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FIELD REPORT

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Lessons from robot-assisted disaster response deployments by the German Rescue Robotics Center task force

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Abstract

Earthquakes, fire, and floods often cause structural collapses of buildings. However, the inspection of such damaged buildings poses a high risk for emergency forces or is even impossible. We present three recently selected missions of the Robotics Task Force of the German Rescue Robotics Center (DRZ), where both ground and aerial robots were used to explore destroyed buildings. We describe and reflect the missions as well as the lessons learned that have resulted from them. To make robots from research laboratories fit for real operations, realistic outdoor and indoor test environments were set up at the DRZ and used for tests in regular exercises by researchers and emergency forces. On the basis of this experience, the robots and their control software were significantly improved. Furthermore, expert teams of researchers and first responders were formed, each with realistic assessments of the operational and practical suitability of robotic systems.

KEYWORDS

ground and aerial robots, human–robot interaction, public safety, rescue robotics, search and rescue

1 | INTRODUCTION

Structural collapse is characterized by the need for making situation assessment in places inaccessible using standard equipment and/or in environments risky to enter for humans. The use of robots, specifically unmanned ground and aerial vehicles (UGVs and UAVs), in situations involving structurally compromised buildings has obvious potential for increasing operational capacity by collecting data, while maintaining the personal safety of first responders. For example, in a pioneering deployment of robots in the earthquake-struck Emilia

Romagna, Italy, 2012, a UAV provided exterior visual information of a church tower for structural damage assessment, and a UGV was used to explore the interior of a dome to assess the state of important religious artifacts (Kruijff et al., 2012). In Amatrice, Italy, 2016, robots were used to provide detailed exterior and interior three-dimensional (3D) models for the planning of shoring operations of two churches severely damaged by an earthquake (Kruijff-Korbayová et al., 2016). In both cases, robotic research demonstrators were used by academic research teams embedded within onsite fire brigade forces—enabled by existing collaborations between academics and first responders in research projects.

This successful long-term collaboration model was incorporated into the setup of the German Rescue Robotics Center (DRZ) (Kruijff-Korbayová et al., 2021), a nonprofit association connecting academia, end users, and industry to facilitate the advancement and transfer of robotic technologies for first responders. DRZ conducts extensive field tests and has established a Robotics Task Force (RTF), which operates together with the Dortmund fire brigade (FwDO) and consists of professional firefighters and researchers. In DRZ RTF deployments, robots are operated by researchers so far. This enables the use of cutting-edge robotic technology, including research demonstrators, for which the fire brigade does not yet have training. The RTF can, thus, evaluate the benefits and shortcomings of novel technology and increase awareness of its potential with first responders. We believe that such collaboration is crucial for advancement, both for determining a relevant research agenda and for driving innovation from the end-user perspective.

2 | RELATED WORK

Urban search and rescue and/or disaster response has a high potential for the use of robots. An analysis of 114 calls completed by the Boulder Emergency Squad from 04/2016 to 12/2021 using unmanned aerial systems reveals the divergence in the assumptions made in research and how state-of-the-art technologies may realistically transition into operational capacity (Ray et al., 2022). For example, most research efforts in robotics for disaster response focus on autonomous and semi-autonomous capabilities of single or multiple robots,[1] and not on their embedding as resources in the operation of the entire first response team and realistic deployment capacity. Similarly, research addressing various versions of situation awareness- and decision-support for robot-assisted teams often focuses on data visualization and processing and the integration of information in interfaces with maps, and not on the use of the information by the various command levels. Information exchange and teamwork support in robotic rescue operations have been the subject of some, if not very much, research. Among others, different aspects of team coordination and role distribution have been investigated (Casper & Murphy, 2003). Practical experiences in competitions and real operations have resulted in recommendations for human–robot teamwork-oriented system design as well as for the design of interfaces for human–robot interaction (Johnson et al., 2017).

Teamwork in the field of emergency response has mostly been studied from the perspective of team performance (Carver & Turoff, 2007; Toups et al., 2016), including for human–robot teams (Burke et al., 2004; Casper & Murphy, 2003; Johnson et al., 2017). A recent study (Power, 2018) provides a comprehensive overview of the three areas of team processing, that is, cooperation, coordination, and communication.

While the early design stages of robotic setups may enjoy simplifications such as continuous sufficient network connectivity, real-world deployments often suffer from a lack thereof due among other things to environmental factors such as obstacle attenuation. The solutions considered in the literature often involve the usage of ad hoc network deployments (Das et al., 2007), redundancy, and advanced networking techniques powered by network monitoring and Radio Environment Maps (Hsieh et al., 2008) for enhancing the networking capabilities of robotic systems.

Competitions are an established tool for benchmarking the capabilities of robotic systems and fostering development, often motivated by a lack of capabilities observed in actual disaster responses. The outdoor competition euRathlon (Schneider et al., 2015) held between 2013 and 2015 was directly inspired by the 2011 Fukushima accident and combined land, underwater, and airborne robots to jointly gather situation data and identify critical hazards. The military robot competition ELROB (Schneider et al., 2015) running since 2006 aims to go beyond research demonstrators and test commercial prototypes in realistic scenarios which have many commonalities with search and rescue or disaster response. Since 2022 the reconnaissance scenario of ELROB is also open to UAVs.

The US National Institute of Standards and Technology (NIST) is developing standardized test methods to quantitatively evaluate rescue robotic systems. These tests are frequently validated and revised in collaboration with researchers and emergency responders under conditions of real response scenarios, for example, during the annual Emergency Response Robot Evaluation Exercises (RREE) (Jacoff et al., 2012; Pellenz et al., 2010). Hosted in a 210,000 m^2-sized training facility called Disaster City, which features customizable full-size mockups of different emergency scenarios like building collapses or train derailments, RREE introduces responders to current robotic capabilities for real-world deployments and provides researchers with valuable feedback for future robotic development.

The RoboCup Rescue Project (Sheh et al., 2016; Tadokoro et al., 2000) setup since 2000 in cooperation with NIST is an example of evaluating specific mobility and dexterity capabilities of single ground robots in controlled standardized environments (Akin et al., 2013).[2] In 2022 and 2023 the RoboCup Rescue German Open featured the DRZ Challenge with a small-scale realistic setup of an

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[1] See Delmerico et al. (2019), Jorge et al. (2019), and Menon and Joy (2019) for recent surveys on the component rescue robotics technology and research.

