need copious amounts of maintenance will be discarded. Failures may stem from physical failure, due to manufacture or unanticipated demands of the environment, or human error, including design failures or operator errors. As of 2004, ground rescue robots exhibited a mean time between physical failures (MTBF) of only 20 h, meaning that robots break every other shift, well below the desired 96 h proposed by the US military as the minimum for ground robots for urban operations [50.43]. In practice, a field ground or aerial robot system consists of two or three robots to provide complete redundancy, plus tools and spare parts.

50.6.1 Mobility

Mobility remains a major problem for all modalities of rescue robots, but especially for ground vehicles being used for urban search and rescue. The challenges for ground robots stem from the complexity of the environment, which is an unpredictable combination of vertical and horizontal elements with unknown surface characteristics and obstacles. The field is currently lacking any useful characterizations of rubble to facilitate better design. However, even without a complete understanding of rubble environments, it is clear that more work is needed in actuation and mechanical design as well as in algorithms that would enable the robot to adapt its mobility style to the current terrain (also known as *task shaping* [50.44]). Aerial vehicles, particularly helicopters, are vulnerable to wind conditions near (or in) structures and obstacles such as power lines, trees, and overhanging debris. Surface and underwater vehicles have to contend with swift currents and floating or submerged debris, placing significant demands on agility and control.

50.6.2 Communications

Robots rely on real-time communications for teleoperation and for enabling responders to see what the robot is seeing immediately. Ground robots communicate either through a tether or via wireless radio. Aerial and surface robots are wireless, while underwater rescue robots are controlled via a tether. The communication bandwidth demands of all modalities are generally high due to the use of video imagery, and the tolerance to communications latency is low due to the control needs. In addition to communications between the tactical rescuers and their robots, it is difficult to report or transfer critical information provided by rescue robots to the strategic enterprise. Disasters typically destroy the communication infrastructure, both telephones and cellular phones, and alternatives such as satellite phones become saturated by response agencies.

Wireless communications with robots remain problematic. Operations below ground or near structures interfere with the physical propagation of radio signals. As shown in high-fidelity US&R response exercises, ad hoc wireless networks established by responders are likely to become quickly saturated, with no way of establishing priority over information. At the World Trade Center, data from the Solem robot deployed in the interior of building WTC4 returned totally black frames for 1 min 40 sec of the 7 min run before wireless communications were totally lost and the robot was abandoned [50.10]. In addition, many wireless robots use lossy compression algorithms to manage bandwidth, which interfere with computer vision techniques, and/or connect through insecure links, raising the possibility that news media might intercept and broadcast sensitive video of trapped victims.

Rescue robots working underground, either for US&R or mine rescue, have two alternatives to wireless communications: either operate with a tether or deploy repeaters to maintain wireless communications. Many wireless robots now can be purchased with a fiber-optic tether; however, these tethers are fragile and may break or tangle. The fiber-optic tether may also tangle with the safety rope used to support the robot during vertical drops. Data for the World Trade Center deployments indicated that a dedicated person was required to manage the tether but that 54% of tether management operations were to allow the robot to reach a more favorable position or to recover the robot after its mission [50.10]. Hybrid communications, in which a robot is primarily on a tether then operates for short distances over a local wireless link before reconnecting to the tether, appear to be attractive.

50.6.3 Control

Robot control can be subdivided into *platform control*, which is usually considered by control theory, and *activity control*, which generally falls under the purview of artificial intelligence. Rescue robots are challenging both for traditional control and for artificial intelligence. The high degree of mechanical complexity of all modalities and the demands of the environment present major challenges for control theory. The robot's activity is usually handled by teleoperation; a human is needed to direct the robot and to perform mission sensing. The well-documented problems of manual teleoperation (see Chap. 32 Telerobotics) argue for increasing autonomy [50.45].

50.6.4 Sensors

Sensors, and sensing, pose the greatest mission challenge; without adequate sensing, a robot may be in an area of interest but be unable to navigate or to execute the larger mission. The physical attributes of a sensor (size, weight, and power demands) impact on whether it can be used with a particular robot platform. Currently sensors are not interchangeable between platforms; standards are needed for footprint sizes, mounting, connections, and display space.

