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SURVEY ARTICLE

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The current state and future outlook of rescue robotics

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Abstract

Robotic technologies, whether they are remotely operated vehicles, autonomous agents, assistive devices, or novel control interfaces, offer many promising capabilities for deployment in real-world environments. Postdisaster scenarios are a particularly relevant target for applying such technologies, due to the challenging conditions faced by rescue workers and the possibility to increase their efficacy while decreasing the risks they face. However, field-deployable technologies for rescue work have requirements for robustness, speed, versatility, and ease of use that may not be matched by the state of the art in robotics research. This paper aims to survey the current state of the art in ground and aerial robots, marine and amphibious systems, and human–robot control interfaces and assess the readiness of these technologies with respect to the needs of first responders and disaster recovery efforts. We have gathered expert opinions from emergency response stakeholders and researchers who conduct field deployments with them to understand these needs, and we present this assessment as a way to guide future research toward technologies that will make an impact in real-world disaster response and recovery.

KEYWORDS

emergency response, extreme environments, search and rescue robotics

1 | INTRODUCTION

Disaster management has been viewed as a cyclical process for several decades (Neal, 1997), encompassing the immediate response to a disastrous event, as well as the longer term recovery efforts and preparations for future incidents. Organizations that are involved in large-scale disaster management activities and policy-making, for example, the United Nations International Strategy for Disaster Reduction (UNISDR; UNISDR, 2015), and the International Federation of Red Cross and Red Crescent Societies (IFRC; SRC, 2016), focus on the need for a multisector approach, incorporating scientific research in all phases of disaster management, along with efforts from government and business entities. A variety of robotic technologies have been deployed in real disaster response scenarios, and have proven that they can be useful (Kruijff-Korbayová et al., 2016; Murphy, 2014). The primary goal of this paper is to provide a concise summary of the state of the art in research areas that are relevant for rescue work, to inform the disaster management community of current research trends and the technological capabilities of the deployable robotics systems of the near future. A secondary goal is to provide some insights into the alignment of this study with stakeholder needs, through several interviews with high-profile experts.

A survey of every relevant development from perception, mechanical design, mission planning, etc., would be far beyond the scope of a single paper. While we attempt to at least touch on major trends across the many disparate topics encompassed by rescue robotics, this paper features a more significant focus on advancements to the state of the art in robot locomotion, human–robot interfaces, and collaborative robot teams. On the other hand, for broad and non-rescue-specific topics such as simultaneous localization and mapping (SLAM), we refer to existing survey papers, which provide far more depth and breadth than we could here. Unlike quantitative assessments of state of the art search and rescue (SAR) robots, such as the evaluations performed by the US Department of Homeland Security and National Institute of Standards and Technology (Jacoff & Messina, 2006; Jacoff et al., 2017, 2014), we are targeting a qualitative assessment of the state of the art in research. While both types of assessments can inform researchers and stakeholders alike, we consider these evaluations from the measurement science community on specific robot performance metrics to be complementary to our analysis of the thematic developments from the research community.

The disaster management cycle is defined with different stages and different levels of granularity depending on the source, but at a high level it takes the form of three or more stages covering the immediate response to a disaster through to the long-term preparation for future events. In this paper, we follow the four-stage disaster management cycle defined by Robin Murphy (Murphy, 2014):

rescue activities during or in the immediate aftermath of a disaster, to save lives or prevent further property damage; timescale of hours to weeks.
reconstruction of property and infrastructure, as well as support for rebuilding the social, economic, and health aspects of the affected communities; timescale of months to years.
of future disasters or mitigation of their effects; ongoing activities.
of the community for what to do in the event of an emergency situation; ongoing activities.

Technology plays a vital role in the *prevention* and *preparation* phases (UNISDR, 2015), and robotic systems have been used effectively in a number of *response* and *recovery* scenarios (Murphy, 2014). These deployments include the use of unmanned ground vehicles (UGVs) to search for survivors and remains in the collapsed rubble after the September 11, 2001 attacks (Murphy, 2004b), and unmanned aerial vehicles (UAVs) to search for stranded people after Hurricane Katrina in 2005 (Murphy, Griffin, Stover, & Pratt, 2006; K. Pratt, Murphy, Stover, & Griffin, 2006). UAVs and UGVs have been used during the recovery stage for inspection of buildings after the 2011 Christchurch earthquake in New Zealand (Murphy, 2014), and for collaborative 3D mapping of damaged buildings after the Tohoku earthquake in Japan the same year (Michael et al., 2012). The tsunami and Fukushima Daiichi nuclear disaster that followed the Tohoku earthquake saw additional use of robots in the recovery phase, with remotely operated underwater vehicles (ROVs) being used to recover bodies in flooded areas (Murphy, 2014), and additional UGVs and UAVs were used to operate remotely in areas of the nuclear power plant that were dangerous for humans (Nagatani et al., 2013). Novel robot morphologies, such as snake-like robots (Arai, Tana ka, Hirose, Kuwahara, & Tsukui, 2008), have also been deployed successfully (Hutson, 2017). Many further examples exist where robots were teleoperated or had partial autonomy and provided enhanced situational awareness of a disaster site for rescue workers (Murphy, 2014).

In the last several years, new developments from the research world have dramatically expanded the capabilities of robotic platforms that can deploy in adverse conditions. Due to this rapidly changing landscape, previous surveys of the state of the art such as (Jinguo, Yuechao, Bin, & Shugen, 2007; Liu & Nejat, 2013; Murphy, 2014; Murphy, Tadokoro, & Kleiner, 2016) require updates to document the latest developments. The rise of vision-based flying robots has enabled many new applications for aerial platforms, which are no longer restricted to near-hover flight in open outdoor areas to maintain global positioning system (GPS) control (Faessler et al., 2016). Research into legged robots has matured significantly as well, with new approaches to control and actuation making it possible to traverse challenging terrain with agility and robustness (Bellicoso, Bjelonic, et al., 2018a; Fankhauser, Bjelonic, Bellicoso, Miki, & Hutter, 2018). Additionally, novel robot morphologies have explored bioinspired designs with promising rescue applications (Horvat, Melo, & Ijspeert, 2017b). As the level of autonomy of field-ready systems has increased, the operator is increasingly decoupled from the need to control a robot at a low level. This trend has created opportunities for the development of novel human–robot interfaces that redefine the way in which operators can interact with one or more robots. Some of these technologies have already made their way into commercial products that focus on inspection or remote sensing tasks, and can be used in the *prevention* and *preparation* phases of the disaster cycle. Other nonautonomous technologies are seeing increasing adoption during the *response* and *recovery* phases, for example, the use of remote-controlled drones to aid in rescuing swimmers (Kwai, 2018), and the deployment of robots and wearable exoskeletons for firefighting (Chia, 2018; SCDF, 2018). The state of the art in this current research era is the focus of our survey.

The contributions of this paper are twofold:

- to present a survey of the current state of the art in rescue robotics research focusing primarily on the period between 2014 and early 2018, for the benefit of both the research community and disaster management stakeholders;
- to highlight, through the expert opinions of disaster management professionals, some deficiencies of current research in addressing the needs of rescue workers, and to identify opportunities for future research directions that will provide enhanced capabilities through the application of robotic technology in the disaster management domain.

This paper is organized as follows. In Section 2, the state of the art for the relevant research domains and robotic modalities is presented. Section 3 provides interviews with expert stakeholders discussing the properties that are required of robotic systems for useful deployment in real-world rescue scenarios, and the aspects of rescue work that are not addressed by current robotic systems. Finally, in Section 4, we analyze the disparity between the research and rescue communities to provide some conclusions about promising avenues for future research that would both advance the state of the art and provide tangible benefits in disaster scenarios.

2 | STATE OF THE ART

In this section, we survey the most recent developments in the relevant robotics research areas, focusing primarily on the period between 2014 and early 2018. We organize the state of the art by robot modality (e.g., ground, aerial), but there is indeed significant overlap in problems of perception, navigation, hardware design, and communication across these domains. Our goal is to capture at least the most significant trends in these research areas, with respect to the capabilities that they enable for SAR applications.

2.1 | Ground robots

One of the primary challenges in the deployment of ground robots in disaster scenarios is the most basic: movement in the environment. Unlike the navigation challenges for other ground-based systems, for example, autonomous cars, where the system can leverage some knowledge about structure in the environment, and generally does not need to overcome significant obstacles to reach its goal, disaster zones do not offer either of these conveniences. The environment is generally unstructured as well as being unknown in advance, and often contains obstacles that must be negotiated in order for a ground robot to traverse to reach goal locations. The popular locomotion types for ground robots offer different advantages in overcoming these challenges. Legged robots offer the ability to step over challenging terrain but require more sophisticated approaches to control. Tracked and wheeled robots, on the other hand, offer stability and straightforward navigation and planning, but at the expense of requiring a continuous path. We consider the state of the art in design and operation across both locomotion types.

2.1.1 | Legged robots

One of the most significant programs to stimulate research in ground-based SAR robotics in recent years was the Defense Advanced Research Projects Agency (DARPA) Robotics Challenge (G. Pratt & Manzo, 2013). The challenge focused on semiautonomous operation in emergency response scenarios, requiring the robot platform to interface with human-engineered environments and tools and overcome nontrivial navigation obstacles. Consequently, many of the robots took on a humanoid morphology (Atkeson et al., 2015; Feng, Whitman, Xinjilefu, & Atkeson, 2015; Johnson et al., 2015; Kaneko et al., 2015; Kohlbrecher et al., 2015; Kuindersma et al., 2016; Tsagarakis et al., 2017). However, some of the highest-placing teams in the competition developed novel morphologies for their platforms. These included a system with four articulated legs that ended in steerable wheels (Schwarz et al., 2017), as well as two platforms that could transform their posture between legged and wheeled configurations to leverage fast motion over flat surfaces and dexterity for more delicate behaviors. Team RoboSimian (Karumanchi et al., 2017) utilized a platform with four general-purpose limbs in a primate-like arrangement, along with active and passive wheels that could be used when the robot assumed a sitting posture. The eventual winners of the competition, Team KAIST, used a platform that was humanoid in design, but could transition between bipedal walking and wheeled rolling when in a kneeling pose (Jung et al., 2018).

