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Solving Disaster-response Tasks at a Nuclear Power Plant under Realistic Conditions

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***Abstract*—Environmental disasters usually trigger devastating damage and, in the worst case, can also cause reactor accidents in nuclear power plants, see Fukushima disaster or other detailed analysis and reports of accident's causes[1]. The correct assessment of natural disasters and the resulting combination with radiological and nuclear accidents, is a major challenge for rescue teams. The conditions under which rescue and recovery operations, as well as exploration and transport tasks, take place are often challenging for emergency responders and involve a certain potential for danger. Serious incidents in the last decades have shown that rescue teams have an urgent need of robotic platforms for fast exploration and scene understanding, especially in scenarios involving radiation. This paper describes the rescue robotic systems used in a test scenario of a nuclear power plant in which the robots must handle sources with real radiation and lessons learned from various application-specific tasks at the EnRicH competition.**

***Index Terms*—Field Robotics, Search and Rescue Robotics, Radiological and Nuclear (RN), Disaster Response, Robotics Competitions**

I. INTRODUCTION

Increasing the flow of information between the robot and the command and control center with operators is the main component of the work. A key aspect is to make the robotic system smarter, which often results in a more complex system to control, but also provides the operator with additional information required for reliable terrain assessment. Afterwards the operator can work out precise plans for further action together with the operations management team, so that an optimal collaboration between human and machine is achieved. Among many other tasks, it is particularly important to be able to quickly display, read, understand, analyze and forward system data (e.g., status and localization data, sensor feedback) in order to avoid misinterpretations and to ensure smooth cooperation between the operational teams. The EnRicH competition[2] gives research teams from universities, technical colleges and also companies the opportunity to test their robotic systems in a real nuclear power plant and compare them with other technologies [9], [8]. In addition, it also offers a chance to present the latest developments and ideas as well as to get direct feedback from responder teams. The tasks in such application-specific robot competitions are diverse and require multi-functional robot and sensor systems with a user-friendly HRI. Thus, this hackathon will test the disciplines of manipulation, exploration, and search and rescue of injured persons. The exploration task involves exploring the building's interior in the form of a 3D map and measuring and mapping radioactive sources.

Fig. 1. Cooperative rescue robots rescuing a simulated injured person at the European Hackathon at the nuclear power plant in Zwentendorf.

The teams have to detect the radiation $(300-1600\mu S)$ and its sources should be detected, measured and marked inside a digital map. The manipulation task consists of identifying

TABLE I
PARTICIPATING TEAMS

Participants and Team Names	**Locomotion Type**		
	Wheeled	***Tracked***	***Flying***
TAUT Dynamics - FH OÖ	x	x	x
Telerob		x	
MSAS		x	
bebot		x	
Hector Darmstadt - DRZ	x	x	
Fraunhofer FKIE	x	x	
RobotTHIx - TH Ingolstadt	x		
Southwest Research Institute SwRI			x
LUCAS - Loughborough University			x

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[1] https://www.iaea.org/topics/accident-reports
[2] https://enrich.european-robotics.eu/

a specific pipe containing radioactive coolant and closing the corresponding valve. In the search and rescue task, the injured persons, represented by dummies, are positioned throughout the building. The robot has to mark the position on the map and bring them out of the danger zone using a suitable tool. The mission time is limited to 45 minutes and the teams can use as many robots as possible at the same time to solve the given tasks as fast as possible. Most of the teams in Table I use tracked robots and thus also have the ability to enter the reactor room via the stairs and the pump room, which is difficult to reach due to a 10 cm high step. All other rooms on the first floor can very well be explored with wheeled robots.