The functionality of a sensor depends on the modality and mission [50.17]. The primary sensor missing from all robot modalities operating outside of water is a miniature range sensor. With a miniature range sensor, the success in localization and mapping seen with larger robots would be transferable to rescue robots. The sensor payloads for other missions depend on those applications; however, two sensor needs for US&R are particularly noteworthy. One is a detector that can perceive victims obscured by rubble; current radars have not been reliable in mixed rubble. Another needed sensor is one that can tell if a victim is unconscious but alive without touching the victim. A robot may be able to see a victim, yet not be able to crawl to the victim and make contact or scrape away enough dirt or clothing to take a pulse. Stand-off detectors such as millimeter-wave radars and gas detectors appear promising but have not been validated at this time.

Smaller, better sensors are not sufficient; improvements in sensing algorithms are also needed. At this time, humans are expected to interpret all sensing data manually in real time. This is a daunting task for many reasons. Human performance is handicapped by physiological factors introduced by sensing through a computer display (also known as computer mediation), the location of sensors at viewpoints low to the ground, generally restricted fields of view, and fatigue. The modality output itself may also be nonintuitive, such as ground-penetrating radar. However, autonomous detection and general scene interpretation is considered well beyond the capabilities of computer vision. This presents a case where neither the human nor the computer can accomplish the perceptual task reliably and argues for investigation into human–computer cooperative techniques for perception. Algorithms that enhance the image for human inspection, supplement depth perception, or cue interesting areas are within the reach of computer vision.

50.6.5 Power

The robot modality and mission poses distinct challenges for power. In general, battery power is preferred over internal combustion because of the logistics difficulties in transporting flammable liquids. While the requirements of each rescue robot application is largely unknown, a partial understanding is emerging of the power profile. For example, the operation tempo of a ground vehicle operating underground is on the order of 3–4 runs, each around 20 min in duration, over a 12–14 h shift, with the robot kept on hot standby for the majority of the shift. Rotary-wing aerial vehicles for tactical reconnaissance and structural inspection show an operations tempo of 5–8 min per face of a building, while fixed-wing vehicles are airborne for less than 20 min. Other rescue missions, such as wilderness search and rescue, will have different requirements but the need for batteries over internal combustion and for determining the power profile is the same.

The size and weight of the power source is important. It may be the single driver in the overall size of the platform and influence key design attributes such as the placement of the payload. A word of warning is warranted: a common design flaw in rescue robots is to locate the batteries so as to maximize stability but with the unintended consequence of making it very time-consuming to reach and replace them in the field without special tools.

50.6.6 Human–Robot Interaction

Human–robot interaction (HRI) has emerged as a major challenge in rescue robotics and has been declared to be an exemplar domain within HRI [50.12]. Robots are part of a humancentric system; even if robots were fully autonomous, responders want the information in real time and the option to modify the robot's tasks. There are at least four key problems to be resolved in HRI. First, there is the issue of *human-to-robot ratio* for operations. Currently a single robot requires between two and three humans, depending on modality, for safe reliable operation. Second, these *operators have to be extensively trained*, which may be out of the question for many response teams. Third, user interfaces for operations do not provide sufficient situation awareness and need improving, which may in turn reduce training demands. Fourth, humans will interact with the robot outside of the operator role and this leads to a need for *affective robotics*. For example, a survivor will have a relationship with the *front* of a robot [50.46] as well as a rescuer working alongside a robot [50.47].

Reducing the human-to-robot ratio is probably the best known challenge for HRI. Unmanned aerial and water-based vehicles for defense and research applications have a long tradition of at least two operators per vehicle, one as a pilot, the other as a payload specialist. The number may increase due to payload or mission complexity or safety (e.g., the requirement for a safety officer). Unmanned ground vehicles have presumed that a single operator is sufficient to drive and look, though studies with ground rescue robots dispute this and show a ninefold increase in performance when two operators work cooperatively [50.42]. Since rescue workers work in teams of two or more, a single-operator single-robot control regime is not essential [50.12]. The need for multiple humans impacts on the viability of alternative scenarios, such as swarms or teams of multiple robots; these may require too many operators unless higher degrees of autonomy and situation awareness are possible.

Training is a related issue in human–robot interaction [50.48]. Rescue workers have limited time compared with military operations to learn about robots and few opportunities to practice. While a bomb squad or special weapons and tactics team for law enforcement may be called out several times each month, a rescue team may be called out only a few times each year. For the near future, rescue workers may not have had prior training or experience with a robot prior to the disaster and be expected to use prototypes with only *hasty* training.

