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Design and Implementation of a Mobile Search and Rescue Robot

Georg A. Novotny and Wilfried Kubinger
UAS Technikum Vienna, Hoechstaedtplatz 6, 1200 Vienna
{georg.novotny,wilfried.kubinger}@technikum-wien.at

Abstract. *For public emergencies such as nuclear accidents or natural disasters, an urgent and reliable description as well as an evaluation of the environment form the basis of all organized search and rescue (S&R) team plans and actions. If this information is not available the risks for the rescue services increases dramatically. Mobile robots help to minimize these risks by providing information about the disaster site to rescue teams.*

This paper discusses the needs and requirements of mobile robots in S&R application areas such as nuclear disasters and evaluates results achieved during the ENRICH 2019 trial based on the system architecture of the mobile S&R robot "Robbie" of UAS Technikum Vienna. The successful participation of the ENRICH 2019 show that the mobile robot is capable of performing S&R actions during emergencies.

1. INTRODUCTION

One of the main reasons for deaths after disasters is that it takes rescue teams too long to discover victims because they need to ensure their own safety [13, 22]. Rescue robots are designed for situations like these that are too dangerous for humans, e.g. hostage taking, nuclear or natural disasters [21]. S&R robots eliminate the need for human scouts to expose themselves in hazardous environments by creating an awareness of the situation at the disaster site by providing immediate feedback to the rescue workers before they enter the disaster site [22]. To support the development of rescue robots, since the beginning of the 2000s a number of robot trials and competitions have been held, such as: "*ELROB*" - The European Land Robot Trail , "*EnRicH*" – European Robotics Hackathon [8], the "*Arctic Robot Challenge*" [1], "*Rescue Robot League*" [27], the "*DARPA*" – Defence Advanced Research Projects Agency [6], the "*EuRoC*" – European Robotics Challenges [10] or the "*EU-FP7-ICARUS*" [12] project and many other. During these trials different tasks need to be solved in various environments, ranging from 2D and 3D mapping to the detection and evacuation of people and manipulation of objects [8, 9, 1, 27, 6, 10, 12].

The remainder of this chapter the requirements for mechanical design, sensor configuration and graphical user interface (GUI) for S&R robots are evaluated, followed by the evaluation of the implemented hardware and the developed software of the FH Technikum Vienna in section 2. The results achieved with these setup are highlighted and discussed in section 3. Concluding section 4 summarizes this work and gives an overview of future work.

Table 1 summarizes the user requirements for S&R robots collected in [7] and [24]. Disaster areas are

Requirements for Search and Rescue Robots	
Topic	**Requirement**
Dimensions	The robot platform must fit on 2 standard Euro pallets (120cm x 160cm x 95cm) and must not weigh more than 100kg
Nr. of Operators	Two people must be enough to operate the S&R robot
Resistance	IP65 for outdoor unmanned ground vehicles (UGV)
Autonomy	Must be possible to immediately switch from autonomous to tele-operated
Sensing	Video (RGB and/or thermal) cameras for visual contact with victims, 3D sensors to generate a structural map of the environment
Communication	Connection loses will occur → ad-hoc networks required
Command and Control	Simple interfacing technologies only on high-level tasks
Ambient Light	Must be capable of working in complete darkness as well as light environments
Energy Requirements	Energy consumption should be lower than 2kVA for recharging
Graphical User Interface	Camera view(s) from robot's perspective + environmental perceptions
	Sensor and status information of initial state and sensors
	Bird's eye view map

Table 1. Summary of system requirements survey, data taken from [7, 24]

usually covered with rubble and debris and can extend over several floors. Therefore the base platform of the mobile robot must be able to manoeuvre in rough terrain and should be suitable for climbing stairs. As stated in [22] track based robots are designed for operation in uneven, debris-covered terrain and are therefore ideally suited for natural disasters, moreover these tank like tracks add stability to the whole robot system [25]. Manipulation of objects is also often required by S&R robots, whether for demining, interaction with victims or for generating an unique camera angle [24].
Now that the system requirements have been defined, following chapter examines the approach of the UAS to integrate these requirements into a S&R robot.