[2] For an overview of the NIST standard test methods see Shen and Jacoff (2019).

incident in a chemical laboratory, including navigation in smoke. Similarly, DARPA Robotics Challenge 2012–2015 (Krotkov et al., 2018; Spenko et al., 2018) tested individual teleoperated robotic capabilities in more complex are close to real-world environments with a focus on the manipulation of tools designed for humans. Next, the DARPA Subterranean Challenge 2017–2021 (Chung et al., 2023; Orekhov & Chung, 2022) focused on underground operations and innovations in autonomy, perception, networking, and mobility where teams had to map and accurately localize objects of interest. Another recurrent competition is the World Robot Summit "Olympiad," including a disaster robotics category (Tadokoro et al., 2019) since 2020 (preliminary in 2018) and featuring several scenarios: the Plant Disaster Prevention challenge, the Tunnel Disaster Response and Recovery challenge, and the Standard Disaster Robotics challenge. Similarly, the ARGOS Challenge 2015–2017 (Kydd et al., 2015) targeted autonomy for gas and oil sites. Finally, the European Robotics Hackathon (Schneider & Wildermuth, 2021) is set up as a chemical, biological, radiological, nuclear and explosive trial in an unused nuclear power station, rather than a competition.

In summary, some competitions tests individual capabilities while others are set up as missions, and most aim at pushing progress in autonomy. Many competitions work with first responders in organizational, technical, or advisory roles. However, none are embedding the robotic teams within realistic deployment conditions and command structures, and in all of them the robots are operated by the developers themselves, not first responders.

Regarding systems that are tested with end users and actually used in real deployments, CRASAR[3] was the first research team who started carrying out real deployments in 2002. Murphy comprehensively summarized the early experiences (Murphy, 2014). Tadokoro et al. also have a variety of real-world missions, especially in Fukushima (Tadokoro, 2019).

In Europe, the projects ICARUS (De Cubber et al., 2013), SHERPA (Marconi et al., 2013), NIFTi (Kruijff, 2014), and TRADR (Kruijff-Korbayová et al., 2015) pioneered the inclusion of the tactical and strategic levels of command and tested deployment in realistic simulated missions in collaboration with first responders. NIFTi and TRADR made it to the real-world and deployed human–robot teams where researchers were embedded within first responders' units after two large earthquakes in Italy, in Mirandola in 05/2012 (Kruijff et al., 2012) and in Amatrice on 01/09/2016 (Kruijff-Korbayová et al., 2016), respectively.

Firefighters are increasingly employing UAVs and UGVs, for example, the mission at Notre Dame, 2019 (Nardi, 2019). They strive to build their own expertise, often in specialized units.

A combined approach has been pioneered at the University of Graz, Austria (n.d.): Since 2018, the university has had a recognized unit of volunteer firefighters, whose tasks include the use of research results to support other fire departments, particularly by participating in deployments.

3 | DEPLOYMENT SETUP OF THE DRZ RTF

3.1 | Robotic command vehicle (RobLW)

For in-field testing and even more during real missions, it is crucial to provide basic logistics, communication, and support for the teams and their robots, to not rely on already heavily occupied civil infrastructure. For these purposes, the DRZ developed the Robotics Command Vehicle (RobLW), a fully equipped emergency vehicle with radio communication, a signaling system, and basic emergency equipment (Figure 1). RobLW can carry multiple UAVs and one mid-sized UGV, is able to set up network communication infrastructure for the RTF, and has a map-based situation awareness system for mission command.

In the RobLW's middle section, two fully equipped workplaces for a team commander and/or robot operator(s) for steering the robots and data management are available. They are embedded in the van's own network and server/client infrastructure, enabling communication (Wireless Fidelity [WiFi], Internet, and dedicated robot communication) and data processing (e.g., calculation of 3D maps). The rear area of the RobLW offers storage capacity for various peripheral equipment and components. Furthermore, the compartment provides a transport storage area for robots. On the roof, a flexible antenna array is set up.

One example of data processing is the usage of a WebODM Server,[4] a web-based tool that uses camera images provided by UAVs to create (offline) a 3D representation of the environment. WebODM provides a scaled point cloud that can be used to measure the area of operation or holes in a building at risk of collapse. This facilitates situation assessment and approach planning (Gawel et al., 2017).

3.2 | Robotic systems

3.2.1 | Unmanned aerial vehicles: The DRZ RTF uses various drones of two distinct classes

The first class contains off-the-shelf commercial drones with proprietary remote controller, software, and radio communication provided by the respective manufacturer, for example, DJI.

The second class contains do it yourself and modified drones. These can carry different payloads and are customized for specific uses. An example is the D1 Copter shown in Figure 2a. It is based on the DJI Matrice 210 v2 platform and is equipped for onboard environment perception and navigation planning (Schleich & Behnke, 2021) with an Intel NUC8i7BEH computer, allowing continued operation in global navigation satellite system-denied environments and even during short communication outages. An Ouster OS0-128 Light Detection and Ranging (LiDAR) enables 3D

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[3] https://www.crasar.org.

[4] Drone Mapping Software: WebODM.

FIGURE 1 Overview of the RobLW (left) with a robot operator steering a UGV from the command center (right) at a two-monitor workstation. RobLW, Robotics Command Vehicle; UGV, unmanned ground vehicle.

FIGURE 2 Examples of UAVs used in DRZ. (a) DRZ D1 Copter equipped with rich sensors and PC (Schleich et al., 2021) and (b) DJI-FPV extended with a 360° camera. DRZ, German Rescue Robotics Center; LiDAR, Light Detection and Ranging; PC, personal computer; UAV, unmanned aerial vehicle.

simultaneous localization and mapping (SLAM) and all-around obstacle avoidance (Schleich & Behnke, 2022) as well as waypoint navigation and exploration with minimal effort from the operator using a gamepad controller. The NUC's iGPU runs convolutional neural network inference for semantic segmentation and person detection from point cloud as well as color and thermal imagery (Bultmann et al., 2023, 2021). For mission control and operator supervision, relevant status information and preprocessed measurements are transmitted over WiFi to a ground station, where the live reconstructed 3D color map is visualized along with images from an Insta360 Air panoramic camera, a FLIR ADK thermal camera, and semantic information.

3.2.2 | UGV with manipulation capability

The RTF uses a UGV with grasping capability (see Figure 8) as an exploration and manipulation platform. A Telerob Telemax Hybrid is equipped with multiple modules to enable operator support with assistance functions, such as 3D-SLAM (Daun et al., 2021), obstacle avoidance, waypoint navigation as well as autonomous exploration. The splash-proof navigation module mounted on the back of the UGV provides perception by combining a continuously rotating LiDAR, an omnidirectional camera, and multiple RGB-D cameras. The sensor module at the gripper consists of a thermal camera, an RGB-D camera, an HDR wide-angle camera, and a zoom camera. The sensor data are processed on the robot using onboard-computing and transmitted via WiFi connection to the operator, who can control and supervise the assistance functions.