II. DISASTER RESPONSE ROBOTS AND EQUIPMENT

A. Tracked Rescue Robot

The mechanical design of the mobile platform (Fig. 2) can be divided into three main parts: chassis, center drives and flippers. The chassis contains all the components as shown in Fig. 6. The center drives can be mounted and dismounted separately from the side for quick repairs. The flipper system is designed that the front and rear flippers can be controlled independently. The robot is driven via two 200 W DC motors for the main gear and two 80 W DC motors to control the flippers. The total weight of the robot with the manipulator and the sensor module is about 60 kg. The body of the vehicle basically consists of carbon frame composite sheets. Aluminum parts are used in places where the mechanical load and power transmission from the engine occurs. Various other fixtures, brackets, mounts and connections are realized with FDM (Fused Deposition Modeling) 3D printing, using ASA (Acrylester-Styrol-Acrylnitril) as material which is well suited for outdoor applications. A design focus is put on keeping the center of gravity as low and central as possible to guarantee the best locomotion characteristics on rough terrain and steep objects. The use of lightweight construction and specific materials makes it possible to develop mobile platforms more easily and at lower cost. A 6-DOF robot arm, consisting of Dynamixel Pro Series motors and gripper system, ensure that the manipulation task can be performed.

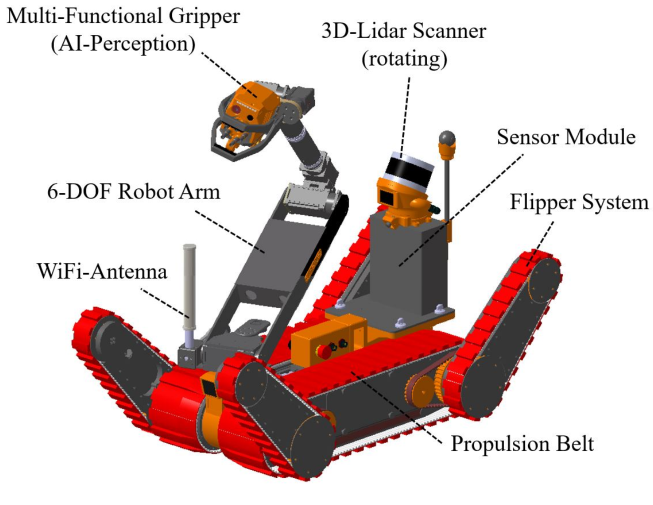

Fig. 2. CAD model of the new tracked rescue robot (Hurrican).

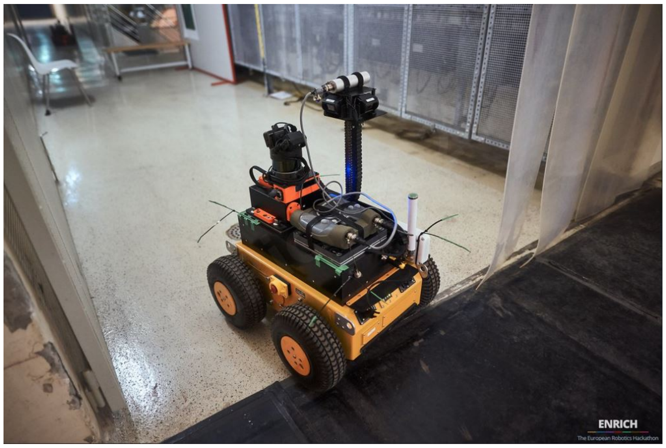

Fig. 3. Wheeled rescue robot (Bumblebee).

B. Wheeled Rescue Robot

The four-wheel robot platform is based on the Cu-Chassis-XT 4WD-Max for outdoor use, see Fig. 3. The chassis is robustly built with an aluminum housing. The delivery state of the manufacturer[3] is extended by several modifications. On top, the mobile rescue platform is upgraded with a specially developed control box including additional motor sensors (external encoder) and a pair of high performance controllers (RoboClaw[4]) which enables the possibility of remote control via ROS and thereby extends the limited range restricted by the original radio control link. The assembly box on top of the platform also provides an unique interface for different adaptive sensor concept modules.