Adaptability is an important feature for robot platforms in disaster environment, not just in their intended design, but also in enabling robustness to damage that might occur during operation in unconstrained natural environments. Inspired by the trial-and-error behavior of animals to adapt to injuries, learning algorithms can be used to enable a robot to rapidly adapt to damage (Cully, Clune, Tarapore, & Mouret, 2015), for example, to the loss of a limb in a legged robot or to reduced range of motion in one of its joints. Modularity and reconfigurability are also appealing properties for legged robot designs (Kalouche, Rollinson, & Choset, 2015), particularly in SAR situations, in which the morphology of the robot can be adapted to best suit the environment in a rapid deployment. Legged platforms that are capable of being easily reconfigured for different missions with modular sensor and actuation payloads (Hutter et al., 2017) offer appealing properties as well, by enabling operation throughout all of the phases of the disaster cycle. One major challenge with the legged locomotion modality is the need to perceive and map the environment to plan safe footholds (Fankhauser et al., 2018), which operation in rough terrain is dependent upon. While many quadrupedal research platforms have been developed (with hydraulic [Semini et al., 2015], electrical [Seok et al., 2013], or series-elastic actuation [Hutter et al., 2012]), only ANYmal (Hutter et al., 2017) has been used in real-world applications (see Figure 2). Outside of the research world, Boston Dynamics has developed several quadrupedal platforms for military applications, including BigDog (Raibert, Blankespoor, Nelson, & Playter, 2008), but no scientific publications exist describing any of their modern systems.

The "quadrupeds" that are deployed most often in rescue scenarios are trained dogs, whose capabilities complement those of human rescuers. Some recent efforts have equipped these working dogs with a sensor payload of cameras (Ferworn, Waismark, & Scanlan, 2015) as well as inertial measurement units, GPS receivers, and chemical sensors (Bozkurt et al., 2014). By augmenting SAR dogs with such mobile technology, rescuers can leverage the advantages of ground-based mobile robots as well as the capabilities of trained working dogs (e.g., cognitive abilities, acute visual, auditory, and olfactory sensing, and ability to overcome obstacles and maneuver through small spaces) to enable robust remote sensing.

2.1.2 | Tracked and wheeled robots

In the years since an initial survey of ground robots from research institutions (Jinguo et al., 2007), many companies have commercialized those technologies. For example, IDMind Lda (IDMind, 2018)

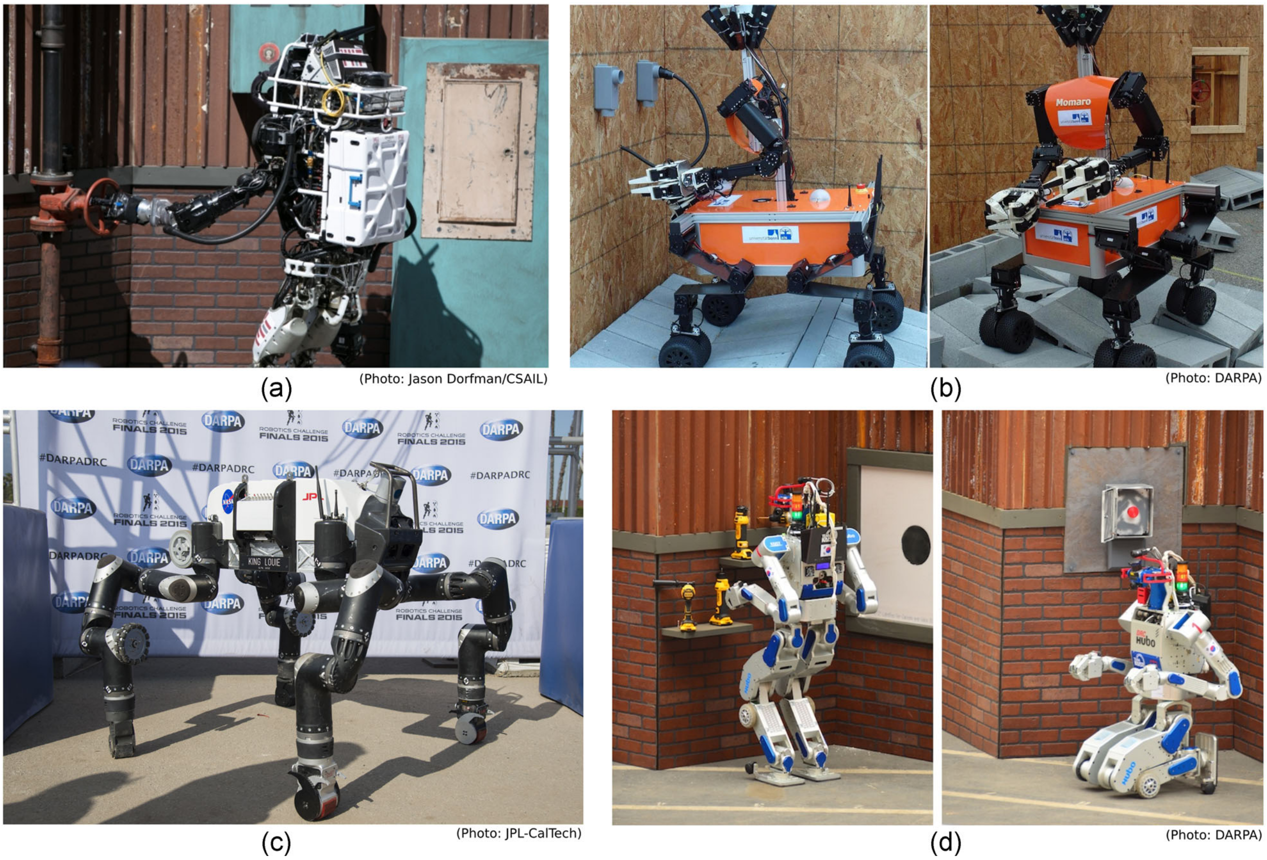

FIGURE 1 Examples of different robot morphologies used by teams in the DARPA Robotics Challenge. Many teams, such as (a) MIT (Kuindersma et al., 2016) used bipedal/humanoid designs, (b) Team NimbRo Rescue (Schwarz et al., 2017) used articulated, wheeled legs, while (c) NASA-JPL's RoboSimian (Karumanchi et al., 2017) and (d) Team KAIST (Jung et al., 2018) utilized platforms that could transform between rolling and walking postures. DARPA, Defense Advanced Research Projects Agency [Color figure can be viewed at wileyonlinelibrary.com]

upgraded the early version of the Raposa tracked robot (Marques et al., 2006) for commercial purposes. Part of the push for the technological development on ground robots is due to their increasing deployment in natural disaster scenarios (Michael et al., 2012; Nagatani et al., 2013). These deployments also push the research community toward increased navigation capabilities on complex terrains, such as driving on stairs (Endo & Nagatani, 2016) or slippery slopes (Yamauchi, Nagatani, Hashimoto, & Fujino, 2017). Companies like Telerob (TELEROB, 2018) offer a whole family of wheeled and tracked robots ready for deployment in harsh environments.

Another push to reach a higher level of maturity for tracked and wheeled robot platforms comes from open robotic challenges. In the ARGOS challenge (ARGOS, 2017), Team Vikings successfully deploy a tracked robot (Pierre, Yohan, Rémi, Pascal, & Xavier, 2017), while Team Argonauts won the final challenge with a tracked robot from the company TAUROB (TAUROB, 2017). For the DARPA Robotic Challenge (G. Pratt & Manzo, 2013), robots like RoboSimian (Karumanchi et al., 2017) and Momaro (Schwarz et al., 2017) showed novel hybrid designs to combine the navigation capabilities of wheels and legs. The RoboCup Rescue competition (Sheh, Schwertfeger, & Visser, 2016) also generates advancements in the state of the art in SAR robotics, for example, in robust perception (Chen et al., 2017) and mission planning (Wu, Lee, & Hsu, 2015).

Several recent European projects have utilized tracked or wheeled ground platforms in different rescue environments. ICARUS (De Cubber et al., 2012) focused on developing integrated tools for SAR, utilizing teams of air, ground, and marine vehicles with ad hoc communication networks. This team included two UGVs with tracked locomotion, one large and one small, with complementary capabilities based on their size and sensing/actuation suites (De Cubber et al., 2013). TRADR (de Greeff, Hindriks, Neerincx, & Kruijff-Korbayova, 2015) developed human–robot teams to permit persistent operation in disaster response scenarios and also included a tracked platform in the team. These tracked robots are upgraded-research version of the original NiFTi robot developed by BlueBotics (BlueBotics, 2012). This team was successfully deployed for inspection of damaged buildings after the 2016 earthquake in central Italy (Kruijff-Korbayová et al., 2016).

While many ground platforms serve as remote sensing platforms in these deployments, two other applications for tracked and wheeled robots that have been explored are victim interaction or extraction, and remote firefighting. Rather than just locating victims, several proposed systems would be capable of spreading open

FIGURE 2 Modular quadrupedal robot ANYmal being deployed in challenging disaster environments (Hutter et al., 2017), highlighting its ability to navigate over rough terrain and in degraded sensing conditions, and demonstrating its resistance to fire and water [Color figure can be viewed at wileyonlinelibrary.com]