3.3 | Network communication platform

Despite state-of-the-art robotic systems already being able to perform with partial or full autonomy, reliable communications remain indispensable for mission configuration and monitoring and for emergency-related real-time teleoperation. Since rescue missions usually exhibit challenging network conditions, such as increased signal attenuation through multiple layers of collapsed walls and electromagnetic interference from malfunctioning devices or damaged power lines, resilient networking solutions are required.

The SKATES (Güldenring et al., 2020) communication platform was developed and integrated in the DRZ networking approach to provide a robust and interoperable means of acquiring sensor data, transmitting steering commands, and enabling real-time multimedia-supported mission orchestration. Through the interoperable nature of the SKATES module's connectivity, a flexible blend of Radio Access Technologies (e.g., WiFi, 4G, 5G, or IP-Mesh networks) is enabled through a multiconnectivity approach to improve the overall robustness of the communication link. SKATES was tested on various occasions, such as a firefighting exercise organized in Viersen, Germany, 2021 (Figure 3), where it was provisioned with WiFi and 5G connectivity, thereby extending the robot's range to reach deeper parts of the field. More details on the SKATES platform are provided in Kruijff-Korbayová et al. (2021) and Güldenring et al. (2020).

3.4 | Joint exercises in living lab, realistic scenarios, and competitions

Deploying research demonstrators in actual disasters requires preparation and training. Since 2018, the DRZ has been performing complex, close-to-realistic scenario tests (Figure 4) together with research project partners and professional first responders every 6 months, to train, refine requirements, evaluate current solutions, and build up team experiences.

During these exercises, researchers/developers from the project and firefighters from FwDO form a joint robot-assisted team. The team has the following composition and command structure: *a mission commander* (firefighter) directs the whole operation; *one or more UAV units* and *a UGV group* are directly subordinated to the mission commander; the UGV group has *a group leader* (firefighter) and consists of several UGV units; each UAV/UGV unit consists of *a pilot/operator* (developer) and a UAV/UGV; for each UAV/UGV there is a *safety officer*; *an information assistant* (developer) located in the RobLW operates the joint situation awareness interface where information from the units is collected; *a network communications unit* sets up an ad hoc network. The exercises typically involve two UAV units and three UGV units, employing the DRZ demonstrators described in Kruijff-Korbayová et al. (2021). The scenarios are variations of a building collapse (outdoor) and an industry accident (indoor). The main focus is on reconnaissance, sometimes also other tasks have been included (victim transportation, closing a valve, neutralizing a leakage, or extinguishing a small fire). The missions typically take approximately half an hour each.

The RobLW is shared by the DRZ RTF, for research, and FwDO, to test it in real deployments. The DRZ RTF setup is regularly tested in joint exercises in the DRZ living lab (Kruijff-Korbayová et al., 2021) and is ready to deploy 24/7.

In contrast to the exercises, rescue competitions often focus on specific tasks (Shen & Jacoff, 2019) and do not account for the complex challenges and procedures of actual deployments. Therefore, the "DRZ Challenge" was developed to resemble the mission-based exercise structure and successfully embedded as part of the RoboCup German Open competition hosted in the DRZ living lab. The challenge mimics the reaction to an accident in a chemical laboratory where an incident with explosive substances has been

FIGURE 3 Deployment of interoperable multilink communication platform designed for DRZ missions, provisioned with 5G and WiFi during a firefighting exercise to supply immersive situational awareness to the rescue forces. 5G, fifth generation; DRZ, German Rescue Robotics Center; WiFi, Wireless Fidelity.

FIGURE 4 DRZ training facilities. (a) Training's hall with NIST UAV and UGV training ground and (b) outside training ground with container and ruble. DRZ, German Rescue Robotics Center; NIST, National Institute of Standards and Technology; UAV, unmanned aerial vehicle; UGV, unmanned ground vehicle.

reported. The procedure of the mission mimics the structure of a disaster response, for example, by starting the mission from within the RobLW, and combines multiple challenges:

- *Perception*: navigation through smoke, thermal inspection of containers, detection of hazmat signs, and mapping.
- *Mobility*: traversal of debris.
- *Manipulation*: door opening, valve operation, and container sealing.

Most tasks are based on NIST standard tests (Shen & Jacoff, 2019), but the combination of various tasks and the procedure resembling a real disaster response requires the participants to demonstrate a comprehensive set of skills and capabilities, which closely relate to the needs of actual deployments.

4 | DEPLOYMENT REPORTS

4.1 | Industrial hall fire Berlin

- *Situation:* On February 11, 2021 a fire broke out in a metalworking factory in Berlin, Germany, and could only be extinguished after more than 12 h of work. Hazardous substances were released during the fire (Figure 5).[5] Due to the high level of damage, an entry ban was issued. On February 22, the Berlin police submitted an administrative assistance request to FwDO for support with special UAV technology as part of fire investigation.

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[5] Link: Grossbrand Berlin.