2. System Concept

Following section explains the hardware and sensor setup of the robot of the UAS as well as the software architecture for successful participation in the EnRicH 2019 trial or other S&R applications.

2.1. System design

Figure 1 gives an overview of the implemented hardware components which are described in detail in the next section. As visualized the setup consists of two main parts, the "*Mobile Robot*" and the "*Operator Station*". Although mobile S&R robots have autonomous capabilities an operator station is needed to provide a safety fallback and teleoperation system. The mobile robot itself needs to be equipped with numerous sensors ranging from 2D and 3D LIDARs for obstacle avoidance and mapping, an robotic arm including an end effector (EEF) for manipulation and front and rear facing cameras for teleoperation.
The remainder of this chapter describes implemented hard- and software needed to provide a mobile S&R robot.

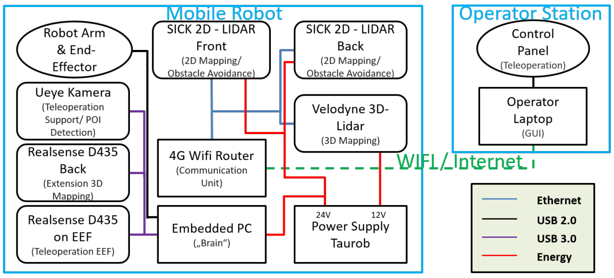

Figure 1. System design overview

2.2. Implementation - Hardware

The track steered mobile robot "*Tracker*" of company taurob GmbH [31] is used as the basic building block. Due to adjustable crawler tracks, a high degree of off-road mobility is provided for maximum versatility [31]. In addition a 4 degrees of freedom (DOF) robot arm, of taurob GmbH, for manipulation tasks was mounted. The Robot Operating System (ROS) API provided by taurob GmbH was the decisive factor for this mobile robot platform. The "*Tracker*", manipulator and the current sensor setup are depicted in figure 2.

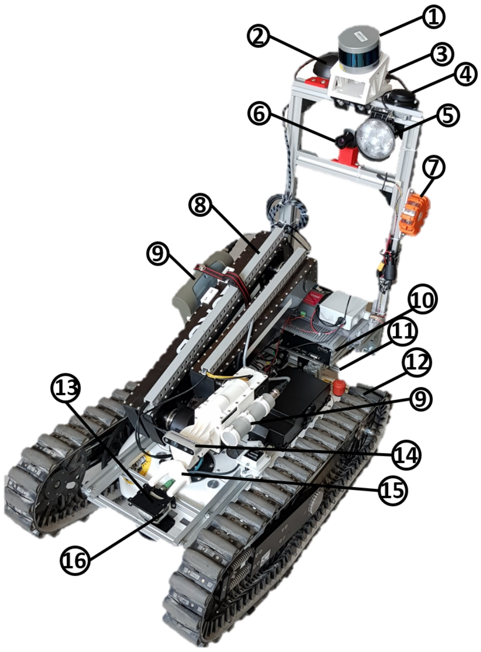

Figure 2. Robbie hardware setup
(1) Velodyne PUCK-VLP16, (2) Wifi/ 4G Antenna, (3) Rear-Facing Intel Realsense D435, (4) Garmin GPS Module, (5) LED Headlight, (6) Ueye UI-3240LE Camera with Camera Mount, (7) Operation Indication Light, (8) Robotic Arm, (9) SSM1+ Radiatiometer with mounted Probe, (10) Embedded PC, (11) Rear-Facing Internal Camera and SICK TIM-551-2050001, (12) taurob Tracker, (13) Front-facing TIM-551-2050001, (14) Intel Realsense D435 mounted on EEF, (15) EEF, (16) Front-Facing Internal Camera and Internal Headlights

To allow a maximum level of flexibility a modular hardware setup consiting of a sensor rig was chosen, thus enabeling easy replacement of sensors as well as software to enable different S&R tasks. A Garmin GPS module was attached to the sensor rig for outdoor localization. For GPS-limited indoor scenarios depth and range sensors were used for localization and mapping. Therefore, a 3D Light Detection and Ranging (LIDAR) Velodyne PUCK VLP-16 [32] and two SICK TIM-551-2050001 [30] 2D LIDARs, one at the front and one at the rear, were attached to the robot. In contrast to the 2D LIDARs mounted in a planar arrangement, the 3D LIDAR was mounted at an angle of 20° to Robbie's direction of travel.

