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German Rescue Robotics Center (DRZ): A Holistic Approach for Robotic Systems Assisting in Emergency Response

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***Abstract*— To meet the challenges involved in providing adequate robotic support to first responders, a holistic approach is needed. This requires close cooperation of first responders, researchers and companies for scenario-based needs analysis, iterative development of the corresponding system functionality and integrated robotic systems as well as human-robot teamwork support, and experimentation, system testing and evaluation in realistic missions carried out with or by first responders. We describe how such a holistic approach is implemented by the partners in the cooperative project A-DRZ for the establishment of the German Rescue Robotics Center (DRZ). The A-DRZ approach addresses important requirements identified by first responders: adaptation of operational capabilities of robotic platforms; robust network connectivity; autonomous assistance functions facilitating robot control; improving situation awareness for strategic and tactical mission planning; integration of human-robot teams in the first responders' mission command structure. Solutions resulting from these efforts are tested and evaluated in excercises utilizing the advanced capabilities at the DRZ Living Lab and in external deployments.**

I. Introduction

Emergency response involves operation in high risk situations and making critical decisions under time constraints despite partial and uncertain information, particularly in medium- to large-scale incidents, such as major fires, floods,

Fig. 1: DRZ command vehicle and the robotic fleet

landslides or collapsed buildings. The use of mobile ground and aerial robots to access dangerous or inaccessible areas can provide significant advantages for operational safety, capabilities, and efficiency of the first responder (FR) team. FRs increasingly employ mobile robots, most often aerial vehicles, and sometimes also ground or aquatic robots. Robots are most frequently used for the reconnaissance of an incident site to increase situational awareness, but also for other tasks. For example, during the Notre Dame fire in Paris, 15/04/2019, teleoperated drones were deployed for aerial surveillance and a teleoperated fire-fighting ground robot pulled a firehose inside the church and sprayed water on the burning ruble [1]. Teleoperation of robots in such situation requires reliable high bandwidth wireless communication, and is exhausting and error-prone. Robots with intelligent autonomous capabilities can be much more effective. However, unlike in industrial settings each first response scenario is different and takes place subject to challenging environmental conditions, such as unstructured terrain, natural lightning and weather conditions and specific disaster conditions such as smoke or collapsed buildings.

The German Rescue Robotics Center (DRZ) was founded in 2018 as an independent non-profit cross-stakeholder institution aimed to bundle and further develop competencies for robot-assisted emergency response among FRs, academia and companies. The DRZ is currently being established

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by the cooperative project A-DRZ. Central to A-DRZ is a holistic approach to robot-assisted emergency response: We pursue application-oriented research and technology development motivated by FRs' needs, carried out in close collaboration with FRs and directly evaluated by them. The required capabilities of the robotic systems are determined with respect to reference scenarios defined by FRs based on their experience. A-DRZ pursues four main scenarios: fire, chemical substance incident,[1] collapsed building and flood. To demonstrate the technical solutions developed in A-DRZ we integrate them into end-to-end systems which we test in joint exercises in deployment-like conditions (cf. Sec. VIII and IX). Such a holistic approach is necessary for the operationalization of robot-assisted emergency and facilitates

The paper presents the main challenges of rescue robotic system development identified for the A-DRZ scenarios (and beyond), and a high level description of the technical components of the holistic solution developed by the A-DRZ partners. We provide references to publications with further technical details and evaluations, where available.

II. Related Work

Most research efforts in robot-assisted disaster response focus on autonomous and semi-autonomous operation of single or multiple robots, and not on the operation of the entire first response team and realistic deployment capacity. Notable exceptions were the approaches followed in the EU-funded research projects ICARUS [2], SHERPA [3], NIFTi [4] and TRADR [5], which included also the tactical and strategic levels of command and tested deployment in realistic simulated missions in collaboration with FRs. NIFTi and TRADR deployed human-robot teams after two large earthquakes in Italy, in Mirandola in 05/2012 [6] and in Amatrice on 01/09/2016 [7], respectively.