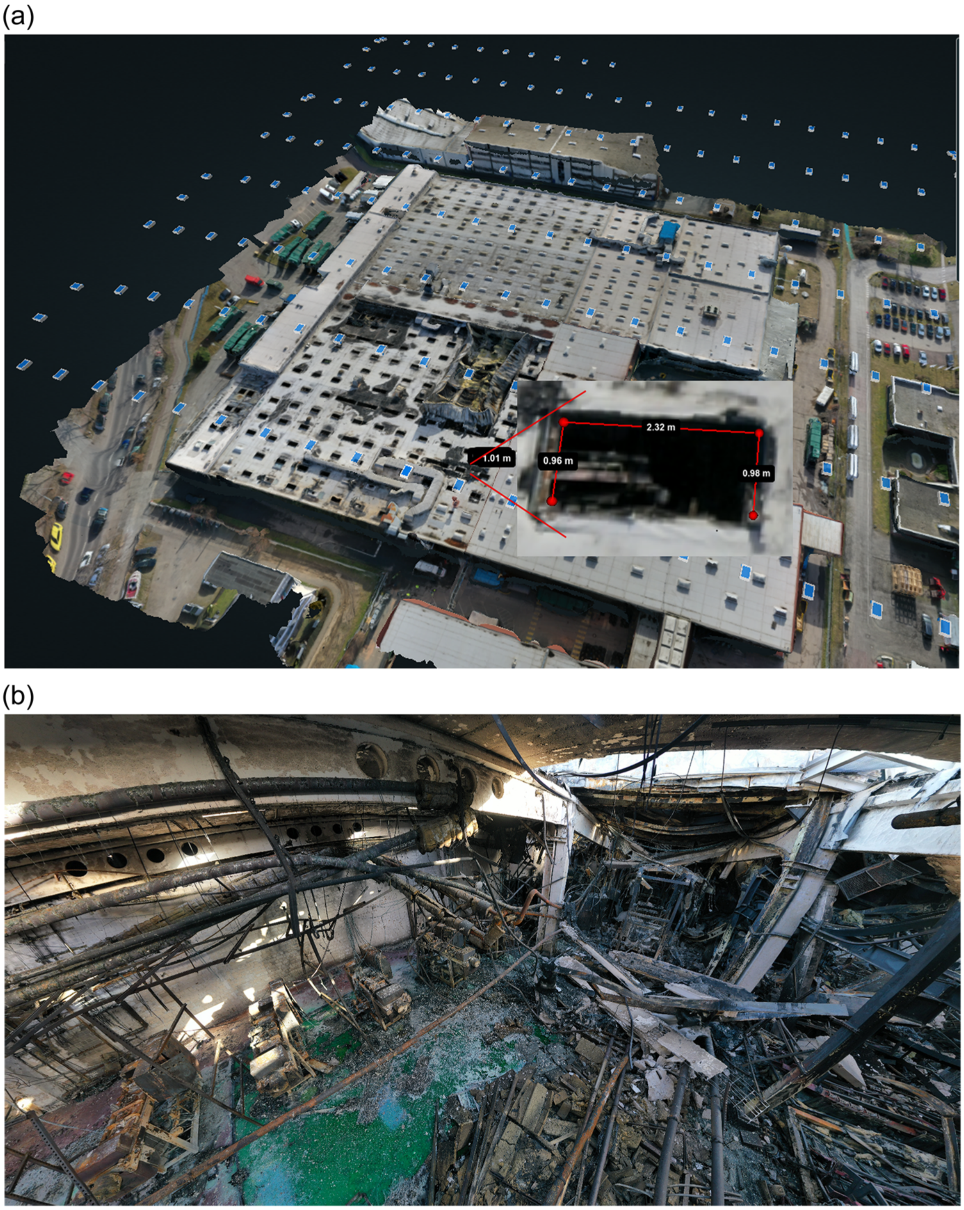

FIGURE 5 Industrial hall: (a) georeferenced 3D model for the mission planning and (b) snapshot out of a UAV-made panorama after the fire. The green substance is highly toxic cyanide. The metal parts and cables hanging around make flying extremely difficult with a correspondingly high risk of losing the drone (Surmann et al., 2021). 3D, three-dimensional; UAV, unmanned aerial vehicle.

- *Team composition:* A team of emergency responders from FwDO, DRZ staff members, and WHS researchers was put together and set off to Berlin for a 3-day mission with the RobLW. The roles needed in the team were: team leader, UAV pilot(s), and IT expert(s).
- *The task* for the team was to build a digital representation of the outside and inside areas of the industrial hall. The RobLW was used on site to process the UAV images to create 3D views while displaying live-streamed footage. Due to the remaining 10–30 cm high and potentially contaminated extinguishing water on the ground, it was clear from the outset that ground robots could not be used.
- *Mission execution:* Since the hall was unknown terrain, first an overview was needed. For this purpose, a meander flight with a commercial DJI Mavic 2 was made 45 m above the hall. The downward-facing UAV images were processed using the photogrammetry software WebODM after landing on an orthophoto and a georeferenced 3D point cloud model of the hall. The model was then used to measure and survey windows and openings for possible entry.

From the openings measured above, it was obvious that flying through the ceiling opening into the hall was possible with a Phantom 4 and a Mavic 2, but two issues needed to be addressed. The small aperture angle of the UAV camera (FoV≈80°) did not allow for seeing the boundaries of the opening while flying through it. The second issue was to fly the UAV back out of the hall, because the UAV cameras could be pointed forward and downward but not upward. To ensure visibility, we performed a multi-UAV sortie, taking a *two-pilot approach*: When the first UAV enters the hall, the second UAV is positioned exactly above the entry point and assists in flying in by providing an external view.[6] While the first UAV autonomously creates the panoramas in the hall, the second UAV waits above the opening, and after completing the shots, the second pilot navigates the first UAV back out through the opening. To fly in, a Mavic 2 was chosen due to the slightly better camera resolution and was equipped with propeller guards. Upon approaching the openings, it was noticeable that the metal of the roof hatches had been severely bent by the fire. This significantly reduced the width of the openings and made it very difficult to fly into the hall. Some openings could not be flown at all.

Another trick was used to capture data from these remaining obstructed positions. A panoramic camera, Insta360 One X (110 g, 15.8 MP), was attached to the Phantom 4 with a 1.5-m-long thin rope and inserted into the respective opening from above. With this, it was possible to record 20 min of video to view all parts of the site.

- *Lessons learned:*
  - (i) *Improved robustness and durability*: Drones used in disaster scenarios have to be engineered to be more robust and durable. Research has led to the development of ruggedized micro UAVs (<30 cm) with a 360° camera that can withstand harsh conditions, ensuring they remain operational during and after disasters. Flying in a hall heavily destroyed by fire is extremely risky and difficult, but the recordings of the high-quality images (5.7k)—especially the panorama images (16k)—as well as video material[7] (4k) were very helpful for the situation assessment.
  - (ii) 360° *Sensing*: To enhance their usefulness in disaster response, drones are equipped with 360° sensors. Research has refined sensor technologies to provide better situational awareness.
  - (iii) *Swarm technology*: Research into drone swarming has been instrumental in disaster scenarios. Multiple pilots and drones can work together as a coordinated team to cover difficult conditions. Algorithms and communication protocols have been developed to enable swarm behavior for tasks, like, area assessment.
  - (iv) *3D Mapping*: Drones are employed for rapid mapping of disaster-affected areas. Research efforts have focused on robust visual 3D mapping techniques based on equirectangular images and create detailed 3D maps for responders to assess damage and plan interventions effectively.
  - (v) *Obstacle avoidance*: Disaster areas can be cluttered with debris and obstacles. Researchers have to develop vision-based advanced obstacle avoidance algorithms for micro UAVs (not able to carry a LiDAR) to help drones navigate safely in complex and dynamic environments.
  - (vi) *Communication reliability*: Maintaining reliable communication between UAV and ground control is vital. Research has led to advancements in communication protocols to minimize signal interference and data loss, even in congested or disrupted environments with much metallic shadowing. Nevertheless, the pilot should take an elevated position on a fire brigade turntable ladder or other roofs.

In summary, ongoing research has played a pivotal role in enhancing the capabilities of drones for disaster response. The captured material was made available to the Berlin police for assessing the situation and for further investigations. Setting up appropriate environments and flying in them must be trained over and over again and incorporated into the fire department's training plan.