As the wheel-driven propulsion concept allows significantly higher locomotion speed in simple terrain, the wheeled robot fulfills the scouting/exploration task of the rescue team during missions together with the tracked rescue robot, described in the previous chapter. Therefore, the wheeled rescue robot is equipped with a 360° LIDAR module used for 2D/3D-mapping of the mission scenario. Continuous feedback of the robot exploration is provided by four analog cameras connected to a four channel video encoder with H.264 compression at 30 fps. Two cameras aligned longitudinal (front/back) and two aligned lateral (left/right) mounted on an extendable chain mast, a so-called zip chain actuator[5], support the operator while maneuvering. In addition, on top of the chain mast a radiation sensor is attached to detect radiation sources early during first exploration missions. It provides the slower tracked rescue robot with necessary information in order to decrease time needed to solve the mission task, for instance closing valves of contaminated pipes.

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[3] https://www.ulrichc.de/product/

[4] https://www.basicmicro.com/Dual-60VDC_c_20.html

[5] https://tsubaki.eu/products/mechanical-components/zip-chain-actuators/

C. *UAV for Indoor Exploration*

The UAVs have the task to reach the $40\,\mathrm{m}$ higher hall through a shaft, to create a 3D map of the environment and to search for radioactive sources. The frame of the UAV (Fig. 4) is based on the open source carbon frame Source One[6] and custom 3D printed parts out of TPE (Thermoplastic Elastomer) for soft mounting sensitive electronics like the IMU. The drone has a dry weight of $570\,\mathrm{g}$ and a total take-off weight of $2100\,\mathrm{g}$. For the motors $1700\,\mathrm{K/V}$ brushless DC motors were selected. Combined with the 7-inch propellers a maximum thrust of approx. $100\,\mathrm{N}$ is achieved with an average flight time of $20\,\mathrm{min}$. As a flight controller a Mamba F7 flight stack was chosen running the iNav firmware[7], which is capable of handling MAVLink messages in order to enable ROS-based control of the UAV. For communication, the drone and remote control use the proprietary Crossfire technology[8]. This R/C link system is made for FPV applications and features long-range, adaptive and robust remote control at $868\,\mathrm{MHz}$. It is capable of two-way communication with real time telemetry, dynamic self-selecting RF power and self-healing frequency hopping. The sensor module is built up from a NVIDIA Jetson Nano on-board computer, a ZED 2 Stereo Camera for spatial localization of the UAV and a BG51 radiation sensor for radiation mapping. In addition to that, a time of flight sensor is used for the altitude estimation. To compensate for the lack of GPS signals an optical flow sensor is used for motion estimation. All computation was performed by the on-board host computer, but transmitted to the operator station only after the exploration task due to WiFi bandwidth limitations inside the nuclear power plant.

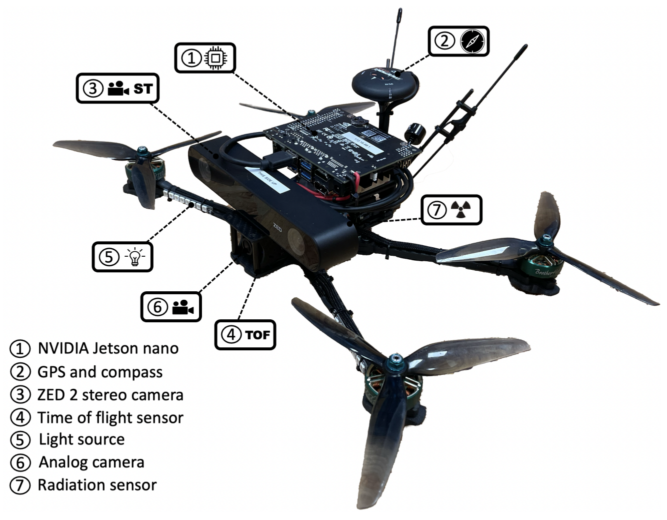

Fig. 4. Overview of the UAV hardware concept.