Rescue robotics challenges and competitions, also push the development of specific autonomous robotic capabilities, testing them either in controlled benchmark environments or in semi-realistic physical deployment conditions. However, they do not address the integration of the robot-assisted teams into the entire first-response operation.

We do not review existing work on the component rescue robotics technology and research, due to space. See [8], [9], [10] for recent surveys; [11] for the design of interfaces for human-robot interaction; [12] for standard test methods.

III. Modularity

As FRs face a wide spectrum of different and highly dynamic situations, adaptable robotic systems reconfigurable in the field could help to handle unforeseen and changing mission profiles. Besides gaining flexibility in the field, modular payloads are also expected to bring multiple advantages for researchers, developers and end users, including: cost efficient re-usability of usually high-priced robotic components on different systems; technical separability into defined sub-units which can be easily maintained and independently developed in lab environments; space-efficient use of limited mission cargo capacity; increased accessibility by using a common control architecture. Therefore, in addition to specialized monolithic systems, a system modularization concept for ground robots with a suitable amount of horizontal payload space was developed by the A-DRZ partners.

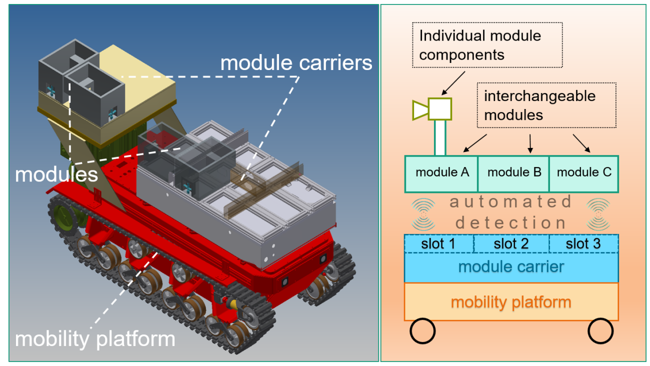


Fig. 2: A-DRZ modularization concept and example implementation on central demonstrator D3

The conceptual core idea is to provide the necessary infrastructure on robotic platforms to encapsulate certain hardware and software as interchangeable modules with defined functionality. The concept differentiates between three main components of such a robotic system (Fig. 2): *mobility platforms*, *module carriers* and *modules*. *Mobility platforms* are responsible for executing locomotion tasks and serve as main power supply for the combined robotic system. *Module carriers* represent a physical interconnection and interoperability layer. They are specifically designed to fit a certain type of mobility platform and give access to its capabilities using a ROS software interface. They also provide the needed communication infrastructure, energy management, and unified physical interface to operate modules. The presence and type of a module is automatically detected to seamlessly integrate it into the software control architecture. *Modules* are designed as independent computational units which can be dynamically attached and detached. They rely on a stabilized 24 V power input and provide a module type specific ROS messages interface for combined control and interoperation purposes. *Modules* which feature their own ROS core are synchronized by using the Multimaster system [13].

IV. Network communications

Even though state-of-the-art robotic systems are highly developed and can perform certain actions partially or fully autonomously, reliable communication is indispensable for real-time teleoperation and interaction between the robot and its operator. In many situations, the robot's tasks must be reassigned, camera images and videos inspected instantaneously, actuators controlled, or sensor values read out. Due to the challenging operating environments in emergency response scenarios, communication is highly challenging. Communication links can be interrupted, e.g., by heavy attenuation of walls when entering into or moving along buildings,

[1] See www.youtube.com/watch?v=ZWD6XDIzc8w for an illustration of the A-DRZ holistic approach in the chemical substance incident scenario.