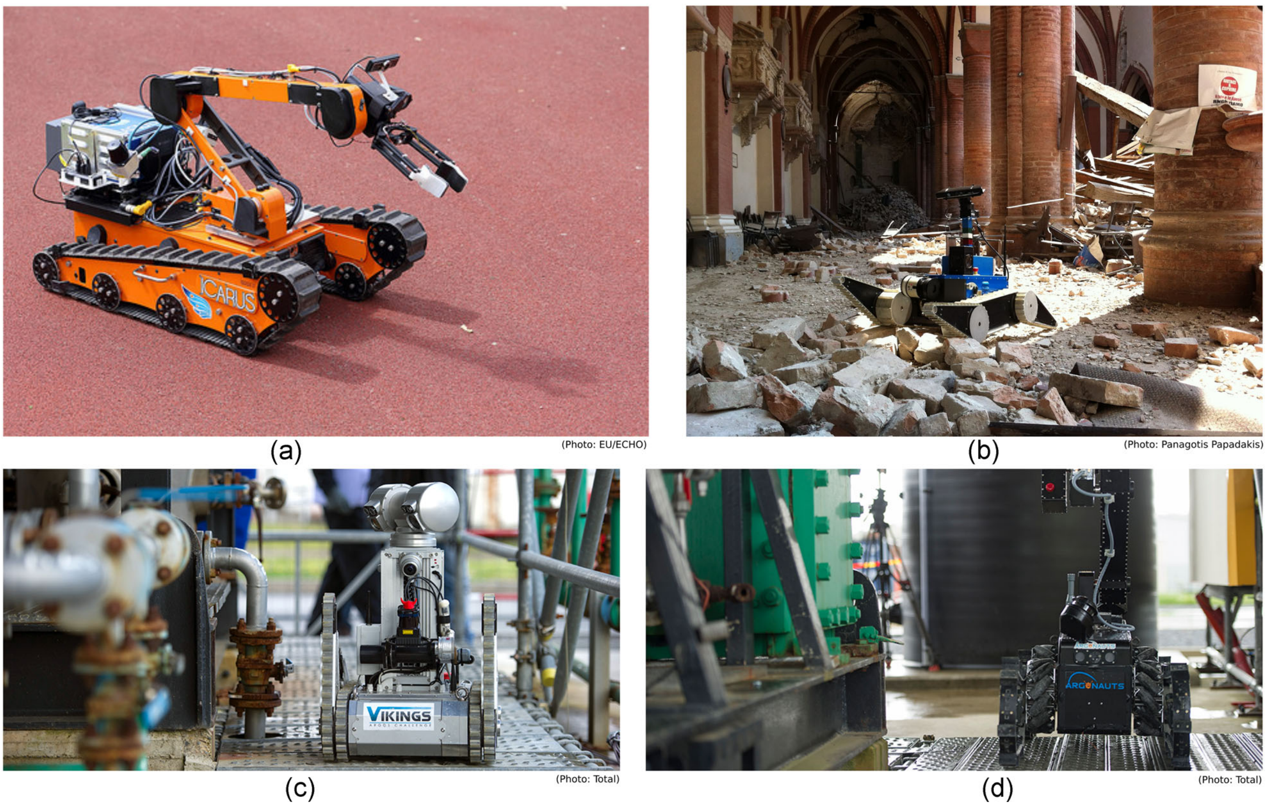

FIGURE 3 Tracked and wheeled robot platforms have been deployed in many recent rescue-oriented projects, including (a) ICARUS (De Cubber et al., 2012), (b) building assessment after the 2016 central Italy earthquake (Kruijff-Korbayová et al., 2016), and (c) the ARGOS Challenge (ARGOS, 2017), which a (d) tracked TAUROB (TAUROB, 2017) robot won [Color figure can be viewed at wileyonlinelibrary.com]

narrow gaps to free victims trapped in rubble (Guowei et al., 2014), or loading an incapacitated victim onto a stretcher and then extracting them under teleoperative (Ota, 2011; Saputra & Kormushev, 2018) or manual control (Iwano, Osuka, & Amano, 2011). Another potential capability for interacting with victims is through telepresence, in which a remote medic can provide support to the victim, or potentially guide the human–robot interaction for rendering aid (Henkel, Suarez, Srinivasan, & Murphy, 2016). Due to the heavy and stable physical properties of some tracked platforms, they also have the potential to fight fires in conditions that would be dangerous for humans by carrying remotely operated water hoses (Schneider & Wildermuth, 2017; SCDF, 2018).

Projects specifically investigating the use of tracked and wheeled platforms in SAR environments are in addition to ongoing research into the navigation and locomotion of such vehicles. Many of these advances, for example point cloud registration for mobile robot localization and mapping (Dubé et al., 2016; Pomerleau, Colas & Siegwart, 2015) and autonomous stair climbing (Ohashi et al., 2017) target deployment for inspection, but would be applicable in the SAR domain as well. While ground robot localization has typically been performed using laser-based range sensors, visual and hybrid laser/visual methods have been proposed (Chen et al., 2017) to improve robustness in SAR scenarios. However, a full survey of advancements in ground robot perception that are not specifically targeting SAR applications is outside the scope of this paper.

2.2 | Aerial robots

Unmanned aerial robots offer many benefits for rescuers in a disaster scenario. Their overhead perspective can be useful for surveying and situational awareness (Erdelj, Natalizio, Chowdhury, & Akyildiz, 2017; Marconi et al., 2012), but they can also navigate through small spaces or fly over obstacles that may be obstructed for ground-based platforms (Falanga, Mueggler, Faessler, & Scaramuzza, 2017; Falanga, Kleber, Mintchev, Floreano, & Scaramuzza, 2018). However, their size and power constraints often mean that their sensor payloads are restricted and their flight time is low, and their fragility requires precise perception and control to avoid collisions or collision tolerant designs, potentially limiting their effectiveness in disaster scenarios.

2.2.1 | Design

Aerial robots are becoming ubiquitous in SAR scenarios thanks to their capability to gather information from hard to reach or even inaccessible places. The use of drones in SAR missions has been fostered not only by advances in control and perception, but also by new mechanical designs and materials. For instance, advances in drones' design and manufacturing have contributed to the development of important features for SAR such as collision resilience, transportability and multimodal operations.

Collision tolerant drones that can withstand collision with protective cages (Briod, Kornatowski, Zufferey, & Floreano, 2014; see Figure 4a) or resilient frames (Mintchev, de Rivaz, & Floreano, 2017; Mintchev, Shintake, & Floreano, 2018) can fly in cluttered environments without the caution and low speed often required for sense and avoid approaches.

The quest for transportable drones that can be easily deployed on the field is the main motivation for the development of foldable frames (Dufour, Owen, Mintchev, & Floreano, 2016; Kornatowski et al., 2017; Mintchev & Floreano, 2016; see Figure 4b). By incorporating foldable structures, a relatively large drone with sufficient payload and flight time can be stored and transported in a small volume, while providing safety for handling by operators, as well as collision tolerance in cluttered environments. Foldable frames are also investigated to reduce the size during flight and traverse narrow gaps and access remote locations (Riviere et al., 2018; Zhao et al., 2018; see Figure 4c).

Most current drones are designed to exploit a single locomotion mode. This results in limited versatility and adaptability to the multidomain environments encountered in SAR missions. Multimodal drones overcome this problem by recruiting different modes of locomotion, each one of them suited for a specific environment or task (Lock, Burgess, & Vaidyanathan, 2013). Among the different types of locomotion modes, flight and ground locomotion (Daler et al., 2015; Kalantari & Spenko, 2014; Morton & Papanikolopoulos, 2017; Mulgaonkar et al., 2016; see Figure 4d) or climbing (Pope et al., 2017; see Figure 4e) are complementary and their combination offers unique opportunities to largely extend the versatility and mobility of robots. The option of aerial and terrestrial locomotion modes allows robots to optimize over either speed and ease of obstacle negotiation or low power consumption and locomotion safety. For example, in a SAR missions, aerial locomotion can be used to rapidly fly above debris to reach a location of interest. Terrestrial locomotion can subsequently be used to thoroughly and efficiently explore the environment or to collect samples on the ground. Scansorial capabilities allow to perch on surfaces and remain stationary to collect information with minimal power consumption. Furthermore, multimodal aerial and terrestrial locomotion also enables hybrid control strategies where, during terrestrial locomotion, steering (Mulgaonkar et al., 2016) or adhesion (Pope et al., 2017) can be achieved or facilitated by aerodynamic forces. Multimodal locomotion has been also exploited to develop FlyCroTugs, a class of robots that add to the mobility of miniature drones the capability of forceful manipulation (Estrada, Mintchev, Christensen, Cutkosky, & Floreano, 2018). FlyCroTugs can perch on a surface and firmly hold on to it with directional adhesion (e.g., microspines or gecko adhesive) while applying large forces up to 40 times their mass using a winch. The combination of flight and adhesion for tugging creates a class of 100 g drones that can rapidly traverse cluttered three-dimensional terrain and exert forces that affect human-scale environments for example to open a door or to lift a heavy sensory payload for inspections.

2.2.2 | Perception and control

With the increasing maturity of visual-inertial odometry and SLAM systems (Scaramuzza et al., 2014), visual state estimation for flying robots in GPS-denied areas has become robust (Cadena et al., 2016),

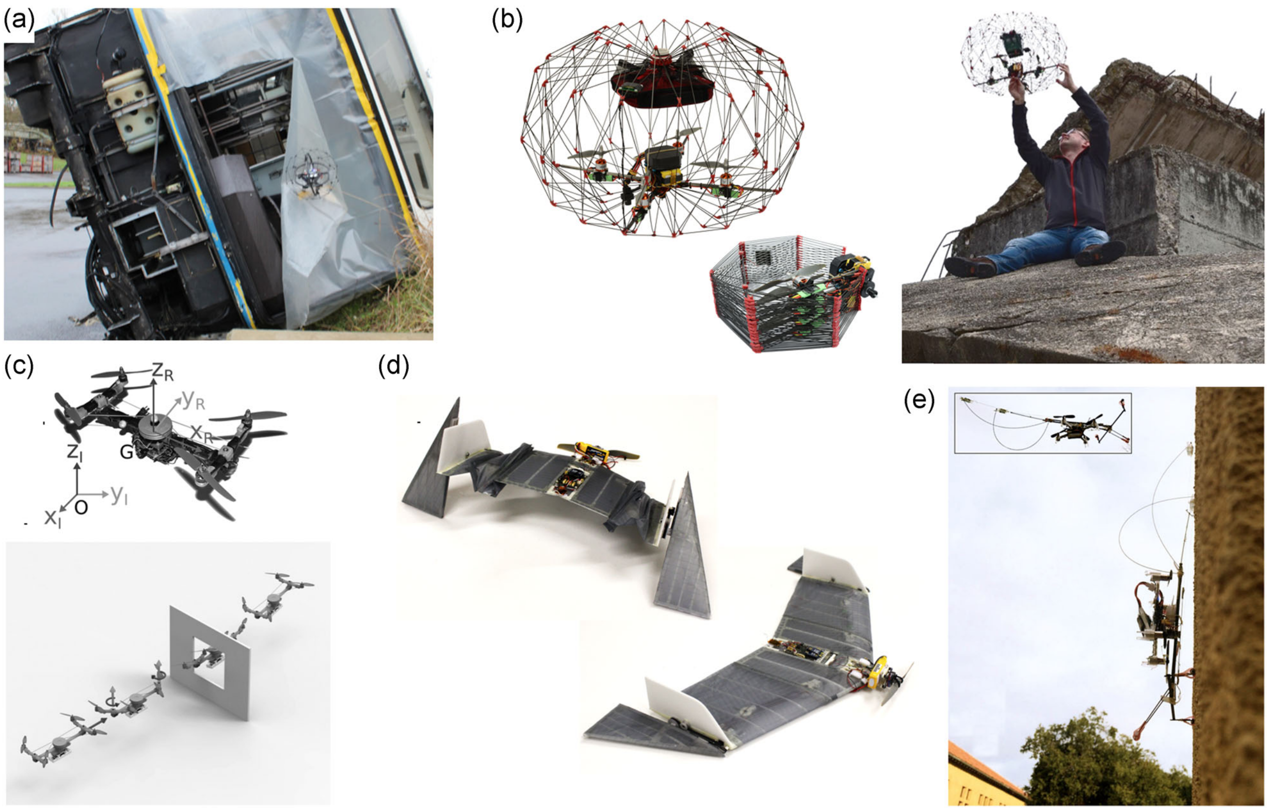

FIGURE 4 A selection of flying robots with novel morphologies, which offer beneficial properties in disaster environments. (a) Gimball being tested in a realistic disaster scenario (Briod et al., 2014). (b) PackDrone, a foldable drone with protective cage for in-hand delivery of parcels (Kornatowski, Mintchev, & Floreano, 2017). (c) A drone able to negotiate narrow gaps by folding (Riviere, Manecy, & Viollet, 2018). (d) Multimodal flying and walking wing (Daler, Mintchev, Stefanini, & Floreano, 2015). (e) Multimodal flying and climbing quadcopter (Pope et al., 2017) [Color figure can be viewed at wileyonlinelibrary.com]