D. *MARC - Modular Adaptive Robot Concept*

A modular and adaptable payload concept for plugging in sensor and actuator platforms such as 3D LIDAR and visual sensor systems and robot manipulator and gripper systems is developed. Complex, heterogeneous, modular robotic systems require manufacturer and user-independent standardized interfaces based on open communication standards and information models in order to enable interoperability and integration. This shall reduce the effort for system integration and sensor calibrating significantly and provide a customized perception of the environment during certain work processes [2].

E. *Human-Robot Interface*

In the remote control mode the motion of the robot is controlled mostly by a Microsoft Xbox 360 controller, which is connected to the operator station. Several cameras and a thermal camera are mounted on the top of a robotic arm and provide live stream for the operator. Fig. 5 shows different types of developed remote controls, depending on how much information is to be visualized. A remote control unit (Fig. 5 right) was developed (RCU 2000) which provides longer operation run-time and is easier to handle and transport. Due to the portability and the weight limit of maximum $30\,\mathrm{kg}$ we have developed a lightweight case with an additional screen and a Laptop as operating unit. The control station is used to visualize all sensor data and to communicate with a new control system instead of the Xbox controller. The right image in Fig. 5 also shows the Master Arm controller, which is an intuitive interface that enables real-time one-to-one control of the 6-DOF robot arm. With the HRI it is also possible to switch between remote control, semi-autonomous and autonomous functions.

F. *Network Communication*

To connect the individual robots with the operator station remotely, a Ubiquiti Networks System is used. In particular, this system consists of a Bullet™AC IP67 dual-band radio in combination with an $9\,\mathrm{dB}$ omnidirectional antenna for each robot plus one for the operator station. While communication with each other, the radios use the proprietary airMAX

Fig. 5. Different types of operator stations for visualization of 3D map, live camera views and radiation value display.

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[6] https://github.com/tbs-trappy/source_one
[7] https://github.com/iNavFlight/inav
[8] https://www.team-blacksheep.com/