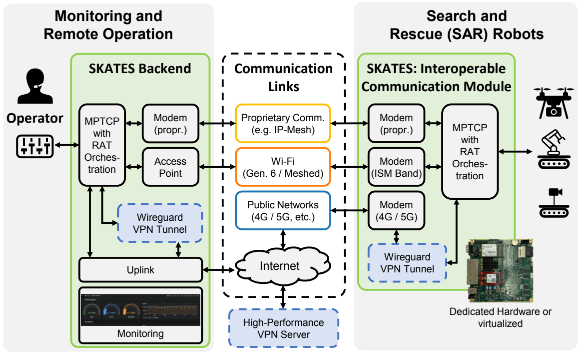


Fig. 3: The SKATES Communication Architecture

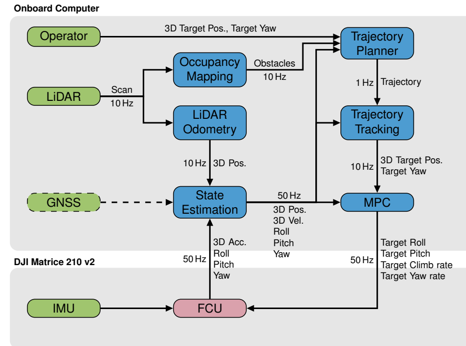


Fig. 4: Structure of our pipeline for fully autonomous UAV flight in emergency scenarios. Green: inputs; blue: software modules; red: the UAV's FCU.

public communication infrastructure may be damaged, or other users and systems cause interference.

To compensate those effects, SKATES [14] (Fig. 3) has been developed and integrated into the A-DRZ approach. A technically detailed description is provided in the corresponding publication. SKATES ensures highly reliable and efficient connectivity between the robotic systems and the remote operators by using a multi-connectivity approach. Here, several Radio Access Technologies (e.g., Wi-Fi, 4G, 5G, or IP-Mesh networks) are orchestrated and used in parallel to compensate errors and failures of individual links and to improve overall performance. SKATES consists of a SOCKS proxy that enables proprietary robot systems to use this multi-connectivity approach without performance degradation and any further adaption required. When using public networks, a high-performance Virtual Private Network allows secure information exchange. A live monitoring tool evaluates the communication link's performance in real-time and summarizes them for the operator. Hereby, shortcomings or limitations of communication channels can be anticipated.

Evaluations show that a unified wireless communication approach for heterogeneous mobile robotic systems is possible. The individual systems can remain in their specific network configuration, while the SKATES communication concept enables flexible integration in the cooperative multi-robot context. In addition, an evaluation of the robotic systems' performance is needed to verify that communication *is* reliable in the challenging situations. As part of the holistic A-DRZ solution, we propose a hardware in the loop simulation approach [15] to enable reproducible testing of rescue robotics systems. Further, ongoing work on the A-DRZ communication architecture focuses on targeted interference generation and testing of wireless connectivity through a variety of tools. We use passive, active, and virtualized interference to create test-cases to ultimately increase the robustness and reliability of the mobile robotic systems. A detailed description of the technical approach along with quantified results is provided in [16].

V. Assistance Functions

FRs experience a lot of stress and high cognitive load during rescue missions [4]. Delicate tasks like precisely piloting an inherently unstable UAV (unmanned aerial vehicle) or operating a UGV (unmanned ground vehicle) in a complex scenario are error-prone and thus can largely benefit from automation.

A. Assistance functions for aerial robots

Fig. 4 shows the A-DRZ pipeline for fully autonomous UAV flight in GNSS-denied (global navigation satellite system) environments. The main components of the pipeline are LiDAR odometry [17], trajectory planning [18], and time-optimal control [19]. Our method works under challenging conditions and requires no prior map of the environment. The UAV estimates its 6D pose in an allocentric map based on measurements obtained with the onboard LiDAR. The position estimates are fused with 3D accelerations from an onboard IMU (inertial measurement unit) to estimate the robot's 3D position & velocity. The state estimate is used to plan collision-free trajectories to an operator-defined target position. If advanced capabilities like inspection of an area of interest or exploration of an unknown volume is required, the target position can also be computed automatically.

The occupancy map for planning is derived from LiDAR measurements and updated during flight. Planned trajectories are sampled by a trajectory tracker, which sends local 3D target positions to our low-level MPC (model predictive controller). The MPC generates a local time-optimal trajectory, consisting of a sequence of roll, pitch, climb rate, and yaw rate commands that guide the UAV to the local target. Subsequently, the commands are sent to the UAV's FCU (flight control unit) for execution. Onboard semantic segmentation and object detection on color and thermal images as well as LiDAR allow to detect people, cars and other objects of interest while enriching the allocentric map.