and offers the promise of more effective UAV platforms for SAR in a wider array of environments. Precise localization of camera-equipped UAV platforms has enabled many applications that are relevant to SAR, such as high-resolution 3D reconstruction (Faessler et al., 2016), fast flight through cluttered environments (Mohta et al., 2018), and terrain mapping for ground robot guidance (Delmerico, Mueggler, Nitsch, & Scaramuzza, 2017). Other perception tasks on flying robots, such as dense map construction for inspection (Bircher, Kamel, Alexis, Oleynikova, & Siegwart, 2018), person tracking (Häger et al., 2016), and forest fire monitoring (Yuan, Liu, & Zhang, 2015) are also relevant for SAR scenarios, and can enable more complex autonomous behaviors from the flying platform. Another important avenue of research is the use of teams of UAVs to provide aerial mapping capabilities for SAR. Heterogeneous teams can enable the integration of different sensor modalities, but require fusion and registration of their heterogeneous data To provide useful maps (Hinzmann et al., 2017; Shen, Zhang, Li, Gao, & Shen, 2017), and such teams must utilize more sophisticated organization and mission planning than single-robot operations (Doherty et al., 2016).

On the control side, while relatively low-speed navigation in open areas at near-hover conditions is mature, there are active research areas pushing to increase the capabilities, robustness, or aggressiveness of aerial robot flights. For example, aerial manipulation (Ruggiero, Lippiello, & Ollero, 2018), aggressive flight (Faessler, Franchi, & Scaramuzza, 2018), and navigation in teams with space constraints (Tang, Thomas, & Kumar, 2017), offer promising applications in disaster environments. Some of these advances is UAV capabilities have been achieved by utilizing model-predictive control, for example, in collision avoidance (Andersson, Wzorek, Rudol, & Doherty, 2016), or reinforcement learning (Andersson, Heintz, & Doherty, 2015; Hwangbo, Sa, Siegwart, & Hutter, 2017) for control policies. One application that requires a tight coupling of both perception and control is dynamic flight through small apertures (Falanga et al., 2017; Loianno, Brunner, McGrath, & Kumar, 2017; Sanket, Singh, Ganguly, Fermüller, & Aloimonos, 2018). These types of trajectories would be necessary in some disaster environments when a flying robot needs to reach inaccessible areas, for example in a collapsed building (see Figure 5). Additionally, many of the relevant research areas have been advanced through multiyear competitions such as the DARPA Fast Lightweight Autonomy program (Mohta et al., 2018) and the Mohamed Bin Zayed International Robotics Competition (MBZIRC, 2018), even if the focus of those competitions were not specifically on emergency response.

2.3 | Marine and amphibious robots

Many disaster events, including floods, earthquakes, and hurricanes, present the need for rescue operations in aquatic environments.

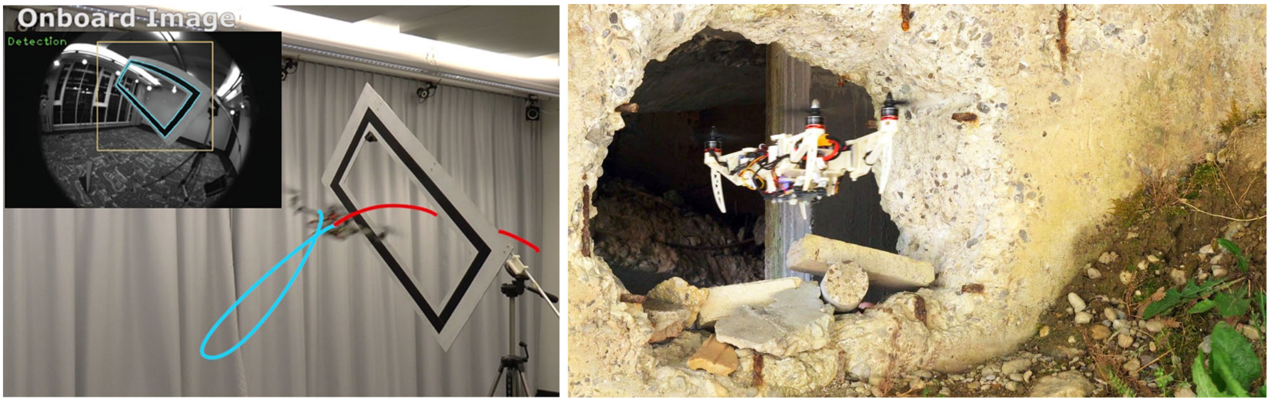

FIGURE 5 Aggressive drone flight through narrow gaps can be achieved with dynamic trajectories and active vision (left; Falanga et al., 2017). A target application for this approach would be to enable a flying robot to enter structures such as earthquake-damaged buildings through small apertures in an emergency response (right; Falanga et al., 2018) [Color figure can be viewed at wileyonlinelibrary.com]

Beyond the need of ground and aerial robots to be simply resistant to weather or adverse conditions, marine and amphibious robots require significant engineering to enable aquatic operation.

A research area that shows promise for SAR applications is biologically inspired robot design and control. Some animals have adapted their locomotion to multiple environments, and are able to change their gait, or switch from walking to swimming or crawling to fit their surroundings. Amphibious robot designs with a salamander or crocodile-like morphology (Gu, Guo, Peng, Chen, & Yu, 2015; Horvat et al., 2017b, 2015) can switch between sprawling-posture walking and shallow-water swimming. While these designs present challenges for controlling gait on a platform with a segmented spine, they offer the possibility to navigate in small or difficult to access areas, over uneven terrain (Horvat, Melo, & Ijspeert, 2017a), as well as in water environments (e.g., flooded buildings and cluttered pipes). These designs have demonstrated robust performance in real-world environments, including 2 weeks of constant operation in field conditions while filming documentaries in Africa (see Figure 7).

Another adaptable design that is targeting SAR applications is an aerial-aquatic robot (Siddall & Kovač, 2014) that can both fly and dive

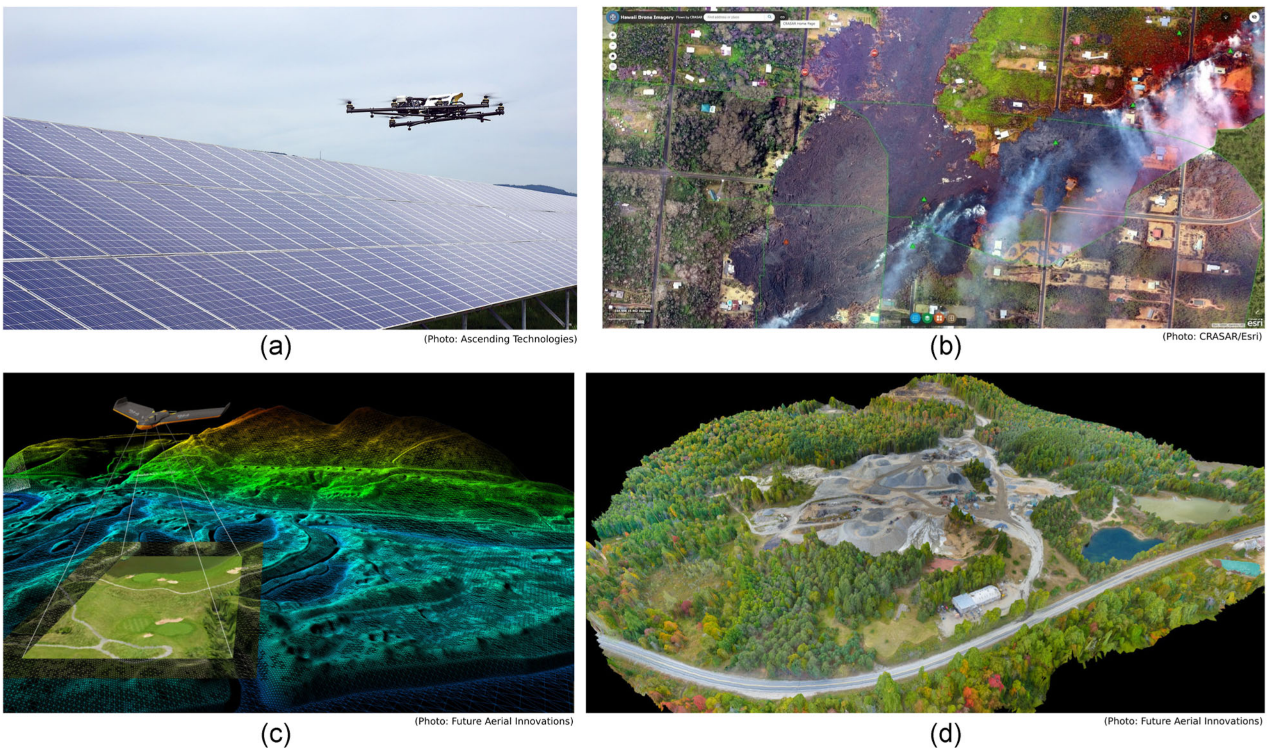

FIGURE 6 Examples of flying robot applications within the disaster cycle include (a) inspection of infrastructure with multirotor UAVs (Ascending Technologies, 2018), (b) real-time mapping of developing disaster situations, for example, the 2018 Hawaiian volcanic eruption (CRASAR, 2018), as well as fixed-wing UAV surveys, in which many images can be captured and postprocessed to generate (c) elevation maps and (d) textured reconstructions of large areas (Future Aerial Innovations, 2018). UAV, unmanned aerial vehicle [Color figure can be viewed at wileyonlinelibrary.com]

into the water for brief submerged operations. While snake robot morphologies do not necessarily focus on an aquatic environment, their bioinspired design makes them relevant to discuss here, and they are often equipped with skins that allow them to operate in extreme environments (Wright et al., 2007). The maneuverability and high degree of freedom of snake morphologies (Liljeback, Pettersen, Stavdahl, & Gravdahl, 2012; Vespignani, Melo, Mutlu, & Ijspeert, 2015) makes them very relevant for SAR activities, particularly in environments with small passable spaces. Also worth mentioning in this context is a snake-like sensor that was developed specifically for SAR applications. While the active scope camera (Hatazaki, Konyo, Isaki, Tadokoro, & Takemura, 2007) has a morphology similar to a snake robot, in the sense that it is long and flexible, it utilizes ciliary vibration for locomotion in tight spaces such as small gaps in collapsed buildings.