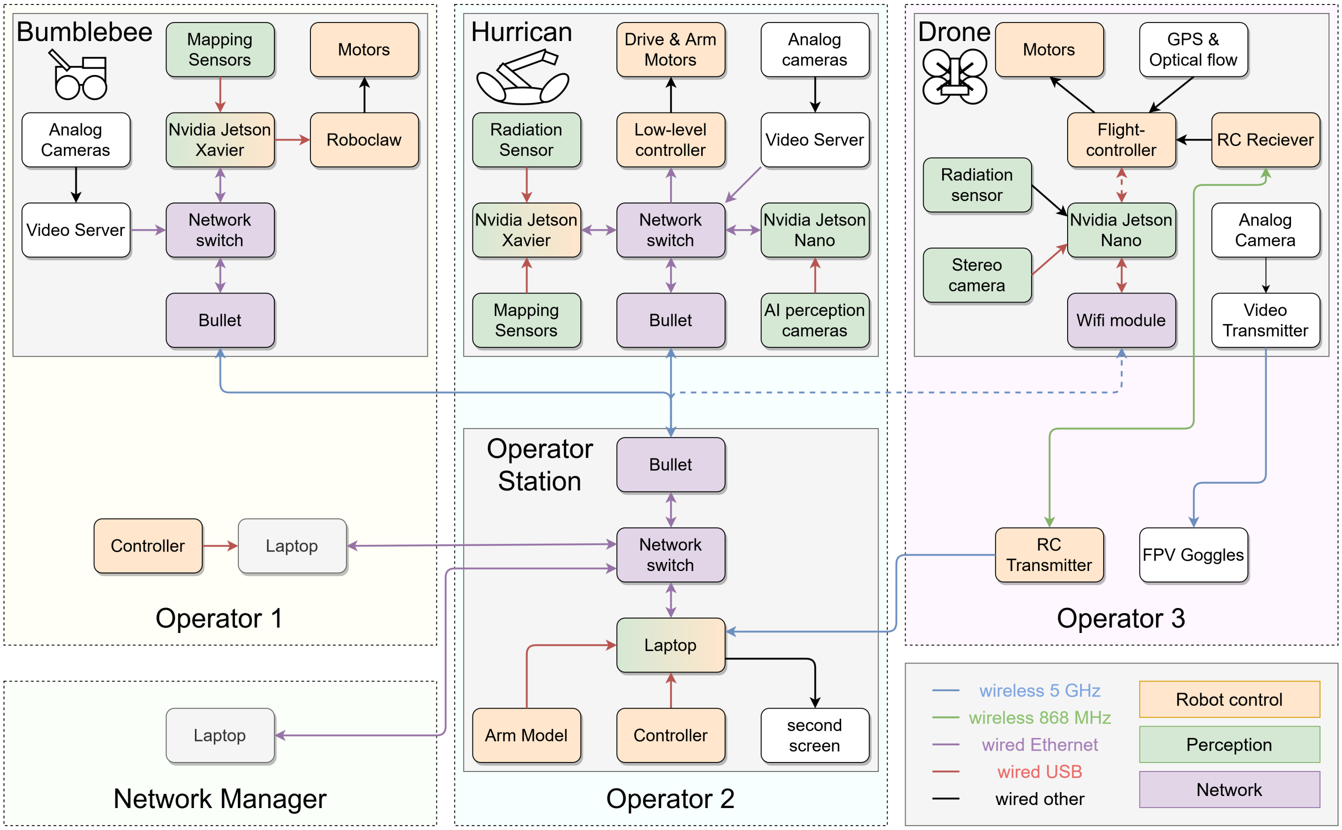

Fig. 6. System architecture with multiple robots and operators.

technology to achieve a data throughput of up to 300 Mbit/s over a distance of more than one kilometer with direct line of sight. On the other hand, the system is fully IEEE 802.11ac compliant, therefore existing infrastructure can be used to extend the range even further.

III. STRATEGY AND MISSION PLANNING

Due to a limited mission time of 45 minutes a sequential execution of the individual tasks is not feasible. Therefore, a strategy to solve multiple problems in parallel has to be pursued. A total of three experienced operators were used for the mission, 2 for the mobile UGVs and one operator for UAV.

A. System Architecture

Fig. 6 shows the system architecture of three robots described in Section II. Each robot is connected to the same WiFi network and is remotely controlled by its own operator. The entire system uses ROS Melodic for data exchange and control with the exception of the steering for the drone, as the network latency is too high for its flight dynamics. To reduce cognitive stress for the operators, a fourth person, called the network manager, monitors the state of the robots and the network connection and can step in as a backup operator if needed. The architecture diagram also shows, that individual functions, especially considering the exploration task, are divided among multiple robotic platforms. This enables the simultaneous operation on multiple locations.

B. Environment Mapping and Localization

To localize itself and generate a map of its surrounding, both ground robots use a Velodyne VLP-16 360° LIDAR, as this sensor allows to choose from a variety of well-known SLAM algorithms (e.g., LOAM [11], LIO-SAM [10], Google Chartographer [4], improved google's cartographer [7] and HectorGrapher [1]). Our localization approach is based on LOAM, as testing showed it to be the most stable algorithm in constrained indoor environments. In addition, a multi-layered mapping model is used to include localized environmental sensor measurements (e.g., Radiation, CO2, ...) and save everything as a 2D map in the GeoTIFF format[9].

As the LIDAR system is too heavy for the UAV, a different approach has to be chosen. Therefore the vehicle uses the spacial mapping feature provided by the Stereolabs ZED SDK.

C. Control and Live Data Streaming

In an environment, where the robot cannot be reached easily in case of a failure, the control system of the robotic system must be given special consideration. In our case the low-level control for each platform is handled by its own dedicated hardware controller and uses RRTLAN [3] to communicate with the high-level controllers. In a scenario where the platforms internal computing system crashes and cannot reboot anymore,

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[9] see the *hector_geotiff* ROS package [5]