Our fully autonomous UAV system, including real-world evaluation, is described in [20], [21]. Here, our UAV system proved reliable during multiple GNSS-denied flights in complex scenarios under challenging conditions. The operator only defined the beyond-line-of-sight target pose in an unknown environment and the UAV autonomously approached it reliably without further human input [20].

B. Assistance functions for ground robots

Complementary to the assistance functions for aerial robots, we develop methods to support the operation of UGVs. Our approach is guided by the concept of sliding autonomy, where the operator can select different levels of autonomy, between direct teleoperation and up to full autonomous behavior, at all times.

One of the main challenges of teleoperation is the operator's very limited perception of the environment. A key functionality to improve operator awareness is the capability to generate meaningful environment models. These models are also a key element of the situation awareness interface (cf. Sec. VI-C). To localize the UGV within unknown, uneven, potentially GNSS-denied environments and to create a map of it, we fuse the measurements from LiDAR, IMU and track odometry in an continuous-time 3D SLAM approach with signed distance function-based scan registration. Consistent global registration is achieved by modeling the trajectory as a factor graph with an efficient branch-and-bound loop-closure detection [22].

To assist the human operator navigating through complex and narrow environments, we predict the postural stability of the UGV in the environment with an efficient pose prediction based on differences of heightmaps [23]. We leverage this to give the operator feedback about the expected stability for executing steering commands with markers in a 3D view of the environment. Furthermore, we use the expected stability as part of a cost function to guide path planning for autonomous navigation to waypoints and autonomous exploration. Traversing unstructured obstacles is highly challenging as UGVs are permanently in danger of falling over in uneven terrain. Therefore, we developed an optimization-based planning approach [24] that computes a whole-body motion plan in advance by optimizing the trajectories of each joint based on a 3D environment model obtained from the robot's external sensors and a robot model. Active steering of flipper tracks maximizes ground contact for improved traction and, if available, the manipulator arm joints are used to further improve stability metrics when traversing uneven terrain. To support the operator during manipulation tasks with arbitrary rigid objects, we provide a versatile grasping assistance function that combines an incrementally segmented 3D scene model with grasp pose detection [25].

The environment modeling for UGVs was successfully evaluated in the Zwentendorf Nuclear Power Plant at the EnRicH 2019[2] competition. The accurate 3D map of the plant's ground level combined with a 3D radiation map was judged to be the best result among all participants and won the mapping award.

VI. Teamwork support

Medium-to-large emergency response missions are complex, with potentially many parallel tasks. On the one hand, robotic assistance increases the complexity, on the other hand, robots make more information available in digital form. The A-DRZ teamwork support functionality is a layer on top of the core robotic systems, which helps to handle the mission complexity and abundance of information by collecting information about an ongoing robot-assisted emergency response mission from different sources, including both human and robotic members of the first response team, integrating it and using it to facilitate situation awareness and provide real-time mission process assistance [26]. In this subsection, we explain the overall system architecture of the teamwork support layer, including the providers, types, and flow of data between the individual components. Fig. 5 shows an overview of the modular system architecture. It contains three major data processing components, shown in the center. Those processing components draw their background knowledge from two auxiliary artifacts, shown on the right. The system users are the members of the human-robot emergency response team: FRs and rescue robots.