4.2 | Flooded town Erftstadt

- *Situation:* The Flood in Western and Central Europe in July 2021 was a natural disaster with severe flash floods in several river basins (Figure 6). Parts of Belgium, the Netherlands, Austria, Switzerland, Germany, and other neighboring countries were particularly affected. The most severe floods were caused by thunderstorm Bernd.[8] The drastic consequences of the storm disaster in Western Germany also made themselves strongly felt in Erftstadt/Blessem. Due to the flooding and a potential collapse of the Steinbach dam, a thousand residents in several localities had to be evacuated from their homes. The Erft and Swist rivers had burst their banks and flooded large parts of the Erftstadt urban area. Long-distance roads such as the federal highways No. 1 (Eifelautobahn) and No. 61 as well as the federal highway 265 were closed as a result of the flooding and road damage. In the Erftstadt district of Blessem, the waters of the Erft flowed through a residential and commercial area and made a new path into the pit of the Blessem gravel plant; several houses were washed out, several others damaged near Blessem Castle. An extensive emergency response mission commenced, including a rescue robotics team of the DRZ.
- *Team composition:* The team consisted of personnel from FwDO, DRZ, UBO, UzL, TUDA, and WHS. It set off to Erftstadt/Blessem for a 2-day mission with the RobLW directly in this very dangerous area at Blessem Castle. The roles needed in the team were: team leader, UAV pilot(s), and IT expert(s).

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[6] We performed a flight in such a multi-UAV two-pilot configuration also during the 2016 deployment in Amatrice, Italy (Kruijff-Korbayová et al., 2016).

[7] UAVs Berlin Video: https://youtu.be/mR05-akD4BE.

[8] 2021 European floods: https://en.wikipedia.org/wiki/2021_European_floods.

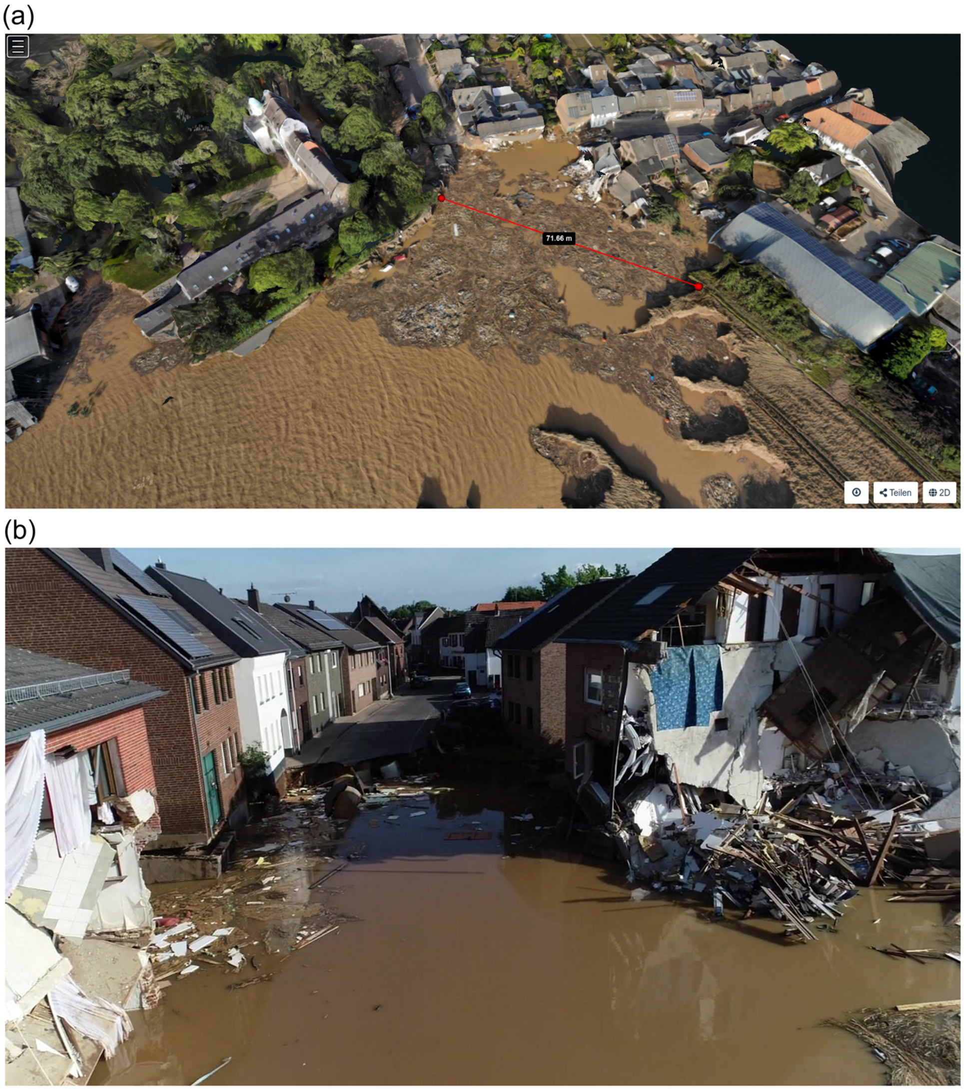
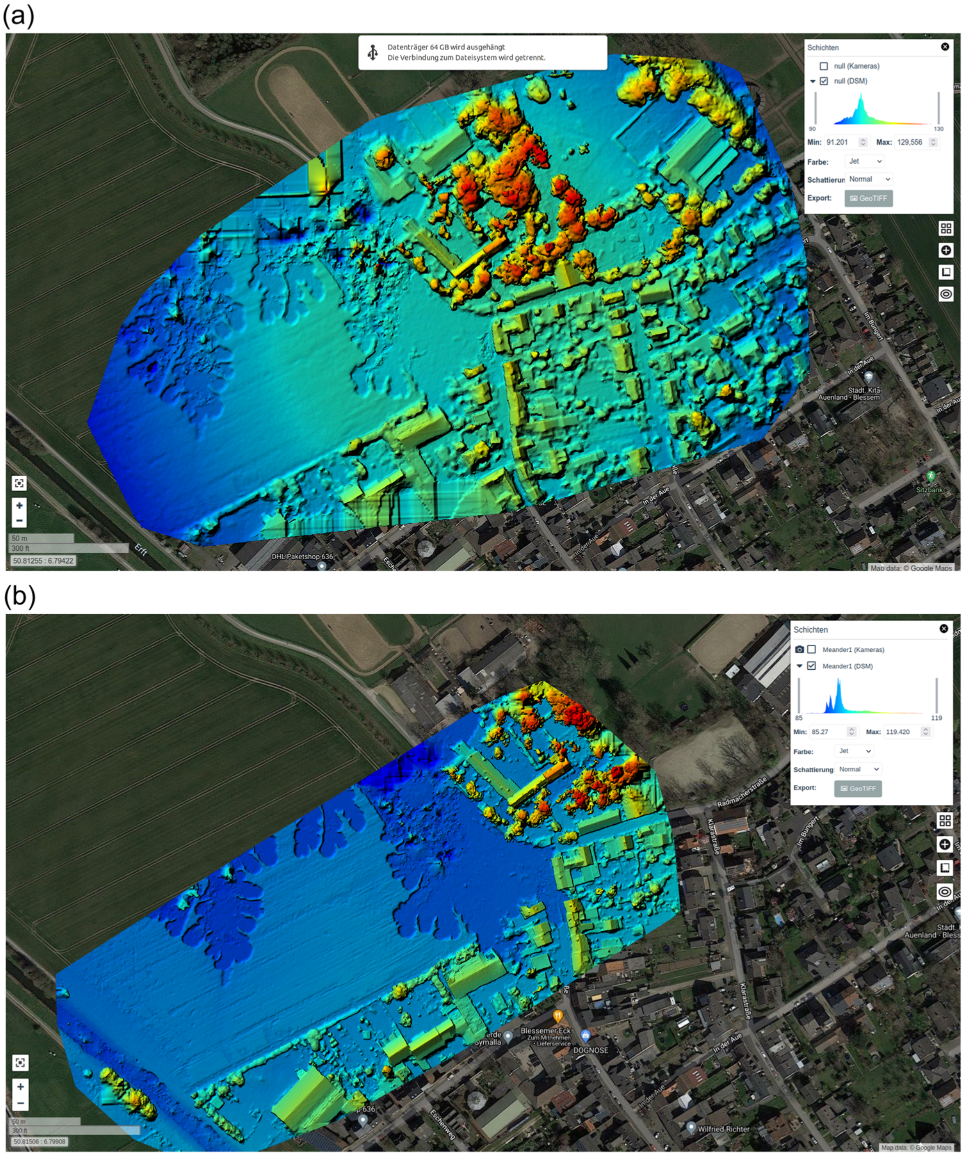