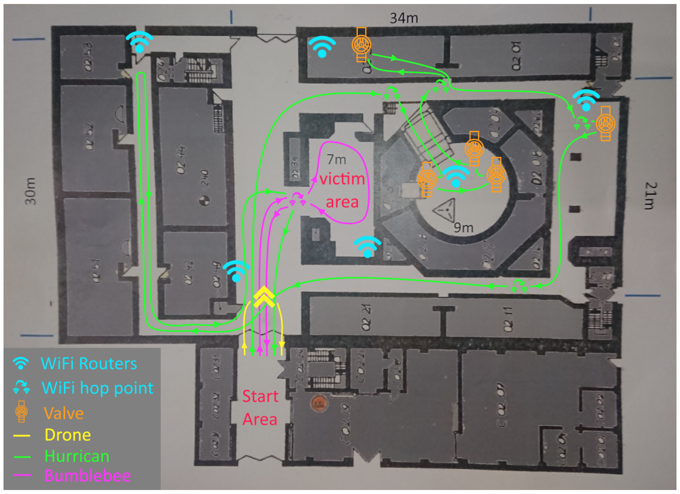

Fig. 7. Mission plan on top of the floor plan of NPP Zwentendorf with an operation time of 45 minutes.

this system enables the direct connection between low-level controller and operator station to steer the robot remotely. In these cases it is also essential to get at least some of the sensor data from the robot back to the operator for feedback about the current state and environment. For this reason we chose to implement a dedicated AXIS Q74 video encoder, which can be used to stream camera images directly over the network. This backup strategy also showed potential in networks conditions, where a ROS-based control of the robot was no longer reliably possible. In a network stress test during the DRZ challenge [6] the system handles bandwidth throttling to $10\,\mathrm{MBit/s}$, an artificial delay of $100\,\mathrm{ms}$ and an additional packet loss of 10% with minor noticeable changes to the operator, even with all three restrictions active at the same time.

D. Detailed Radiation Detection

The used Automess 6150AD5/E device is a radiation protection measuring instrument for the measurement of photon radiation (gamma and X-rays) where the measured value is H*(10). In connection with a probe it is also suitable for the detection of alpha and beta radiation. Within the scope of this competition, the gamma probe 6150AD-18/Ex was used, whose measuring range is from $0.1\,\mathrm{uSv/h}$ to $10\,\mathrm{mSv/h}$. An RS232 interface is supported for connection to a PC and a developed ROS driver provides a continuous data exchange between robot and operator station. With the probe mounted on the robot arm of Hurrican and an measurement rate of $1\,\mathrm{Hz}$, we were able to pinpoint the location of radiation sources to within a few centimeters.

E. System Performance and Mission Plan

While the $45\,\mathrm{min}$ long missions were no problem for Bumblebee, the drone had to return early due to its limited battery capacity of $8000\,\mathrm{mAh}$. Hurrican came near its maximum operation run-time of about $55\,\mathrm{min}$. However this does not pose a problem, as a longer mission time could be solved with a stopover in the start area, where the hot-swapable battery could be exchanged in less then $30\,\mathrm{s}$. Initial tests on sight showed that our wireless $5\,\mathrm{GHz}$ network system could not penetrate the convoluted rooms in combination with the thick walls. As a solution the direct connection was switched to use the provided network infrastructure. Due to their intended nature as a point-to-point connection, the bullet radios actively denied the automatic handover and had to be switched to a new access point manually. Overall, these constraints led to the creation of a mission plan (see Fig. 7) in advance to coordinate the interactions between the operators and their robots. Crossfire, on the other hand, was able to convince with its transmission performance and quality. During the entire UAV missions, there was no interruption of the radio connection with only $10\,\mathrm{mW}$ transmission power. Due to the maximum transmission power of $1\,\mathrm{W}$, longer distances can certainly be covered. However, the national regulations for the permitted transmission power must be complied with.

IV. EXPERIMENTAL RESULTS

All experiments were successfully carried out in a real scenario at the Zwentendorf nuclear power plant. The individual tasks and robot performance were evaluated as follows:

A. Manipulation Task

The mobile manipulation robot in Fig. 8 shows the easy handling when closing the valves. The advantage over other systems (e.g., parallel grippers) is that the robot arm does not have to be aligned precisely when closing the valves due to partially flexible tool pins. In teleoperating mode, the operator has an excellent overview due to the camera position and thus, can target the objects faster.