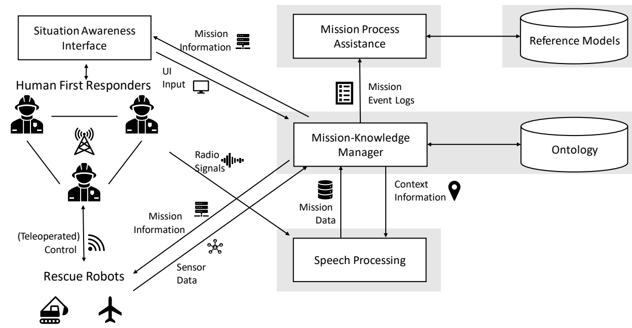


Fig. 5: The A-DRZ teamwork support System Architecture

A. Speech processing

All radio communication among the human team members is continuously captured and processed by the speech processing component (cf. Fig. 5). This component receives the radio signals as raw audio streams, transcribes them using ASR (Automatic Speech Recognition), and interprets them using state-of-the-art NLP (natural language processing) techniques. Currently, two different ASR frameworks are integrated into the A-DRZ pipeline and selected dynamically. One is cloud-based, the other is locally installed. Cloud-based solutions usually have better performance, but also require an internet connection. Because such a connection might be problematic in an emergency situation, we include a locally installed solution as backup. After an assessment and comparison of common cloud-based as well as local ASR solutions we decided to use the cloud-based Cerence Mix ASR and for the locally installed ASR, Mozilla Deepspeech [27], extended with domain-specific vocabularies [28].

Next, the NLU (Natural Language Understanding) modules serve to semantically interpret the messages exchanged between the team members and thus to follow the dialogues in terms of both content and communicative goals. Several parallel NLU processes provide (1) the dialogue act type (Intent) [29]; (2) a semantic representation (Frame) [30]; (3) the semantic roles expressed in the utterance. This allows

[2]https://enrich.european-robotics.eu/

Fig. 6: SAI visualizing the situation in a 3D map

us to track the allocation and execution of tasks within the mission and supports further analysis of the mission state.

The speech processing components are evaluated on team communication data collected during A-DRZ exercises. Intermediate results for ASR show around 20% word error rate; the NLU components have so far accuracy of around 80%. The components are being further developed. The transcript, intent, semantic role, and frame are passed to the Mission Knowledge Manager for further processing.

B. Mission knowledge manager and ontology

The MKM (Mission Knowledge Manager) is a knowledge (domain and context) service for central collection and semantic/ontological processing of high-level mission data. It forms the backbone and interface between speech processing, process assistance and situation awareness interface. The MKM uses a semantic repository and reasoning component in combination with an ontology representing the available generic mission knowledge to combine the interpreted speech data with information from other sources, including sensor data from the robots and UI inputs from the FRs. The semantic repository manages the facts in the ontology, providing functions for manipulating and querying. The reasoner component provides logical and rule-based reasoning functionalities, allowing to infer new information based on the ontology. It employs HFC [31] for the semantic repository and reasoner. HFC is a theory-agnostic forward-chainer, comparable to other popular semantic repositories.

The derived information (mission events) is then broadcasted to other system components such as the situation awareness system or the process assistance.

C. Situation awareness interface

Situation awareness is a crucial factor for all actors involved in emergency response operations. It is formally defined as "*the perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*" [32]. In emergency response operations this, for example, means to gain perception of the topographical and spatial conditions in which an emergency event takes place, to understand where specific units are located, to which location each unit is moving and which task it is working on. As robotic systems can collect and provide a great amount of different data, situation awareness requires tools going way beyond classic paper-based implementations, e.g., maps, to make the utmost use of the robotic capabilities. Therefore, a digital Situation Awareness Interface (SAI) for the management of human-robot teams in emergency response operations is developed in A-DRZ, to support the FRs in achieving situation awareness by visualizing the aforementioned aspects. The visualizations need to support a variety of different scenarios, ranging from large scale events, like forest fires, to accidents with toxic substances inside a factory, according to the A-DRZ reference scenarios.

The A-DRZ SAI (Fig. 6) is a frontend application connected to a backend system providing services to store and access data via REST interfaces. These services provide access to map and 3-D building data, and to a time-series database storing robot sensor data. The MKM services (Sec. VI-B) are also part of the backend services. All robots participating in the operation register in the backed by calling the REST endpoint of a registration service, providing information about their capabilities and data transport parameters. Dedicated services manage data transfer from and to robots. The data transfer mechanism is specific to the connected underlying robotic system. Currently, connections to ROS-based robots are fully supported, using a multi-master setup with one ROS-master running in the backend.

This system architecture with a central storage of data allows multiple instances of the interface having consistent views on the situation. The developed interface provides different views on the data and different interaction options depending on the user's role within the command chain. Higher hierarchical levels responsible for the overall strategy have a more abstract view on the data, the lowest levels have a detailed view on specific human-robot teams.