While novel morphologies are interesting from a research perspective, and offer promising qualities for SAR once the technology is more mature, stakeholders in marine environments have primarily focused on semiautonomous surface vessels and remotely operated vehicles (ROVs). Similar in many ways to ground-based platforms that carry a complement of sensors and can perform surveys or patrols, research into unmanned surface vessels (USVs) commonly focuses on applications in port areas using USVs as modular sensor platforms (Howard, Mefford, Arnold, Bingham, & Camilli, 2011). The euRathlon (now European Robotics League Emergency Robots) competition (Ferri et al., 2016) included marine ROVs as members of cooperating robot teams, and many commercially available ROVs were utilized during the recovery phase after the 2011 Tohoku earthquake and subsequent tsunami in Eastern Japan (Matsuno et al., 2014). Although available ROVs are frequently utilized in underwater missions that include manipulation, their operation requires significant attentional load by the operator for these tasks. Recent work on an embodied ROV (Khatib et al., 2016), which behaves as an undersea robotic avatar, promises to increase both the capabilities and ease of use for ROVs, particularly for manipulation, through the use of novel interfaces and partial autonomy.

2.4 | Human–robot interfaces

Most research in the field of human–robot interaction (HRI) for SAR applications is focused on enhancing teleoperation, which is the dominant approach for semiautonomous field-ready robots (Sheridan, 2016). Teleoperation allows off-site operators to control robots in the crisis area and gain situational awareness through a video stream or other sensory data (Baker, Casey, Keyes, & Yanco, 2004; Casper & Murphy, 2003). Traditionally, teleoperation in SAR typically required two humans per robot: a robot operator and a problem holder (Murphy, 2004a). The operator's job was to safely drive the robot in the environment, taking into account the obstacles and robot's configuration. The complexity of robot hardware and overall stress made this task cognitively heavy and therefore did not allow the operator to pay enough attention to the mission. The goal of the problem holder was thus twofold: to assist the operator and to perform the actual task of the mission, for example a visual search.

The goal of robotics research in SAR is to reduce or even invert this human–robot ratio, i.e. to enable one human to control one or several robots. While teleoperation and supervisory control using feature-rich interfaces, such as the array of joysticks, game controllers, and exoskeleton arms used in the ICARUS project (Govindaraj et al., 2017) can potentially make the rescuers' life easier, first responders tend to rely on the most robust, well-known, and proven technologies (de Greeff et al., 2018). This suggests that more intuitive interfaces which require less training could ease adoption by rescue team.

As an alternative to conventional teleoperation interfaces, such as joysticks or remote controllers, whole-body gestures are considered a promising solution for achieving natural and intuitive interactions while reducing training time for naïve users. The SHERPA project approached this problem by introducing the "busy genius"—a rescuer colocated with robots and equipped with a set of wearable devices for multimodal interaction (Marconi et al., 2012). Since the rescuer is also busy with other activities the interaction happens sporadically and relies on a mixed-initiative system (Cacace et al., 2016), where the the mission planner utilizes delegation

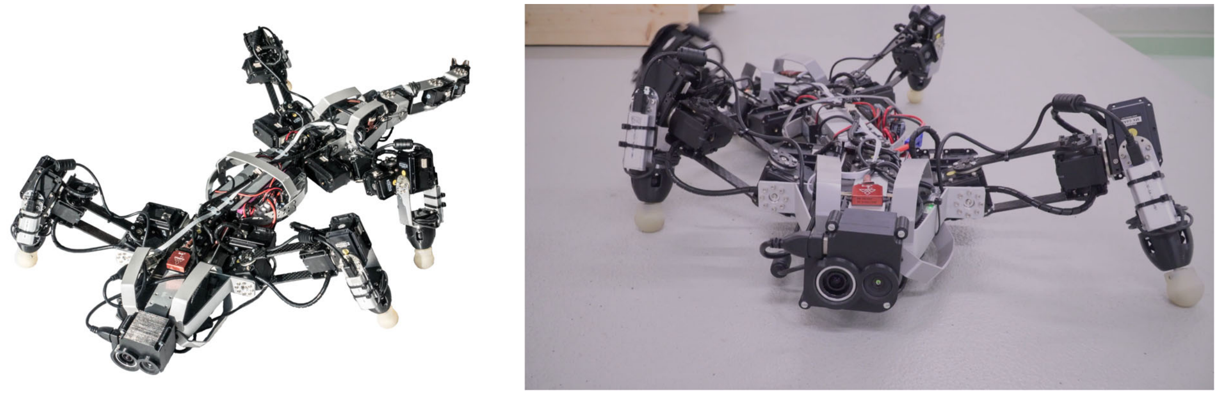

FIGURE 7 Amphibious robot Krock2, which uses a sprawling posture for crawling locomotion on land, is able to swim in water, and can maneuver through tight spaces using coordinated limb and spine actuation (Horvat et al., 2015, 2017b) [Color figure can be viewed at wileyonlinelibrary.com]

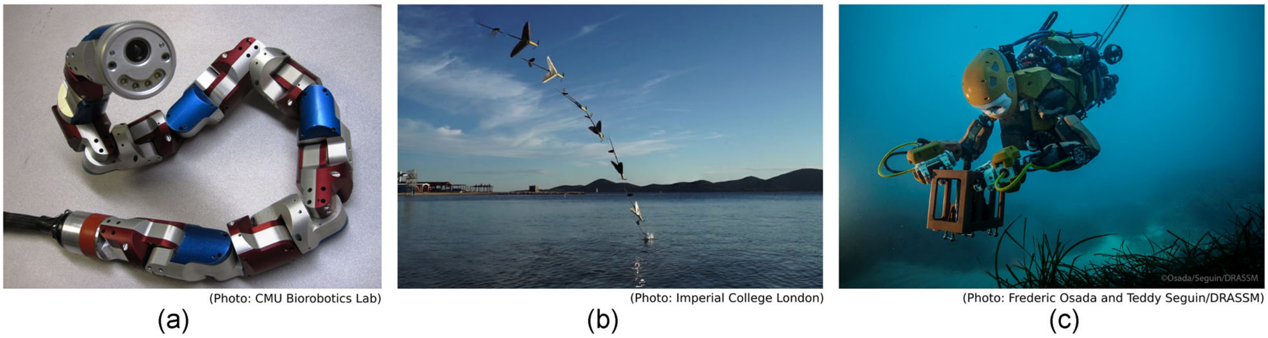

FIGURE 8 Examples of novel robot morphologies with applications to rescue robotics: (a) Snake robots can maneuver into small spaces (Wright et al., 2007), (b) hybrid aerial-aquatic robots can perform surveys in littoral environments (Siddall & Kovač, 2014), and (c) the OceanOne embodied ROV offers an intuitive avatar for underwater manipulation (Khatib et al., 2016) [Color figure can be viewed at wileyonlinelibrary.com]

(Doherty, Heintz, & Kvarnström, 2013) to distribute tasks to a potentially heterogeneous team of agents. Further extending the concept of wearable interfaces, Wang et al. (2015) developed an exoskeleton for the whole-body human-in-the-loop teleoperation of a humanoid robot for SAR. In addition to visual feedback, the exoskeleton applies forces on the waist of the operator To display the state of balance of the robot, hence eliciting corrective teleoperated actions. Within the Symbiotic Drone project, Rognon et al. (2018) developed the FlyJacket, a soft exosuit for the embodied interaction with drones (Figure 9). The FlyJacket records the upper torso gestures of the pilot and translates them into pitch and roll commands for a fixed-wing drone (Miehlbradt et al., 2018). Visual and auditory feedback is provided to the user from sensors mounted on the drone. Visual cues are complemented with kinesthetic feedback To facilitate training and improve flight performances.

Within the context of teleoperation, a relevant research topic is shared control (Tonin, Leeb, Tavella, Perdikis, & Del Millán, 2010), namely the capability to modulate the level of autonomy of the machine. Dell'Agnola, Cammoun, and Atienza (2018) recorded physiological signals from users during the teleoperation of a drone, and extracted features from them to estimate cognitive workloads. This experiment is a first step toward the development of advanced shared control paradigms for SAR applications where user cognitive workload is exploited to modulate the autonomy of the machine and to assist the user to achieve flawless and robust interactions with distal machines.

When the operator is deployed alongside the robot and shares its environment, one may use instead proximity interaction modalities, that assume that a direct line-of-sight to the robot is available; then different interfaces can be used, ranging from standard joysticks (e.g., for low-level control of UAVs) to hands-free gesture-based interfaces based on sensorized armbands (Wolf, Assad, Vernacchia, Fromm, & Jethani, 2013), armbands (Cacace et al., 2016; Gromov, Gambardella, & Giusti, 2018), smart watches (Villani et al., 2017) or voice commands (Gromov, Gambardella, & Di Caro, 2016).