To enable accurate tele-operation, the LIDARs were used in combination with appropriate software (see section 2.4) to generate a 2D and 3D map of the environment, giving the user insights into the environment from Robbie's point of view (POV), as shown in figure 3 (8) (7). To include the environment behind Robbie, which cannot be captured by the 3D LIDAR an RGB-Depth (RGB-D) camera, the Intel D435 [18], has been mounted slightly facing downwards on the sensor tower of the mobile robot. An additional Intel D435 was mounted on the base plate of the EEF to facilitate tele-operation of the EEF and Image Based Visual Servoing (IBVS) [4]. In addition, a Phidgets Spatial Inertial Measurement Unit (IMU) was mounted on the base platform to improve localization using sensor fusion such as Extend Kalman Filters and to provide input for tip-over control [5, 20, 23]. To enable an elevated POV, a universal camera mount with an attached Ueye UI-3240LE [17] camera was mounted on the sensor rig. Finally, to enable radioactive and nuclear (RN) detection, the robot was equipped with a radiometer SSM1+ [29].

The processing of this sensor data is a computationally complex process, so an industrial computer with the following specifications was also installed on Robbie's base platform:

- 1 × Intel Core(TM) i7-7700T (4 Cores, 8 Threads) @ 2.90GHz
- 1 × GeForce GTX 1050 Ti
- 2 × 16GB DDR4 2133 MHz

The visualization of these different sensor readings is a difficult task. Therefore an intuitive GUI for Robbie was developed, which is discussed in the next section followed by the implemented software.

2.3. User Interface

The user interface is the essential component for promoting situational awareness [24]. To underline this statement, the reader's attention is drawn to the fact that an S&R robot was rejected in the tragedy of 9.11. because of a too complex user interface [24].
Figure 3 shows the operator station, of the UAS Technikum Vienna, with the associated user interface and control panel.

As depicted on the left hand side of figure 3 the user interface is split into three parts:

1. **Log-Screen / Command input** (Figure 3 (1))
   All log messages of the running software are displayed here, this is a necessity to detect software system errors. In addition, these terminal windows can be used to start/restart any software modules, this allows a maximum level of flexibility.

2. **GUI** (Figure 3 (2))
   The GUI allows the operator to perceive the environment from Robbie's POV, which is a necessity for S&R robots [24]. This is achieved by live streams from the cameras (8). In the default configuration, the internal, forward and backward facing cameras of the tracker and the elevated RGB camera are streamed. Furthermore, the 2D map generated by the SLAM approach discussed in section 2.4 is visualized in the middle part of the GUI as shown in (7), providing a bird's eye view for the operator. Finally, sensor values (4), such as the internal temperature, battery voltage and estimated time to shutdown and the detected emitted radiation are displayed in counts per second. The developed GUI thus visualizes all suggestions for a good user interface evaluated in [24], which further enables the optimization and interoperability of the available resources and accelerates access to the victims [7]. In addition, it is also possible to visualize additional sensor values and information by a simple mouse click (5), such as a 3D map, the additional camera on the gripper, the backwards

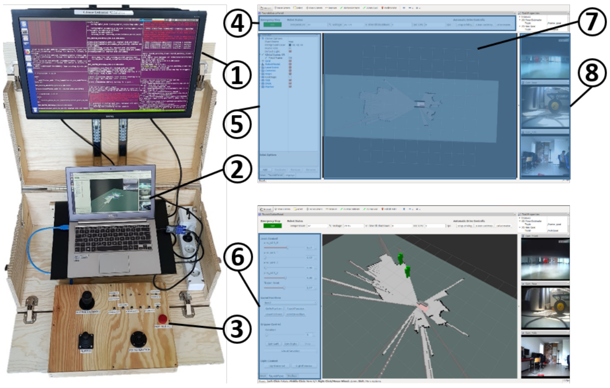

Figure 3. left: Complete operator station right: GUI (1) Logscreen / Command input, (2) GUI depicted in more detail on the right, (3) Control panel for teleoperation, (4) Sensor readings and emergency of switch, (5) Topic visualisation checkbox, (6) Additional teleoperation toolbox, (7) Map visualisation toolbox, (8) Image stream from Robbie's POV