The A-DRZ SAI is being developed in a user-centric, use-case-driven bottom-up approach, with regular evaluations in user studies and integration tests, making use of the facilities and infrastructure provided by the DRZ living lab (cf. Sec. VIII). Evaluations conducted so far, both remote user studies and on-site studies with end-users, showed that the system allows a human operator to plan operational orders for the robotic units and monitor their execution. The ability to see information in"real time" and the visualisation of relevant mission data on the map were seen as major advantages by the end-users, and can significantly increase situation awareness of the FRs on site.

D. Mission process assistance

Making sure that all necessary first response steps have been taken and managing parallel tasks in medium-to-large missions may be challenging. The A-DRZ Mission Process Assistance (MPA) is designed to reduce the cognitive load by presenting a status of the ongoing emergency response and generating recommendations for further action (cf. Fig. 7). MPA receives the mission event log from the MKM (Fig. 5) and contextualizes it within the reference model. The reference model describes every process that can be executed

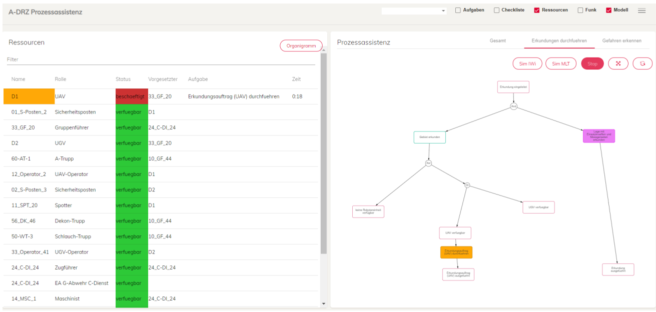


Fig. 7: MPA interface visualizing the resource list and the process model

during a mission, including both high-level processes, e.g., mission types, and low-level processes, e.g., dealing with a hazardous substance [33]. MPA matches the executed activities to the reference model to identify and visualize the currently executed processes, including both those activities that were already executed and those activities that should be executed next. This way, mission commanders can see the current situation and plan ahead for the near future [26].

In addition, the reference model contains information about which process step must be carried out by which type of resource (role of a FR), so the MPA recommends the available resources with the ability to perform the next process step. E.g., if a process step must be performed by a machinist, the concrete machinists currently available in the emergency response are recommended by the system. Furthermore, MPA displays an overview of all resources, including both humans and robot, and their status. The status shows whether a resource is available or not. If a resource is currently executing a process, MPA shows what process and for how long. This information can be crucial for time-limited processes, e.g., tasks under respiratory protection.

Online evaluations were carried out regularly to measure the MPA's usability. Here, experts from the rescue domain were presented the simulation of a mission and its mapping by the MPA in a video conference. They then answered an online questionnaire, which tested the MPA both for usability according to DIN EN ISO 9241-11 and for aspects relating to the acceptance of the technology. The latest evaluation results attest the MPA usefulness for the mission overall and understandable presentation of the mission sequence.

Evaluation of the teamwork support in a realistic mission has been postponed due to the Covid-19 pandemic. We are preparing a hands-on remote evaluation using simulation.

VII. Demonstrators

The A-DRZ holistic approach places high value on integration and operationalization. To this end, A-DRZ features several central and decentral demonstrators for research and development. The four central demonstrators are experimental platforms considering specific use cases or technical aspects of collaboration among A-DRZ partners. They are used for integration and evaluation of developments into the common A-DRZ tool set and capability spectrum and become the first set of rescue robots of the DRZ (Fig. 8). Several decentral demonstrators are utilized by the respective project partners for research on specific topics and components. The central demonstrators are mainly characterized by their different capabilities and use cases. They are intended to represent a certain class of robot and are assigned into one of the following categories:

- D1: Small aerial demonstrators used for exploration
- D2: Medium sized ground demonstrators for exploration and manipulation of the environment
- D3: Heavy duty ground demonstrators used for rescuing and transport of heavy payloads
- D4: Newly developed modular robot platform demonstrators with interchangeable payload modules

A. Aerial demonstrators

The aerial demonstrator D1 [20] is a DJI Matrice M210 V2 retrofitted with an Intel NUC quad-core, an Ouster OS0-128 LiDAR, a FLIR ADK thermal camera and two Intel RealSense D455 RGB-D cameras. The NUC performs real-time onboard processing of sensory data as detailed in Sec. V-A, while the iGPU and a Google EdgeTPU allow to run inference for Machine Learning models onboard.