FIGURE 6 Urban flooding: (a) 3D model for the mission planning and (b) flooded road, mission: person search, Erftstadt/Blessem, Germany 2021 (Surmann, Slomma, et al., 2022).

- *The tasks:*
  1. live air observation of the demolition edge and alerting in case of further demolition or changes, especially to secure the emergency forces in search for missing persons in buildings behind the demolition edge,
  2. generating high-resolution 3D models for the purpose of further mission planning directly on site even without power, Internet, or mobile phone connection,
  3. detailed inspection of all buildings/structures that could not be accessed or reached by responders because many people were missing, and
  4. creating clear and easily accessible documentation for the emergency services.

- *Mission execution:* Since the environment was destroyed over a large area, planning with existing information was not possible. So, first a drone (Yuneec Typhoon) was used to get live and overview images of the area and to record the extent of flooding and the water flow direction. Second, systematic flights, that is, meander flights, were planned and executed with commercial UAVs (Mavic 2, Phantom 4). From these images, a georeferenced orthophoto and 3D point cloud model was created using WebODM. In addition to the meander flight, a 360° panorama was created by taking individual photographs to obtain an overview as quickly as possible. On the basis of the orthophoto and the 3D point cloud model, a detailed investigation was planned and executed with a DJI first-person view (FPV) drone. Especially the inaccessible and partially destroyed buildings and vehicles were inspected (Figure 6). All information aggregated during the flights was compiled into a presentation and presented to the command staff later that night. Due to the destroyed infrastructure (no electricity, no Internet), only the RobLW could be used for data processing on site, which was accordingly heavily utilized. On the following day, further meander



(a)

Datenträger 64 GB wird ausgehängt
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Min: 91.201 Max: 129,556
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Farbe: Jet
Schattierung: Normal
Export: GeoTIFF

FIGURE 7 Elevation profiles of consecutive days (a and b). The comparison of the two elevation profiles shows that the water has sunk by about 40 cm within 1 day, threatening further demolitions due to the lack of water backpressure. On the basis of the information, the emergency forces were pulled back by 100 m from the demolition site.

flights were performed, comparing the resulting 3D model and elevation profiles with those of the previous day (Figure 7). The resulting height difference of about 40 cm shows a significant water runoff, which is why the protection zone along the edge of the break-off had to be enlarged again.

- *Lessons learned:*
  - (i) *Swarm technology*: Large-scale emergencies like the flooding require the deployment and coordination of many UAV teams (see Section 4.1).
  - (ii) *Robust technology*: The failure of the infrastructure (power, Internet) necessarily requires the operation of power and Internet-independent vehicles, such as the RobLW.
  - (iii) *Georeferencing and photogrammetry*: Especially for large-scale damage events, the systematic aggregation of individual images into large high-resolution maps, which can be overlaid with Google maps is particularly helpful to assess the current extent of destruction.
  - (iv) *Mission planning*: The calculated georeferenced 3D point clouds and orthophotos are very suitable for further mission planning, especially detecting critical locations (e.g., the break-off edge and partially destroyed houses) and documenting subsequent detailed inspections with small FPV drones. AI-based automatic planning is requested and under current research.
  - (v) *UAV hardware*: Robust, durable, and small FPV drones with a large camera aperture angle are great for the detailed inspection of collapsed houses. More autonomous behaviors are required. Small, invisible 360° UAVs are under development.
  - (vi) *Human factor*: Due to lack of experience, and thus the inability to use robots, on the part of the new first responders, the UGV

and the larger UAV were not used. The mission commander was clearly facing a dilemma to decide whether a robot deployment would add value or (only) disturb. Deployments of the other UAVs were initiated and significantly influenced by suggestions made by the researchers involved.

4.3 | Residential complex fire Essen

- *Situation:* On the night of February 22, 2022, a large residential apartment building in Essen, Germany caught fire. Fanned by a storm, the fire spread quickly, so the entire southwestern facade was in flames. After the extinguishing work, 39 apartments on four floors were completely burned out. Others were destroyed by smoke or extinguishing water. Due to the partly massive destruction, an entry ban was imposed. Although no persons were missing after evaluation of the occupant numbers, the actual situation remained unclear due to the entry ban, which is why air and ground robots of the DRZ were requested.
- *Team composition:* The roles needed in the team were: team leader, UAV pilot(s), camera copilot(s), UGV pilot(s), safety officer(s), and IT expert(s).
- *The task* consisted of reconnaissance, clarification of the cause of the fire, and documentation of the scene. Small FPV drones (<1 kg) with a 360° camera were deployed for the first time worldwide directly on February 22 for reconnaissance in the particularly heavily destroyed central part of the building complex and on February 23 ground and aerial robots were deployed in the less destroyed outer areas.

☐ *Day I: FPV + 360° Reconnaissance*. As mentioned above, the *task* on the first day was the exploration of the particularly destroyed areas, especially on the upper floors, which were no longer accessible due to the destruction of the stairs. For this purpose, the RobLW was additionally equipped with eight different drones and brought to the site. At the beginning of the *mission*, a georeferenced 3D model of the operational environment was created by means of a 10-min meander flight and subsequent 15-min model calculation. The model was used to plan two FPV flights with a 360° camera. For example, a flight of 4:30 min allowed five apartments to be completely examined. Videos of the flights and the created maps are available online.[9]

  - *Lessons learned:* FPV flights with a 360° camera create an impressive immersion. The small and lightweight drones can safely inspect collapsed buildings faster than humans, especially on the upper floors and severely damaged areas with non-existent staircases. The 3D models can be computed based on 360° videos (Surmann, Thurow, et al., 2022).