Proximity interaction techniques can take advantage of *pointing gestures* to intuitively express locations or objects with minimal cognitive overhead; this modality has been often used in HRI research e.g. for pick-and-place tasks (Brooks & Breazeal, 2006; Cosgun, Trevor, & Christensen, 2015; Droeschel, Stückler, & Behnke, 2011; Großmann et al., 2014), labeling and/or querying information about objects or locations (Akkil & Isokoski, 2016; Brooks & Breazeal, 2006; Pateraki, Baltzakis, & Trahanias, 2014), selecting a robot within a group (Nagi, Giusti, Gambardella, & Di Caro, 2014; Pourmehr, Monajjemi, Wawerla, Vaughan, & Mori, 2013), and providing navigational goals (Raza Abidi, Williams, & Johnston, 2013; Gromov et al., 2016, 2018; Jevtić, Doisy, Parmet, & Edan, 2015; Tölgyessy et al., 2017; Van den Bergh et al., 2011; Wolf et al., 2013). Such gestures can enable rescue workers to easily direct multiple robots, and robot types, using the same interface (see Figure 10).

SAR missions that use multiple data-gathering robots face peculiar issues for real-time data transfer, management, filtering

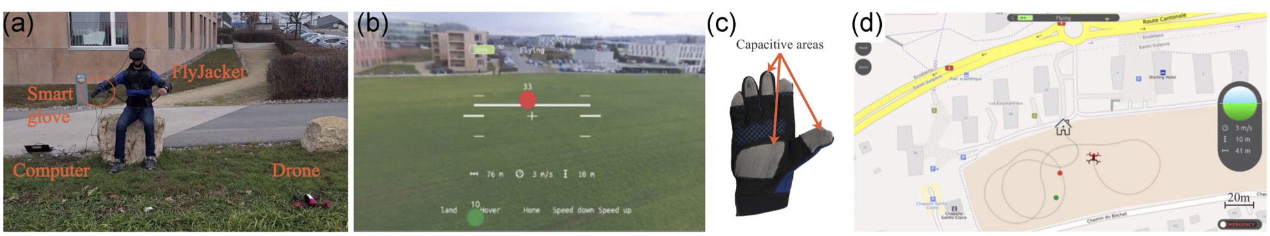

FIGURE 9 (a) Simulation of a SAR mission where a drone is used to geotag points of interests by a human operator using a symbiotic jacket for control (Rognon et al., 2018). (b) The drone streams real-time video feedback to the goggles of the user. (c) The user wears a glove equipped with capacitive sensors. Point of interests are tagged by pressing the middle or the ring finger against the thumb. (d) The points of interest populate a map that can facilitate the planning of the intervention. SAR, search and rescue [Color figure can be viewed at wileyonlinelibrary.com]

and presentation to rescue workers (Balta et al., 2017). Moreover, deployments involving mixed human–robot teams pose difficult challenges from the system design perspective (Kruijff et al., 2014); in this context, achieving efficient coordination also requires the ability to interpret the high-level task assigned to each unit (Yazdani, Scheutz, & Beetz, 2017).

2.5 | Projects involving multimodal robot teams

Several recent projects have explored the use of robot teams in SAR scenarios. The contributions from these projects cover many of the topics already discussed in this paper, in addition to problems of communication and coordination for heterogeneous teams of robots and human operators. These projects have involved disaster management stakeholders at a fundamental level, and their experimental evaluations have been focused on practical SAR and disaster scenarios.

The TRADR project explored persistent human–robot disaster response, and developed methods for 3D LiDAR-based mapping and localization (Dubé et al., 2016; Gawel et al., 2017), while focusing on the dynamics (de Greeff et al., 2015), ethics (Harbers, de Greeff, Kruijff-Korbayová, Neerincx, & Hindriks, 2017), and management strategies (Kasper, 2016) of working in heterogeneous human–robot teams. The robot team was able to provide operators with a third-person view for precise ground robot operation (Gawel, Lin, Koutros, Siegwart, & Cadena, 2018), and generated 3D maps of inaccessible indoor environments (Dubé et al., 2018; see Figure 11). Contributions from the ICARUS project (Cubber et al., 2017) included research into human–robot collaboration (Doroftei, Cubber, & Chintamani, 2012) and data management for a multirobot teams (Balta et al., 2017). The SHERPA project (Marconi et al., 2012), whose goal was to enable robotic-assisted SAR in alpine environments, investigated cognitive (Blumenthal et al., 2016; Yazdani et al., 2017), organizational (Doherty et al., 2013), as well as technological (Rahman, 2014) aspects of communication in a heterogeneous team.

The RoboCup Rescue Robot League is a long-standing competition (Sheh et al., 2014, 2016) focused on developing performance standards for robotic systems in urban SAR applications while encouraging advancement of the state of the art in the capabilities of these systems by its participants. More recently, several robotics competitions have also focused on SAR or disaster robotics scenarios. The European Robotics League Emergency Robots Competition that requires cooperation of ground, aerial, and marine robots in an emergency response scenario (ERL, 2018). The Mohamed Bin Zayed International Robotics Challenge (MBZIRC) competition in 2020 will include a challenge where ground and aerial robots will extinguish simulated fires in a scenario representing a fire in a high rise building (MBZIRC, 2018). Rapid exploration and mapping of complex underground environments by teams of robots will be the focus of the forthcoming DARPA Subterranean Challenge (DARPA, 2018), which is well aligned with other existing research efforts into remote sensing for situational awareness above ground. Disaster robotics will also be one of four challenge areas in the World Robot Summit (WRS, 2018), taking place in 2018 and 2020. This event will feature several competitions placing robot systems into disaster and rescue roles such as inspection and maintenance, and emergency response in a tunnel.

The authors represent the member labs of a large-scale, multi-year consortium project sponsored by the Swiss National Science Foundation (SNSF), called the National Centre of Competence in Research (NCCR) Robotics (NCCR, 2018). The NCCR consortium recently completed its eighth year, and throughout the project, one of the main research focus areas has been mobile robots for rescue operations, with an emphasis on walking robots, flying robots, and collaborative teams composed of both modalities. Our focus on heterogeneous teams leverages the complementary capabilities, both to each other and to human operators, of different robot modalities to provide benefits in the a SAR scenario. The goal is to enable robots in the team to work alongside humans and to augment their abilities and improve their safety and efficiency as rescuers. This is accomplished through the development of novel human–robot

FIGURE 10 Human–robot interface from (Gromov et al., 2018, 2014), in which the operator uses pointing gestures, estimated from sensors worn in armbands, to provide navigation commands to both flying and legged robots [Color figure can be viewed at wileyonlinelibrary.com]

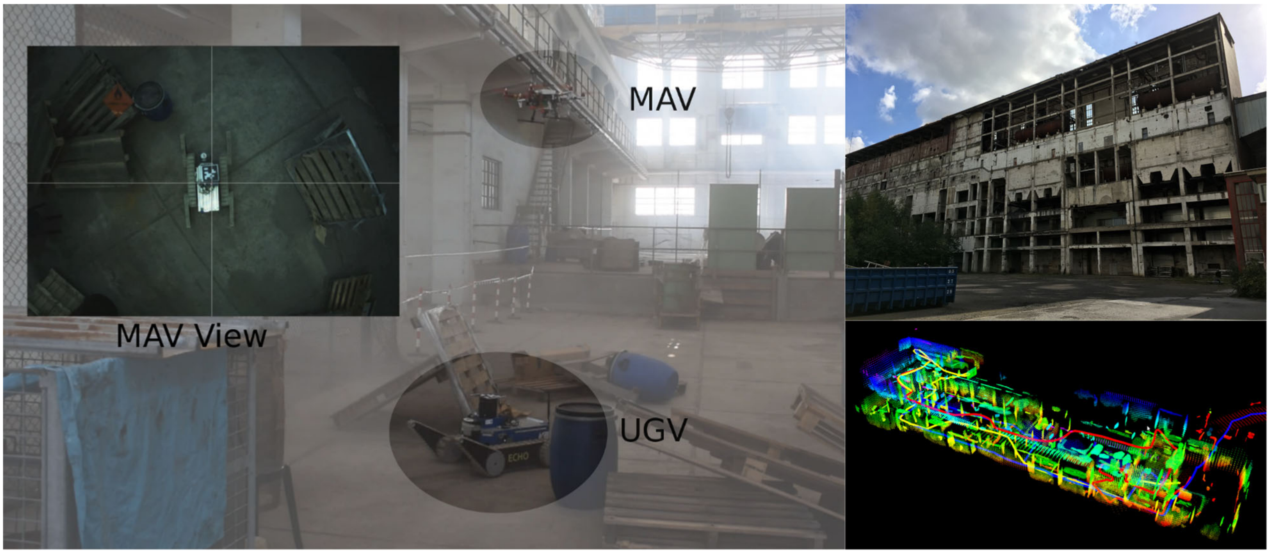

FIGURE 11 Operation of TRADR robot team in a decommissioned power plant. This deployment generated an accurate 3D map of the interior, and the use of an air-ground team of robots allowed the microaerial vehicle (MAV) to provide the operators with a third-person view of the ground robot for precise remote operation (Dubé et al., 2016; Gawel et al., 2018) [Color figure can be viewed at wileyonlinelibrary.com]

interfaces, and control and perception algorithms that allow human operators to dynamically switch between full autonomy and shared control as the rescue situation demands. Throughout the project, the member labs have made fundamental contributions in perception (Fankhauser et al., 2018; Gawel et al., 2017; Scaramuzza et al., 2014), control (Bellicoso, Jenelten, Gehring, & Hutter, 2018b; Faessler et al., 2018), and human–robot interaction (Gromov et al., 2016; Rognon et al., 2018), for flying (Falanga et al., 2017; Mintchev & Floreano, 2016), legged (Hutter et al., 2017), and amphibious robots (Horvat et al., 2017a). A recent research focus has been on field readiness and deployments in real-world environments, and to that end, teams of flying, walking, and amphibious robots from NCCR have performed demonstrations in increasingly challenging and realistic environments, moving from indoor mock-up scenarios (NCCR-Demo, 2017),