Furthermore, commercially available UAVs with a weight between 250 g and 2 kg are used for training and missions (i.e. DJI Mavic series). These are controlled by a mobile phone and are therefore dependent on a stable radio connection [34]. The UAVs can automatically generate 360° panoramas or additionally carry a small 360° camera (Fig. 10c).

B. Ground demonstrators

Demonstrator D2 is based on a Telerob Telemax Hybrid extended with multiple modules to enable the development and evaluation of the assistance functions described in Sec. V-B. Our navigation module mounted on the back of D2 provides perception (a continuously rotating Velodyne VLP-16 LiDAR, an Insta360 Air 360 degree camera, a RealSense D435 RGB-D camera and an Xsens MTi 100 IMU) and onboard computing (Intel NUC quad-core and Nvidia Jetson Xavier AGX) in a compact splash-waterproof form factor. The sensor module at the gripper of D2's manipulator complements the available sensor information with a Flir Boson 640 thermal camera, a RealSense D435 RGB-D camera, an HDR wide-angle and a zoom camera.

Demonstrator D3 is based on RUAG's mobile platform GARM and designed as tracked support vehicle with narrow structural width. D3 features an electric drive, high capacity Li-ion accumulator, front lights, 2D LiDARs and 2 frame style mounting points. It serves as a flexible payload carrier, and fully supports the A-DRZ modularization concept as well as the interchangeable mission payload system.

Prevention of initial fires in industrial plants was the specific application scenario motivating the development of the ground demonstrator D4. The base structure of D4 follows the A-DRZ modularization concept and was realized with a focus on cost efficient construction. D4's mobility platform is designed for high-velocity traversal on industrial

(a) UAV demonstrator D1 (b) UGV demonstrator D2 (c) UGV demonstrator D3 (d) UGV demonstrator D4

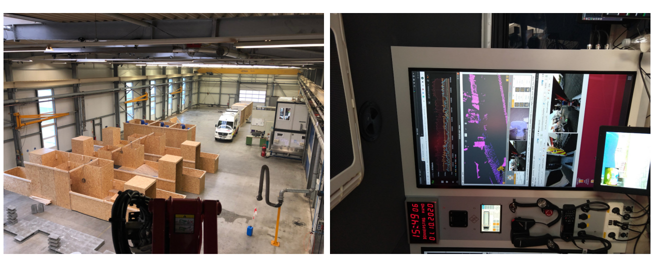
Fig. 8: Central robotic demonstrators with assistance functions developed and evaluated by A-DRZ

floors and makes use of certified UGV components. While a top-mounted module carrier allows D4 to operate the full spectrum of A-DRZ payload modules, development and testing of fire-detection and fire-fighting modules has priority.

VIII. Living Lab

Testing and evaluation are further crucial aspects of the A-DRZ holistic approach, and thus high priority. The DRZ is operating a $1300\,\mathrm{m}^2$ large hall (Fig. 9a), where it has set up a Living Lab with testing and evaluation facilities. The hall accommodates various obstacle courses for testing robots, as well as a workshop area, segregated workplaces and offices. The Living Lab possesses technical equipment for experiments, such as a high volume Motion Capture system with 40 cameras for accurate tracking of UGVs and UAVs during testing and evaluation in one of the largest coherent motion capture areas in Europe (35x10x10 m). The Living Lab will also be used for training and certification purposes related to rescue robotics.