facing camera, the autonomously detected people or the local and global cost map for the autonomous drive. In addition, the GUI can also be used for tele-operation of the robot arm in case the connection to the control panel fails, so that a redundant tele-operation system is available (6).

3. **Control panel** (Figure 3 (3))
   The control panel for teleoperation is used to tele-operator Robbie. Here the steering of the base platform as well as the robot-arm is handled. Further the autonomous "come-home" functionality can be started and stopped.

2.4. Implementation - Software

The Robot Operating System (ROS) [14] is used as high-level API to evaluate sensor data and control actuators. To improve the tele-operation process, a GUI plug-in for rviz [19] has been developed, which displays all sensor data and enables tele-operation of the robot arm (see figure 3).

For 2D and 3D mapping the open source frameworks Cartographer [15] and Octomap [16] were implemented. The main advantage of the Cartographer algorithm is the ability to detect and calculate online loop closure with graph optimization, which minimizes the absolute translation and rotation errors during map generation [15]. Octomap, on the other hand, uses a probabilistic estimation of the occupancy of 3D space and represents the environment in octaves, which consists of occupied voxels [16]. Figure 4 visualize a generated 2D or 3D map with these SLAM approaches using the LIDAR sensors listed in section 2.2, recorded during the EnRicH 2019 trial.

To overcome the need for manual victim recognition and mappinga ROS package based on Octomap and YOLO-ROS [2], a convolutional neural network (CNN) for object recognition in RGB images, was developed. By utilizing ray casting and the Bounding Box the x and y coordinates of the victim, with the 6 DOF transformation between the map frame and the RGB camera frame, is calculated. Detected victims are visualized on the 2D and 3D map of the GUI. By utilizing 2 different sensors to calculate the position of the victim thermal imaging cameras can also be used for victim detection.

Further a ROS package for automatic drive has been developed which uses the move-base-flex framework [26], a flexible navigation framework, and SMACH [3], a task level architecture for building complex robot behaviors. Currently two path planners are implemented. The Timed Elastic Band (TEB) planner, a planner that takes travel time into account. Movement is not calculated by the simulated forces within the virtual elastic band, but by optimizing the travel time and the path [28]. The TEB planner calculates several feasible paths and selects the fastest one. If the planner does not reach the target, recovery behaviours are called up. After each behaviour call the planner tries to reach the target again. If the target is still not reachable, the next recovery behaviour is called. After all three implemented behaviors are executed, the local scheduler is switched to the Dynamic Window Approach (DWA) algorithm. The DWA breaks up the global plan into smaller windows, whereby only the current and the next window are used to calculate the path [11]. The speeds within the next window are calculated using the current robot speed, the possible acceleration of the robot and objects to be avoided. The target tolerance of the DWA planner is increased to ensure that the target position can be reached. If the planner cannot reach the specified target, the recovery behaviours are called up as with the TEB planner. If the system still cannot reach the target after calling all recovery behaviors, the execution of the local and global planner is terminated. The SMACH script then returns an error and waits for a new target. The first implemented recovery behavior clears the cost maps, the second moves the robot back for 0.3m or 5 seconds and the third turns the robot 360° on the spot.

During the exploration the radioactivity is continuously measured with the radiometer. After exploration the nuclear radiation of the area around the driven path is estimated using a Gaussian process. The amount of radiation is then visualized and piled over the 2D map together with a legend, further the radioactivity is also visualized in the 3D map.
Section 3 now introduces the results achieved using this system concept during the 2019 EnRicH trial.

3. Results and Discussion

Table 2 evaluates the System Readiness Level (SRL) of the mobile Robot of the UAS Technikum Vienna based on the survey evaluated in [7, 24]. Using the survey results of [7] and [24] Robbie's SRL is defined as 9/10, since only the IP65 resistance could not be fulfilled.