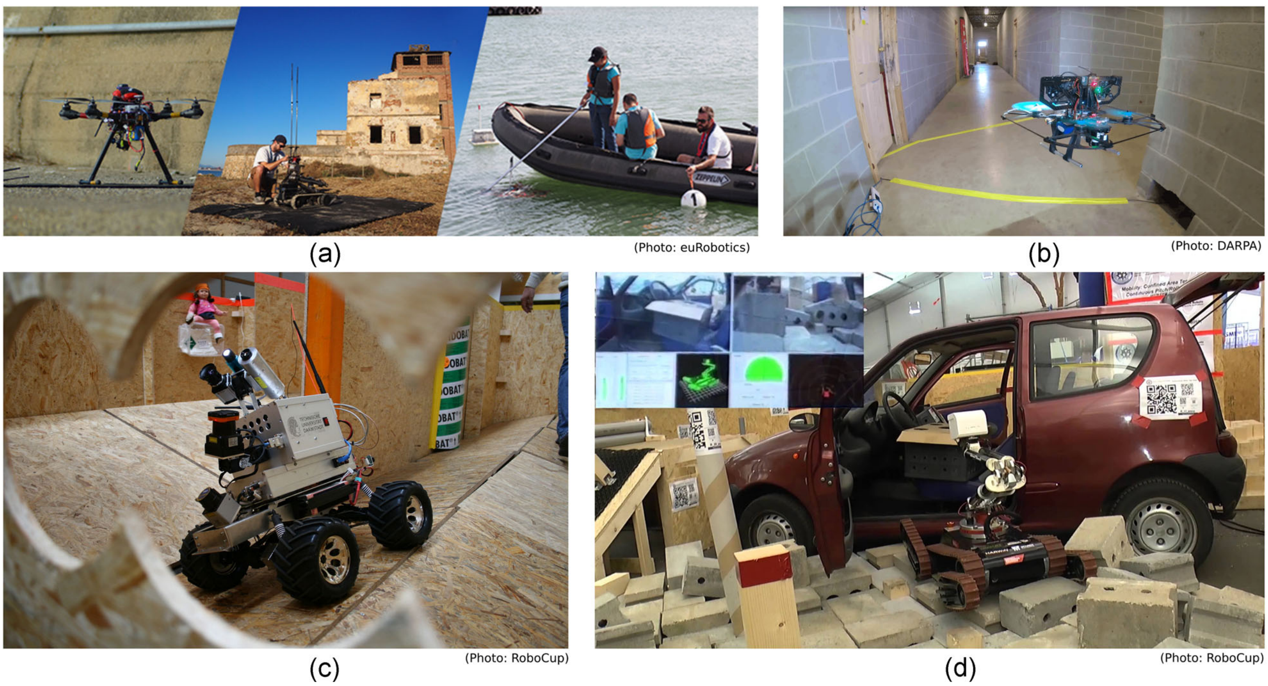

FIGURE 12 Many robotics competitions emphasize rescue environments and applications: (a) The European Robotics League Emergency Robots Competition (ERL, 2018) requires teams of marine, aerial, and ground robots to accomplish tasks within a common mission, (b) DARPA's Fast Lightweight Autonomy and Subterranean Challenge (DARPA, 2018) focus on UAV and robot team operations at high speed and over long distances in challenging environments, and (c, d) the RoboCup Rescue (Sheh et al., 2016) Competition has been developing performance standards since 2000 [Color figure can be viewed at wileyonlinelibrary.com]

to the European Robotics League Emergency Robots Competition (ERL, 2018), and a week-long event in a military rescue training facility. This event, Advanced Robotic Capabilities for Hazardous Environments (ARCHE), utilized the damaged and partially collapsed buildings at the training site to demonstrate the capabilities of the robots developed within the member labs on coordinated missions, and featured a public outreach day to showcase the technologies to over 200 stakeholders and visitors (ARCHE, 2018). Examples of the realistic environments at the ARCHE site can be seen in Figures 2 and 5 (right).

3 | REQUIREMENTS FOR FIELD DEPLOYMENT

To understand the needs of rescue stakeholders with respect to robotics and technology, we interviewed several high-profile experts to obtain their perspectives. These individuals work as active rescuers and response coordinators in fire and natural disaster response, as well as several academic experts who work closely with disaster management professionals during large-scale SAR deployments. The experts and their affiliations are summarized in Table 1. We sought to understand the desirable properties of currently available robotic technologies that are in practical use in these scenarios, as well as goals for the next generation of rescue robot systems. In addition, our interviews investigated the aspects of present-day research systems that are not beneficial for the rescue stakeholder community. The feedback that we received highlighted several major themes in the requirements of robotic systems for deployment, which are organized by topic below.

3.1 | Ease of use

The simplicity and ease of use of robotic systems, or rescue technology in general, is of great importance to stakeholders. According to Emanuele Gissi, Professional Fire Chief of the Corpo Nazionale dei Vigili del Fuoco (National Fire and Rescue Service) in Rome, Italy, the simplicity of firefighter-robot interaction is a major factor in the use of technology in deployments. “As a principle, we always try to use the simplest technology that is good enough to solve a specific problem. This lowers the training requirements for our teams and, in general, improves reliability of the tool in harsh conditions, like those in a rescue operation” (Gissi, 2018). This perspective is echoed by Prof. Tetsuya Kimura of Nagaoka University of Technology, a developer of the World Robotic Summit (WRS) competition in 2020 (Kimura et al., 2017), that low operator training requirements are important criteria for adoption by stakeholders, and that this aspect is often not addressed by the research community (Kimura, 2018). Consequently, many stakeholders choose not to use sensitive or complicated systems if they risk failure due to the challenges of real-world environments, according to Hisanori Amano, Chief of Planning for Community-based Cooperation at the National Research Institute of Fire and Disaster in Tokyo, Japan, and more than half of the robotic platforms in use across Japan can be used by every member of the fire brigade (Amano, 2018a).

Logistical concerns are also important factors in the decisions of stakeholders to deploy particular technologies. According to Prof. Robin Murphy of Texas A&M University, who is also Vice President of the nonprofit Center for Robot-Assisted Search and Rescue (CRASAR), commercially available robotic platforms can often be more convenient to use in field deployments (Murphy, 2018). Off-the-shelf platforms can typically be transported by plane and charged more easily in the field than specialized systems with high energy density batteries and high power demands for recharging, potentially requiring generators and further equipment.

Similarly, bringing specialized hardware into foreign countries during an international aid mission can present challenges from import or use restrictions, according to Richard Brogle, CEO of the Drosos Foundation and a volunteer with the Swiss Agency for Development and Cooperation (SDC), a humanitarian aid branch

TABLE 1 Rescue stakeholders who who were interviewed for this paper

Expert name	Organization	Domain
Prof. Robin Murphy	Texas A&M University	Research
	Center for Robot-Assisted Search and Rescue	Disaster deployment
Dr. Richard Brogle	Drosos Foundation	Humanitarian aid
	Swiss Agency for Development and Cooperation	Disaster response
Hisanori Amano	National Research Institute of Fire and Disaster (Tokyo)	Firefighting
Dr. Emanuele Gissi	National Fire and Rescue Service (Rome)	Firefighting
Prof. Satoshi Tadokoro	Tohoku University	Research
	International Rescue System	Disaster deployment
Robbert Heinecke	Joint Fire Brigade (Rotterdam)	Firefighting
Prof. Tetsuya Kimura	Nagaoka University of Technology	Research
	International Rescue System	Disaster deployment

Note: These experts operate either exclusively in the domain of emergency response, or at the interface between deployed response and academic research.

within the Swiss government (Brogle, 2018). It may therefore be more effective to base deployed systems around commercially available hardware that can be acquired on site if necessary.

3.2 | Capabilities and robustness

The capabilities of rescue robots as well as their reliability and robustness in field deployments are central to their adoption by stakeholders. For example, the ability to automatically recovery from failures during a mission is a highly desirable feature for time-critical deployments (Kimura, 2018). Hisanori Amano notes that the reliability and endurance of robotic systems are among the primary criteria for use of robotic systems in fire brigades across Japan, with a priority on the use of high performance rather than high technology (Amano, 2018a,b). Reliability in harsh conditions is also paramount in Italian fire brigades, according to Emanuele Gissi. From 2015–2017, they flew over 2000 missions with UAVs, which directly or indirectly contributed to the rescue of 291 victims of the 2016 Amatrice earthquake. However, UGV platforms have not demonstrated the level reliability or industrial robustness necessary to be extensively deployed (Gissi, 2018). CRASAR has also utilized flying robots extensively due to their versatility in many different disaster scenarios (Murphy, 2018). Both Emanuele Gissi and Robin Murphy note that although their organizations are open to the evaluation of new technologies in *simulated* rescue scenarios, often through collaborations in academic research projects, actual disaster response deployment requires heavily vetted technology (a technology readiness level of at least 8) to avoid making the situation worse through the use of unverified technology (Gissi, 2018; Murphy, 2018). For example, while artificial intelligence is a hot topic in the research domain, these approaches are not yet reliable enough to leverage in the field (Kimura, 2018).

According to Tetsuya Kimura, "endurance, reliability, and safety are important for actual deployment, but not so much paid attention by researchers, because such issues are not easy to write technical papers comparing to performance" (Kimura, 2018). Deployable tech thus should involve cooperation between technology manufacturers, end users, and researchers, but the choice of platform is often influenced by whoever has significant political power (Kimura, 2018). However, communication with stakeholders is also very important to provide realistic expectations about capabilities and limitations of robotic technologies. Rescue workers who do not interface with the research community may overestimate or underestimate these capabilities (Tadokoro, 2018). This misalignment may result from the influence of science fiction, or from a history of doing things without technological intervention.

3.3 | Robots as tools

Among the respondent stakeholders that we interviewed, most indicated that the primary role of robotic technology in their teams is as a tool for information gathering or for performing physical tasks that are outside of human capabilities; as an augmentation rather than as a replacement for human rescuers.

In disaster scenarios, robotic technology is important for information gathering in an autonomous and/or distributed way in areas that have high risk, for tasks that humans cannot perform, or for tasks where autonomy can improve their efficiency. Physical task execution, particularly when conventional equipment or humans do not have enough capability is a particularly relevant area in which robots can be utilized effectively. For example, SAR missions that require operation in confined spaces, under water, or at high elevation, as well as in contaminated, explosive, or high-temperature environments are excellent candidates for robotic rescue technology as a way to reduce the risk to humans while also extending their capabilities (Tadokoro, 2018). Robots that possess capabilities that would require specialized training for humans gives them an opportunity to serve as a tool requiring less training for the operator. As an example, the most common type of robots owned by fire departments across Japan are underwater ROVs to conduct searches, allowing personnel who are not trained as divers to contribute to search operations (Amano, 2018b).