Situation awareness is defined by *Endsley* in [50.49] as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." *Drury* et al. [50.50] have defined types of situation awareness within search and rescue based on an analysis of RoboCup rescue tasks, while *Casper* and *Murphy* [50.51] and *Burke* et al. [50.42] have examined operator situation awareness in technology insertions. User interfaces are a key component in facilitating situation awareness. In rescue robotics, user interfaces are generally primitive and work through the operator's visual channel to provide robot, task, and situation awareness of the state of the robot, task progress, and the general operational environment. To highlight the importance of user interfaces, one robot at the World Trade Center was rejected because of the complexity of its interface [50.10]. While the user interface for fieldable rescue robots primarily display the video output from the robot, experiences from RoboCup rescue suggests that a good interface will both facilitate commanding the robot (inputs) and will provide three types of information (outputs):

- the robot's perspective: camera view(s) from the robot's current position, plus any environmental perceptions that enhance the general impression of telepresence
- sensor and status information: critical information about the robots internal state and its external sensors
- if possible, a map: a bird's eye view of the robot situated in the local environment

There has been a move towards videogame-like interfaces for ground vehicles; this is consistent with the 10 min *rule* of human–computer interaction that states that if a user cannot figure out how to use the main function of a computer within 10 min, the interface is flawed. However, the videogame interface may facilitate rapid,superficial control of the robot at the cost of limiting the transition to expert control which might not be best handled by a handheld controller. In general, all assessments of rescue robot interfaces agree that the operator's visual channel is overloaded: the operator is expected to see too much and is likely to miss important information or become quickly fatigued. The use of other modalities such as sound, spoken language, and tactile feedback is warranted, though care must be taken to consider whether such modalities will work in the noisy environs of a rubble pile or will interfere with personal protection equipment.

The focus of human–robot interaction on the operator and human–robot ratio has led to the issues associated with humans *in front* or *beside* the robot to be ignored. Ideally, rescue robots will interact with trapped survivors and facilitate their care and comfort. Likewise, a robot may be inserted into a confined space to act as the surrogate for a team member, such as a team leader or safety officer. Studies show that people view these robots socially, that is, they may ascribe traits of being scary or unhelpful based on the way the robot looks and moves [50.46]. Therefore, affective robotics applies to rescue robots as well as entertainment robots.

50.6.7 Evaluation

Evaluation of rescue robots is difficult not only because of the diversity of platforms and missions but also because each disaster is truly different. In addition, robots are part of a humancentric system: they are operated by humans in order to provide information to humans. Evaluation of the performance of a rescue robot system at an actual disaster is currently ad hoc. No computer or physical simulation for predicting the performance of robots and humans in a disaster has been validated; indeed, there is little argument that simulations are far easier than a real response. The difficulties of simulation are exacerbated by the differences between disasters. For example, the World Trade Center was unique in terms of the large amount of steel and the density of the collapsed material, while earthquakes and hurricanes are different from terrorist events.

Metrics for measuring performance remain a worthwhile quest. Quantitative metrics, such as the number of survivors or remains found, do not capture the value of a robot in establishing that there are no survivors in a particular area. Performance metrics from psychology and industrial engineering are only now beginning to be applied. These methods require enhanced computer and full-scale simulations in order to collect data. Data collection on human and overall system performance during a disaster has been done through ethnographic observations and are now moving to direct observations of situation awareness during demonstrations [50.42, 52]. Direct data collection during a disaster may not be possible as methods may interfere with performance (and therefore be unreasonable, if not unethical) and arouse fears by operators of *Big Brother* and being held liable for any errors in operation.

50.7 Conclusions and Further Reading

Rescue robots are making the transition from an interesting idea to an integral part of emergency response. Aerial and ground robots have captured most of the attention, especially for disaster response, but water-based vehicles (both surface and underwater) are proving useful as well. Rescue robots present challenges in all major subsystems (mobility, communications, control, sensors, and power) as well as in human–robot interaction. Man-portable and man-packable systems are the most popular because of their reduced logistics burden, but the size of the platforms exacerbates the need for miniaturized sensors and processors. Wireless communications remains a major problem. While recent deployments have relied on polymorphic tracked vehicles, researchers are investigating miniature planes and helicopters, new robot designs, especially biomimetic, and alternative concepts of operations. Standards are currently under development and this will help accelerate the adoption of rescue robots. The annual IEEE Workshop on Safety, Security and Rescue Robotics is currently the primary conference and clearinghouse for research in rescue robotics.

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