Figure 4 visualizes the environment mapped dur-

Requirements for Search and Rescue Robots		
Topic	**Robbie**	**Status**
Dimensions	112×58×120cm, ca 75kg	☑
Nr. of Operators	Only one operator required	☑
Resistance	Currently no IP certificate due to active cooling	☒
Autonomy	Can be easily switched using GUI or control panel	☑
Sensing	Five image-streams provided, as well as 2D and 3D maps	☑
Communication	Automatic drive counters connectivity problems	☑
Command and Control	Intuitive GUI and operator station developed	☑
Ambient Light	Can be operated during day and night due to two LED headlights	☑
Energy Requirements	0.36kVA	☑
Graphical User Interface	Three image-streams on start-up, additional 2 can be started manually	
	Battery Voltage, Remaining operation time and sensor readings in status-bar	☑
	2D map on start-up, 3D map can be visualised manually	☑

Table 2. Evaluation of Robbie's applicability using the survey in [7] and [24]. For a description of the requirements see table 1.

ing the EnRicH 2019 as a 2D, 2D with marked radioactive sources and as a 3D map. As the 2D map (upper left) depicts, the calculated loop closure of the cartographer node distorted the map, resulting in sloping walls. This also led to the fact that two radioactive sources were merged into one by the radioactive mapping approach, since the odometry of the mobile robot is not recalculated during loop closure. As can be seen in figure 4, the generated 3D map is only partially dense, which means that a dense 3D reconstruction was not possible in all regions. This may be because the range of the 3D depth sensors is too short or because the mobile robot was driven through these regions too fast.

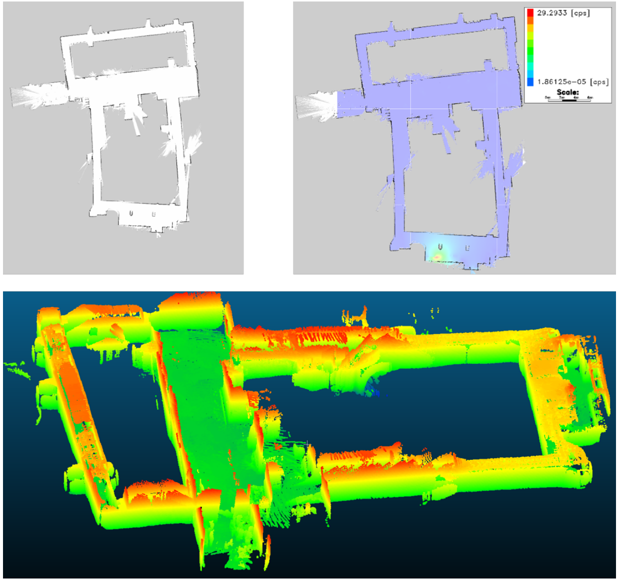

Figure 4. Created maps: upper left) 2D map, upper right) map overlaid with radioactivity measurements bottom) 3D map

4. Conclusion and Outlook

In this paper the needs of S&R robots with regard to the system requirements were examined from the operator's POV. Furthermore, the approach of the UAS Technikum Vienna to implement the requirements was examined. Search and rescue robots have to cover a wide range of application areas. Starting with the robot's tele-operation, autonomous object recognition and imaging, up to the processing and visualization of sensor data for the operator. The search and rescue robot of the UAS Technikum Vienna is able to generate different maps (2D and 3D), has autonomous capabilities like human victim recognition or autonomous drive and has an easy to use graphical user interface for the operator. The tracker base platform in combination with the robot arm and the end effector allow a high off-road mobility and offer maximum flexibility for manipulation.
Future projects will deal with the tasks of tele-operation of the robot arm with the help of motion controls, the enhancement of the human recognition package by merging the already existing RGB data with point cloud data using Bayesian sensor fusion and visual servoing with reinforcement learning for optimal gripper positioning. Further, to provide real-world S&R capabilities it is necessary to look into possibilities to water-proof the mobile robot.

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