B. Exploration Task

The SLAM algorithms described before are running on each robot platform onboard in real-time. This allows for a independent exploration of each robot. To visualize the result, a multi-layered mapping model showing 2D, 3D and radiation data is rendered on the robot and sent as an image stream to the operator station (see Fig. 9 right).

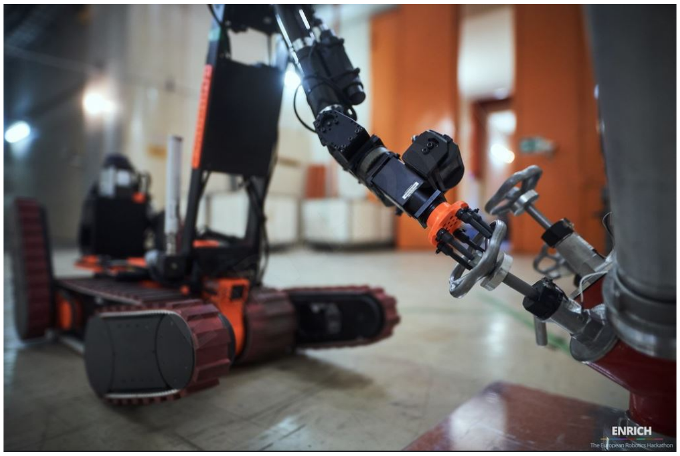

Fig. 8. Previous version of Hurrican with 6-DOF arm and simple valve tool.

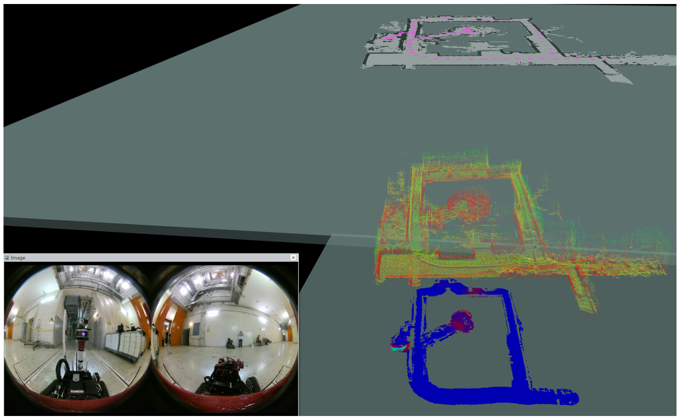

Fig. 9. 360° view from Insta360 Air camera; radiation, 2D and 3D view as a multi-layer mapping model of the NPP.

The real-time fusion of the maps from multiple robots could not be achieved due to limited network bandwidth. However, as the data representation is the same, all maps can be combined retrospectively after the mission has been completed.

C. Search and Rescue Task

Especially for wheeled robots this task is challenging, since it is necessary to traverse (up and down) one higher single step to get access to the area (pump station) where the person to be rescued is located in that scenario. Against expectations, test runs reveal our wheeled robot being able to access the pump station due to just sufficiently narrow axial distance, even though maneuvering on top of the step is barely possible. As the wheeled robot has enough time left during the mission, it sets about the search and rescue task equipped with an onsite improvised passive lever (Fig. 1). This simple tool, attached on a rigid lug of the robot base, consists of three parts: Two identical oblong carbon plates with $40\,\mathrm{cm}$ length and a carbine in order to be able to hook onto the chest strap of the person to be rescued. The components are screwed together once each interface, hence the lever has three 1-DOF joints (hinge joints). Thus, once adjusted to a specific TCP-height of the carbine, the lever folds down to the ground under load and the injured person is pulled out of the danger zone. That property prevents the robot from tilting and provides higher agility. That robot/arm constellation mainly benefits from the levers simplicity and low expenditure of time to be built. As the TCP-height has to be adjusted manually and no feedback of the lever is available, there is an opportunity for improvement.