The operationalization of the solutions developed in A-DRZ is strengthened by setting up the DRZ robotics command vehicle, RobLW (Fig. 1), to serve as an emergency command vehicle for the FRs to control the robots at an incident site. It is a van equipped with a garage for demonstrator D2 and two workplaces inside the car (Fig. 9b).



(a) DRZ Living Lab (b) Robot control post in RobLW

Fig. 9: A-DRZ testing and operationalization

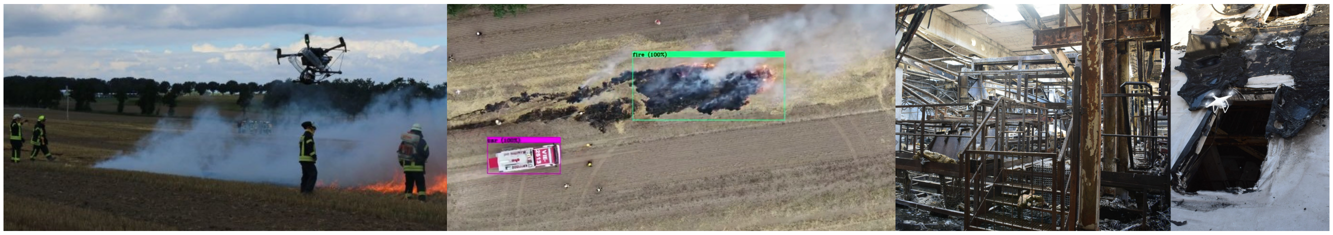
IX. Practical experience

Practical experience as part of the A-DRZ holistic approach includes a broad spectrum of activities: individual robot tests; integrated robotic system tests; robotic competition participation; joint exercises with FRs; deployments to real incidents. As a first joint exercise the small UAVs (demonstrator D1) participated in a wildfire exercise of the Fire Brigade in Viersen, Germany, 08/2020. The second joint exercise was performed with small UAVs (D1) and UGVs (D2) in Bad Oldesloe, Germany, 11/2020. The small UAVs (D1) already participated in two real deployments, at the heathland and forest fires in the German-Dutch border area of Niederkrüchten, 04/2020, and after an industrial fire in Berlin, 02/2021 (Fig. 10c).[3] On all these occasions the robots provided exceptionally helpful data to FRs, and developers gained insights to guide further work. Additionally, new data sets have been collected that are particularly valuable for further training of AI algorithms (Fig. 10b).

X. Conclusions and Outlook

We presented the A-DRZ holistic approach to the development of robotic systems for emergency response assistance. It involves close cooperation of first responders, researchers and companies for scenario-based needs analysis, iterative development of the corresponding system functionality modules and integrated robotic systems with human-robot teamwork support, as well as experimentation, system testing and evaluation in realistic missions carried out with and by FRs. The A-DRZ approach addresses important requirements identified by FRs: The modularity concept facilitates the adaptation of operational capabilities of robotic platforms; The SKATES communication architecture ensures robust network connectivity; The autonomous assistance functions for aerial and ground robots alleviate stress and cognitive load for remote robot control; The Situation Awareness Interfaces and Mission Process Assistance improve situation awareness for strategic and tactical mission planning; moreover, the speech processing of team communication facilitates the acquisition of mission progress information; The DRZ Living Lab provides advanced facilities for testing and evaluation of individual robots and integrated systems; Finally, joint exercises and external deployments test the integration of human-robot teams in the FRs' mission command structure. The important conclusion is, that the holistic approach works, and A-DRZ could already deliver added value to FRs during deployments, The system capabilities are being further improved, based on FRs' feedback. Once it is possible again to carry out joint exercises on site, we will do so, to evaluate the FRs' hands-on experience and obtain more mission-specific data. We are also developing benchmarks to facilitate systematic tests and comparisons.

[3] Joint on-site exercises were not possible in 2021 so far, due to the Covid-19 pandemic.



(a) Vegetation firefighting exercise (Viersen) (b) Use of AI fire detector (Viersen) (c) Destroyed building inspection (Berlin)

Fig. 10: Practical experience with A-DRZ Demonstrators during joint exercises with first responders

Last but not least, the DRZ Living Lab is being extended with an outdoor testing field.

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