This sentiment is echoed by firefighters, since fires present many situations that are dangerous to both rescuers and victims. "The technology we are looking for are UGVs and UAVs that would be able to inspect and report back autonomously in harsh, wet, dusty, smoky conditions" (Gissi, 2018). Hisanori Amano further states that they do not expect robots to replace firefighters for general operations, but ideally in indoor spaces that firefighters can not reach due to space constraints or fire, as well as for UAVs to provide an aerial perspective that is otherwise not obtainable in real time (Amano, 2018a). In agreement is Robbert Heinecke, a team leader for the Gezamenlijke Brandweer (Joint Fire Brigade) in the Rotterdam area of the Netherlands. While robots should not be a full replacement for humans, they can provide situational awareness inside of dangerous areas, helping to lower the risk for both rescuers and victims (Heinecke, 2018).

Rescuers need robotic tools that are "better than a dog" (Brogle, 2018), since dogs are capable of searching for victims, and can be maneuverable and fast even in tight spaces, and indeed are often deployed alongside humans in rescue operations. Thus, for urban SAR, in which collapsed structures may render many spaces inaccessible for humans, robots must be able to outperform a dog (e.g., climb/crawl through spaces of ~10×10 cm) to provide added value for rescue workers. Robots available for SAR have traditionally been too big or too slow to enhance the capabilities of rescue workers with these types of constraints (Brogle, 2018).

3.4 | Situational awareness and remote sensing

One of the most important capabilities of robotic platforms in this domain is the ability to collect and transmit sensor data to human operators such that they can provide situational awareness beyond what the rescue workers can normally obtain. Robotic platforms are particularly well-suited for this role due to their ability to fly or enter dangerous environments, as well as the availability of sensor modalities that transcend human perception (e.g., accurate 3D range sensing, chemical sensors). A full sensor suite on-board a firefighting robot, which can detect and localize heat, gases, or smoke, would provide its operators with real-time understanding of the hazards inside a burning building (Heinecke, 2018). Generation of high quality, complete maps for a wide area search (Kimura, 2018), as well as persistent sensing (Murphy, 2018), are also possible using current technologies.

Real-time 3D maps are one of the most useful data representations for first responders, as they allow for localization and navigation even in environments where visual sensing is compromised. In the immediate response to a disaster event, rescuers need 3D maps of building interiors to be produced within minutes (Brogle, 2018); such rapid exploration and mapping is still an active research area in the academic community and thus not yet feasible in field-ready systems. Additionally, before-and-after exterior 3D maps of a region are desirable to perform a quick triage of damaged structures (Brogle, 2018). A recent example of a successful 3D reconstruction mission in damaged building occurred after the August 2016 earthquake in Amatrice, Italy (Gissi, 2018). A team of UAVs and UGVs entered two partially collapsed churches to generate textured maps of the interior to assess the damage (Kruijff-Korbayová et al., 2016). This mission demonstrated the effectiveness of robotic systems at such a task during the *recovery* phase of the disaster cycle, in which the speed of generating a maps (tens of minutes) is compatible with a mission timescale in which lives are not at risk.

3.5 | Levels of autonomy

The level of autonomy of robotic systems dictate the manpower required to operate them, but also the complexity and adaptability of the system. Full autonomy in real-world rescue situations is currently difficult to apply in real cases, according to Satoshi Tadokoro (Tadokoro, 2018). However, there is a strong preference for semiautonomous behaviors, rather than full manual control (Heinecke, 2018), to reduce the attentional load on the operator or allow them to multitask or operate multiple systems simultaneously. It is considered important, however, to have human in the loop (Heinecke, 2018) to guide the robot's behaviors on tasks that typically evolve dynamically during the mission.

3.6 | Data management

Ultimately, if the robotic systems are providing situational awareness and sensing to the rescue workers, an important consideration in system design is thus the management of the data. According to Robin Murphy, the focus from researchers is often on the robots themselves and not the effective and rapid delivery and distribution of the data to the user (Murphy, 2018). If the goal of robotic deployment is to provide real-time remote sensing to the user, then a mission-oriented, rather than platform-oriented, focus should be a primary concern of the research community. Another dimension of this is that in a large-scale mission, having a single coordinated system, integrating many different systems, computers, and operators from a common command post, is unrealistic due to the complexity of multiagency and multifunction disaster response. A typical response will consist of many different systems that are not necessarily communicating or being coordinated together or by the same group, and thus the operators need to manage and synthesize multiple data streams and organize highly distributed and loosely coupled teams of heterogeneous systems. So, although a centralized and coordinated system may be an easier solution to many aspects of mission deployment, it is unrealistic in practice (Murphy, 2018).

4 | CONCLUSIONS

One of the primary goals and contributions of this paper is to assess and evaluate the ways in which the research community is aligning its work with the needs of SAR workers, and to identify areas in which more effort could be applied to reduce the disparity between the robotic systems from the research and field-deployment domains. To that end, we have analyzed the state of the art across robot morphologies, locomotion types, and designs, as well as the algorithms they use for perception and control, and the interfaces through which users can command and interact with them. We have also interviewed experts with deep experience in deploying robotic systems in disaster environments to understand the current usage patterns for robotic systems in these scenarios, and to understand their current and future needs. This section analyzes these needs with respect to the state of the art and to current avenues of research within the community to understand the degree to which these efforts are aligned.

With the aim of reducing training and ease the interactions between rescuers and robots, research into novel human–robot interfaces (see Section 2.4) has investigated natural gesture-based proximity interactions as well as symbiotic control of embodied flying robots and shared control for semiautonomous behaviors. These approaches offer promising features, but most deployed robots are controlled through traditional interfaces (radio control, computer, or mobile device app), often less intuitive and natural, but more robust and reliable. Additionally, most research platforms are not engineered for the same level of accessibility as commercial off-the-shelf systems, so for the simplest possible solution, stakeholders can utilize these platforms, likely sacrificing some advanced capabilities and autonomy for a lower cost and easier-to-use system. However, recent advances in perception and control for autonomous behaviors could be leveraged to provide a seamless and simple interface for the user. By enabling greater autonomy in the platform, interaction with the user can occur at a higher level of abstraction, but such a complex system then introduces more failure modes with respect to simpler configurations. Regarding the practical challenges in deploying custom platforms in field environments, hardware designers should consider developing platforms from at least off-the-shelf components, with the simplest possible interfaces for charging and data transfer, to reduce equipment requirements and enable a simpler end-user experience in deployment.

While the design and capabilities of ground robots have matured in recent years, and now include general purpose, reconfigurable, and easily portable quadrupedal platforms (see Section 2.1.1), ground robots are infrequently deployed in active rescue environments, but have found use in the types of inspection and assessment tasks that occur during the *recovery*, *prevention*, and *preparation* phases of the disaster cycle. Aerial robots, on the other hand, have achieved a level of field readiness that has enabled their use in both *recovery* and *response* stage operations. Marine robots are also used extensively during *recovery* operations, but these platforms typically require manual piloting, and thus could benefit significantly from advances in autonomy and usability.

One barrier to further penetration of robotic technology in this domain is the gap in robustness for performance and reliability between commercially available platforms and research systems. While development of robust algorithms is somewhat rewarded in the research community, robustness in hardware and robotic systems alone often does not receive the same emphasis in terms of funding or publishing, resulting in a priority toward novelty rather than effectiveness in research. Off-the-shelf platforms therefore typically demonstrate better robustness but lower capabilities than custom research systems primarily due to the significant investment of engineering effort in commercial systems, and unless the scientific review process adjusts its priorities to value contributions in system robustness to a greater degree, we can expect this trend to continue. However, for robot morphologies with no commercial options (e.g., legged robots), advances in reliability would enable significant opportunities for use in the rescue community.

Based on our analysis, regarding the role of robotic systems in rescue deployments, there is good alignment of research efforts with field requirements. While current adoption of autonomy and state of the art platforms for real-world deployments has been limited, the recent large-scale research projects that have involved rescue stakeholders at a fundamental level have targeted the applications that our experts have identified as most desirable. This indicates that the direction in which the research community is moving will lead to greater adoption of these technologies by stakeholders in the future. In particular, the use of legged or tracked ground robots for remote sensing and inspection, and semiautonomous UAVs for conducting aerial surveys, is seen as a very valuable tool for situational awareness during the immediate response to an event, as well as for assessment during the recovery phase of the disaster cycle. Generation of high fidelity 3D maps in real time is a capability that is currently not possible with most commercial platforms, so research platforms currently provide significant added value in that domain. An important aspect of existing research work is the emphasis on human–robot teams, which is consistent with the desire of stakeholders to maintain a human in the loop during deployments in dynamic situations where priorities may change quickly. However, there is a need to further reduce the size and complexity of these systems if they are to be used more ubiquitously, and more important to increase their speed if they are to be used in disaster response. While there has been progress toward smaller and faster platforms, reaching the level of a dog or human with the capabilities of robotic systems is still firmly in the future.

Work in developing human–robot interfaces aims to help reduce the operator's attentional load or provide a force multiplication factor to extend the ability of one operator to command multiple robots. This effort is consistent with the needs of stakeholders, as it focuses on maintaining a human in the loop during operations while leveraging the autonomy of the robotic platforms as a way to simplify their use.

Efforts toward the development of integrated, centrally organized systems or robot teams are interesting from a research perspective, but do not address the immediate needs of SAR personnel. While the development of distributed systems with deeper integration is a good long-term goal for the research community, and may eventually contribute to systems that are easier to deploy and use during crises, the current needs are for individual systems that can be deployed independently of each other in a loosely coupled team, but that can provide data in a system-agnostic way. Managing and synthesizing such data from multiple sources should therefore be a consideration during the development of SAR systems.

Considering all of these factors, the direction of research developments are well-aligned with the needs of rescue stakeholders. While some of the efforts from the research community are more forward-looking than the current requirements for field deployment, it is necessary to consider the time required to reach a technology readiness level that can be used in critical situations. In light of this, developments on the research side are consistent with the long-term, future needs of rescue workers, and an investment in fundamental research in these areas at the current time will lay the foundation for robust and reliable technology that can be used in future deployments. However, efforts from the research community to develop systems that are robust and capable enough for real-world rescue scenarios has been insufficient. While it is unrealistic to expect robotic systems with a high technology readiness level to come directly from the academic domain without involvement from other organizations, more emphasis on robustness during the research phase may accelerate the process of reaching a high level for use in deployment. Finally, research efforts should focus on the barriers to adoption of new technologies by stakeholders, namely the ease of use, endurance, and the capabilities for collection data and speed of transmitting that to rescuers for real-time situational awareness. An important highlight from this survey is the importance of continued engagement with rescue stakeholders throughout the research process, to ensure that the priorities of both groups remain aligned.

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