V. CONCLUSION AND FUTURE WORK

This paper describes the use and benefits of a complete robotic system for the competition-based approach in general and goes into detail about the European Robotics Hackathon event with RN tasks and scenarios. The great success of the developed robotic platforms and control interfaces at the competition has demonstrated the simple use, operation, flexibility and usefulness of the design. The participation in EnRicH was extremely helpful for the evaluation and further development of the systems. The identification of weaknesses and possible improvement approaches of the described systems are a result of researching further solutions from such application-related competitions. Consequently, the following proposed improvements will be further explored in the future:
a.) Especially for the reconnaissance tasks, the scanner has to be tilted by about 30° (Fig. 2). This results in a larger field of view for this multi-line LIDAR and we can thus better detect higher objects with a denser point cloud of the 3D map.
b.) The end-effector should have several functions, in order to be able to grab individual objects in addition to turning valves, see new CAD model in Fig. 2.
c.) Rescuing and recovering injured persons is considered a very important task. An improved manipulation and transporting tool should facilitate handling of injured persons.
d.) The communication technology played an essential role especially in the described scenario. In many cases the use of existing network infrastructure is not feasible, therefore a network-independent repeater system is necessary in the long term.

REFERENCES

[1] Kevin Daun, Marius Schnaubelt, Stefan Kohlbrecher, and Oskar von Stryk. Hectorgrapher: Continuous-time lidar slam with multi-resolution signed distance function registration for challenging terrain. In *2021 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 152–159. IEEE, 2021.

[2] Raimund Edlinger and Andreas Nuechter. Marc-modular autonomous adaptable robot concept. In *2019 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 1–7. IEEE, 2019.

[3] Raimund Edlinger, Michael Zauner, and Walter Rokitansky. Rrtlan-a real-time robot communication protocol stack with multi threading option. In *2013 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 1–5. IEEE, 2013.

[4] Wolfgang Hess, Damon Kohler, Holger Rapp, and Daniel Andor. Real-time loop closure in 2d lidar slam. In *2016 IEEE international conference on robotics and automation (ICRA)*, pages 1271–1278. IEEE, 2016.

[5] Stefan Kohlbrecher, Johannes Meyer, Thorsten Graber, Karen Petersen, Uwe Klingauf, and Oskar von Stryk. Hector open source modules for autonomous mapping and navigation with rescue robots. In *Robot Soccer World Cup*, pages 624–631. Springer, 2013.

[6] Ivana Kruijff-Korbayová, Robert Grafe, Nils Heidemann, Alexander Berrang, Cai Hussung, Christian Willms, Peter Fettke, Marius Beul, Jan Quenzel, Daniel Schleich, et al. German rescue robotics center (drz): A holistic approach for robotic systems assisting in emergency response. In *2021 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, pages 138–145. IEEE, 2021.

[7] Andreas Nüchter, Michael Bleier, Johannes Schauer, and Peter Janotta. Continuous-time slam—improving google's cartographer 3d mapping. *Latest Developments in Reality-Based 3D Surveying and Modelling*, pages 53–73, 2018.

[8] Frank Schneider and Dennis Wildermuth. *The European Robotics Hackathon (EnRicH): Fostering Robotic Solutions for the Radiological and Nuclear Application Domain*, pages 174–185. 01 2021.

[9] Frank E Schneider and Dennis Wildermuth. The european robotics hackathon (enrich). In *International Conference on Robotics in Education (RiE)*, pages 174–185. Springer, 2020.

[10] Tixiao Shan, Brendan Englot, Drew Meyers, Wei Wang, Carlo Ratti, and Daniela Rus. Lio-sam: Tightly-coupled lidar inertial odometry via smoothing and mapping. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 5135–5142. IEEE, 2020.

[11] Ji Zhang and Sanjiv Singh. Low-drift and real-time lidar odometry and mapping. *Autonomous Robots*, 41(2):401–416, 2017.