☐ *Day II: Joint UGV/UAV deployment*

  - *Task and setup:* The rapid fire spread was surprising for experts. To avoid similar events at other buildings, fire cause clarification was of high importance. The Essen police submitted an administrative assistance request to the FwDO asking for site inspection support. Consequently, a team consisting of emergency services from FwDO providing a UAV (DJI Matrice M300) and staff members from DRZ and TUDA with a tracked ground robot (see Figure 8) was composed and set off to Essen for a 1-day mission with the RobLW. The *task* was to create a digital 3D model and images of the inside of four flats in the vicinity of the presumed origin of the fire.
  - *Mission execution:* After a meeting of the forces from the local police, FwDO, DRZ, and TUDA, a walk through the stable parts of the building was performed to assess the conditions. The initial inspection helped to identify potential risks for the ground robot operation, such as narrow passages, large loose rubble, and wire meshes from burnt-out couches. Three inspections with the robotic systems were performed: One for each of the two flats on the first floor, which took roughly 45 min each, and a third inspection of the two flats on the second floor, which took 75 min. To mitigate the risks of losing the robotic system during the exploration of the first floor, TUDA personnel had visual contact with the robot from a safe distance for most parts of the mission and maintained radio contact with the robot operator. Due to the concerns about the structural integrity, this was not feasible for the second floor. Instead, a UAV was deployed to provide an outside camera perspective on the robot operation, which was shared with the UGV operator via a tablet showing the live video stream from the UAV. After inspection, the lower part of the robot was covered with a hazardous dirt crust consisting of wet, burnt ashes. Hence, the robot was decontaminated at the local fire department in Essen.

The 3D models of the environments were created with a robust LiDAR SLAM system (Daun et al., 2021) developed as part of the A-DRZ project. The system combines LiDAR range observations, inertial-sensor, and odometry measurements in a joint optimization problem to compute robust and accurate 3D models and trajectory estimates. First 3D models of the explored environment could be computed live during the mission. To optimize the quality and provide tools to enable fire investigators to interact with the model, the data were processed again offline and submitted 1 week after the incident.

- *Lessons learned:*
  (i) *Robot mobility*: The narrow shape of the ground robot allowed a deployment to most parts of the environment and to even pass through very narrow passages like a jammed door on the second floor. The tracked drive worked well for traversing stairs, debris, and rubble. However, especially in curves, caution was necessary as the tracks tended to dig into the loose ground. The traversal of the environment took rather long.

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[9] YouTube videos: Essen 360°, PanoViewer, DenseMapping.

FIGURE 8 Residential fire, Essen: (a) front view from a 360° image showing the protected UAV and a staircase destroyed by fire and (b) side view, mission: person search, cause of fire, Germany 2022. UAV, unmanned aerial vehicle.

(ii) *Network connection*: While driving inside the building with reinforced concrete walls and floors, the radio communication between the UGV and the robot operator was heavily dampened. This resulted in a temporary loss of WiFi connection with the robot, hindering the control of the assistance functions (see below). However, the UGV is equipped with a second high-power proprietary radio connection which proved to be more reliable.

(iii) *Assistance functions*: Due to the challenging characteristics of the environment, robot operation was very difficult. The visualization of the registered point cloud (Daun et al., 2021) with the 3D robot model in the user interface (Fabian & von Stryk, 2021) strongly helped to navigate through narrow environments, as potential collisions with the surroundings could be precisely assessed. Furthermore, the rendering of virtual pinhole cameras (Oehler & von Stryk, 2021) from the omnicamera helped to improve the operator's situational awareness. However, the availability of these assistance functions to the operator depended on the availability of the WiFi network, which was available inside the building for an estimated 70% of the time with sufficient connection quality. In times without available WiFi connection and thus assistance functions, safely controlling the robot proved more challenging. Due to concerns about the performance of the control system in loose ground, no more complex assistance functions such as autonomous waypoint navigation were deployed.

(iv) *Multirobot collaboration*: The deployment of a UAV to provide an outside perspective of the UGV for the exploration of the second floor was helpful to improve the operator's situational awareness, especially in areas without available assistance functions due to poor WiFi connectivity. A drone equipped with a SKATES module acting as a movable relay may improve radio communication in future missions.

(v) *Robot robustness*: Although developed as a research demonstrator, the developed splash water protection was necessary to perform the mission as extinguishing water was dropping from the ceiling and the system needed to be decontaminated after the mission.

(vi) *Team interaction*: Mission command (professional first responders) and robot operation personnel (research staff) had worked together during the joint DRZ exercises 3.4. This had helped to learn about communication, capabilities, and deployment procedures—enabling an efficient execution of the overall deployment. In our opinion, this is especially crucial for the participation of researchers without experience as first responders in real deployments.

(vii) *Deployment preparation*: As the deployed UGV is still under active development and a research demonstrator, extensive system checks at home and traveling to site on the day before deployment helped to mitigate risks. However, the trade-off between response delay and efficiency needs to be chosen for every mission.

5 | DISCUSSION OF LESSONS LEARNED AND OUTLOOK

Over the past 10 years, we have observed a shift in priorities regarding the usage of UAVs and UGVs for structural collapse inspection: at the beginning there was focus on livestream images (e.g., Emilia 2012; Kruijff et al., 2012), then models were computed offline (e.g., Amatrice 2016; Kruijff-Korbayová et al., 2016), nowadays—thanks to technology advances—models can be computed in short time and used onsite for further mission planning, for example, exterior models used for measurements (cf. Section 4.1). Regarding data products for postmission analysis, such as detailed inspection of structural damage, there is a shift from 3D point cloud models to georeferenced, semantic 3D models and to localized high-resolution panorama pictures and further data processing with advanced photogrammetry and AI algorithms. On the other hand, 3D point cloud models are very useful for teleoperation.

UAVs are becoming smaller and are equipped with better cameras (IR, 360°, zoom) for delivering high-quality pictures (>4k). Flight modes are improving and provide more and more support for the pilot. This makes UAVs very suitable for reconnaissance, especially in structural collapse scenarios with tight, damaged conditions and rubble, which are difficult for UGV traversal. On the other hand, UGVs are generally better equipped for manipulation (e.g., opening doors, removing obstacles) and to carry varying payloads. Also, first responders note (p.c.) that air turbulence caused by UAV rotors poses a concern for spreading air pollution in some scenarios involving hazardous gasses. A typical mission process involves quick overview flights for initial planning and determination of ingress points, and multiple subsequent UAV and UGV sorties for detailed inspection and/or data collection. This means that the remote presence and taskable agent roles defined by Murphy (2014) are often mixed, as data products are being used for problem solving on the spot, to determine what can be done during a mission at all, involving eye-inspection of both pictures and models. Consequently, there is a demand for quick creation of data products for mission planning. In the future, this needs to include map representations of trajectories and timeline calculations, integration of data from multiple sources, and dynamic projections for fast-changing situations. We plan such extensions of the Situation Awareness Interface described in Kruijff-Korbayová et al. (2021). Further research on user interfaces is needed to appropriately support different tasks and roles in the team and communication between team members.

Our experience regarding mission planning and task assignments is that the first responders often do not know how to employ robots and what they can ask for in terms of available capabilities. The researchers involved in the DRZ RTF bridged this gap successfully by proposing possible actions and proactively contributing to the mission. Mission commanders who had previous exposure to UAVs/UGVs in action during joint exercises were more likely to request the RTF deployment.

We have repeatedly observed the need for multirobot collaboration. On the one hand, we need to automate existing data capture and processing for larger areas with multiple small, affordable UAVs based on consumer platforms. On the other hand, UAV-UAV or UAV-UGV collaboration is needed to support teleoperation in situations where a primary UAV/UGV operator needs an external view (provided by a secondary UAV/UGV), for example, for manipulation, entering and navigating in a (damaged) structure, traversing ruble, or passing through obstacles. The primary operator needs to be able to (verbally) coordinate with the secondary operator. They also need a Camera Copilot to view the secondary video feed and provide additional guidance. Automation of the secondary operator's task is an interesting future research opportunity.

Furthermore, more research is required to autonomously operate off-the-shelf UAVs not only in the vicinity of obstacles, but in confined spaces where loss is probable. Size and weight limitations mandate ground-based computation of live-streamed images and remitted control commands over wireless connections. The next important developments are needed in SW and AI, especially latency-aware perception and planning, fusion of local scene models, automatic assessment, better simulation (for planning and training), and handling changes in highly dynamic settings. Together, this will enable a small team of operators to configure and oversee a UAV swarm in real time during continuous operation from a ground station.

The RTF team composition varied, depending on the task(s), whether both UAV(s) and a UGV were used, and the circumstances. The following role distribution evolved with growing experience of the RTF: UAV/UGV pilot(s); camera copilot(s) in case of multirobot collaboration; UGV safety officer for distant observation; IT expert(s) for data processing; and team leader, who is also the one to interface with the first responder corps. We did not use payload specialists

(Murphy & Tadokoro, 2019). During joint exercises in the DRZ living lab, we have also experimented with more complex teams using multiple UAVs and UGVs simultaneously (Kruijff-Korbayová et al., 2021). In this case, we introduce a more hierarchical command structure, in which the UAVs are assigned directly to a mission commander, whereas UGVs form a group assigned to a group leader who reports to the mission commander. The integration of robotic (sub)teams into the established first response command structures needs more work in the future. Further research is needed to specify "blueprint" structures and roles for various types and sizes of missions, and include explicit planning of the command structure and role assignment in mission planning.

Given the critical character of data acquisition, even for autonomous mobile robotic platforms, meaningful developments are also due in the network communications field. The deployment use cases in Section 4 validate the relevance of multilink communications, as it was observed that relying solely on one technology may yield a limited range and performance in rescue scenarios. Expanding on that, the robustness expected from networking solutions in real-world environments must be evaluated before missions through use-case-related inspection and test procedures. In our current work the procedures developed so far, such as the vSTING (Patchou et al., 2022) illustrated in Figure 9 and STING (Arendt et al., 2021), will serve as a base for repeatable assessment, validation, and certification processes of robotic systems in their ability to perform in network environments with constrained connectivity. Furthermore, merging network communication considerations into autonomous navigation could result in communication-aware autonomous mobility with prospects of increased network robustness. A concrete and envisioned instance thereof is to restore lost network connectivity through adequate autonomous repositioning. Finally, as the exploration of collapsed buildings likely involves multirobot teams, the allocation of spectrum must be planned and enforced to ensure that each robot disposes of enough resources for its wireless transmission needs.

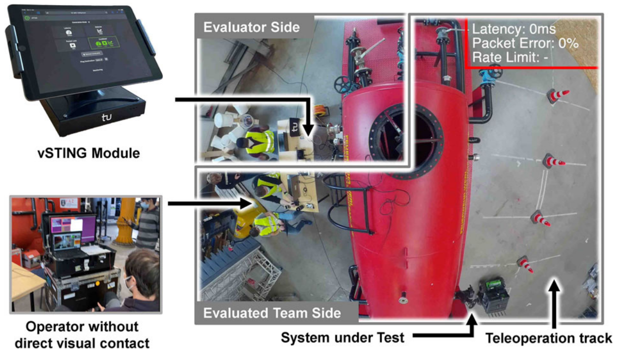

FIGURE 9 Successful application of the vSTING approach (Patchou et al., 2022), as an additional challenge at the Rescue Robotics League (German Open 2021 and 2022). Teams must teleoperate the rescue robotic platforms through a course under emulated network constraints.

Across the board, it holds that the rescue robots must provide robust functionalities that can be quickly deployed. This goes down to apparent banalities, such as automation of setup processes and standard system-go checks. Adhering to these procedures in joint exercises is crucial to be well established for RTF deployments. Similarly, competitions provide the opportunity to further seed these insights in the rescue robotics community, by considering mission organizations in the competition structure and addressing the combination of versatile capabilities.

6 | CONCLUSIONS AND FUTURE WORK

We presented our experiences from recent deployments of the DRZ RTF. The DRZ RTF model based on continuous long-term close collaboration between researchers and first responders (firefighters) benefits both sides. Testing cutting-edge robotics technology, including research demonstrators, in joint exercises and real deployments enables researchers to gain better insight into end-user needs and operational conditions and identify appropriate research priorities. First responders gain deeper awareness of the advanced technologies, assess the functionalities, and learn to employ them in missions. Together, they identify future potential benefits.

The technologies involved in robot-assisted disaster response are developing very fast, and first responders normally do not have sufficient expertise. This requires the RTF model of researchers bringing in cutting-edge technology and—as the technology matures and becomes established—providing corresponding training and transfer of experience. Therefore, these goals are part of the DRZ long-term vision. Scenarios in the DRZ Living Lab and exercises carried out jointly by the RTF and additional first responders as well as researchers are set up to reflect the experience gathered so far and explore further challenges.

The future research topics identified in this paper are being addressed in the project *Establishing the German Rescue Robotics Center* (E-DRZ) that started in 2022.

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