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Design of an Autonomous Robot for Mapping, Navigation, and Manipulation in Underground Mines

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***Abstract*— Underground mines are a dangerous working environment and, therefore, robots could help putting less humans at risk. Traditional robots, sensors, and software often do not work reliably underground due to the harsh environment. This paper analyzes requirements and presents a robot design capable of navigating autonomously underground and manipulating objects with a robotic arm. The robot's base is a robust four wheeled platform powered by electric motors and able to withstand the harsh environment. It is equipped with color and depth cameras, lighting, laser scanners, an inertial measurement unit, and a robotic arm. We conducted two experiments testing mapping and autonomous navigation. Mapping a 75 meters long route including a loop closure results in a map that qualitatively matches the original map to a good extent. Testing autonomous driving on a previously created map of a second, straight, 150 meters long route was also successful. However, without loop closure, rotation errors cause apparent deviations in the created map. These first experiments showed the robot's operability underground.**

Fig. 1. Research robot returning from its exploration of an restricted area within a silver mine. Under difficult underground environmental conditions, this robot focuses on endurance and autonomy.

I. Introduction and Related Work

Underground mines are dangerous environments and safety is paramount as emergency services and help are often hours away. From 1839 through 2010, there were 726 mine disasters in coal as well as metal/nonmetal mines in the United States alone, resulting in 15,269 fatalities [1]. In order to put less humans at risk, robots could be the obvious solution here (see Fig. 1).

Rescue robots can support the work of mine rescue teams in case of a disaster or inspect the mine before human intervention. In addition to increasing safety, the monetary factor and reliability are of interest. In recent years, mining is increasingly evolving towards a man-less mine. The big keywords are *automation* and *digitalization* towards *Mining 4.0* [2]. Possible additional use cases from the mining perspective are degradation monitoring and rapid mapping. In all cases, cooperation with humans and other machines is a declared interim goal. Thus, in the near future, a lot of robots and machines will operate underground.

In contrast to conditions above ground, subterranean environments involve various additional challenges: Darkness, maximum humidity, rough terrain, and mud pose a special challenge for robotics. During mine disasters, air doors might be closed representing an additional obstacle for exploring robots. Particular difficulties of mines lie in the absence of global navigation satellite systems (GNSSs), communication limitations [3] caused by rugged rock, and the unstructured environment. Due to wireless communication limitations, autonomy is a key requirement for underground robots. Not least because of this, DARPA announced its *Subterranean Challenge* [4] in early 2018. Among the tasks are mapping, navigating, object recognition, and moving obstacles in not just human-made tunnel systems, but also underground urban spaces and natural cave networks.

One of the pioneers in underground robotics is the *Groundhog* project [5]. A four-wheeled, custom-built vehicle was sent to partially collapsed mines. It locally generated 2D maps and extracted images and laser scans. The experiments demonstrate long endurance, however, with 1.2 meters in width and a maximum velocity of 15 centimeters per second, the robot is rather large and slow. Even larger is the pick-up truck used by researchers at CSIRO [6] that was equipped with protection against mist spray, an inertial measurement unit (IMU), two fixed as well as one spinning 2D LIDAR for mapping a copper and gold mine with speeds up to 30 kilometers per hour. According to the presented figures and the attached video, the mine seems to have a flat ground and a large cross-section. The authors obtained fast and accurate models using mine survey data. In recent years, robot manufactures provided a variety of models to the

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market, in some cases in a modular fashion giving customers options to assemble a robot use case driven. One example is an unmanned ground vehicle (UGV) that was sent to an old silver mine where the robot recorded various environmental parameters such as temperature and humidity which then could be located in a navigation map [7]. Furthermore, the robot captured color images from which a textured 3D model of the mine could subsequently be created. The robot has a similar footprint as the robot presented in this paper. None of the aforementioned robots is equipped with some kind of manipulator that could be used for, e.g., tool or material handling. In contrast, the V-2 robot presented in [8] is a traditional bomb squad robot equipped with a manipulator arm used for underground mine rescue and recovery missions (which include visual inspection and air quality sampling). The arm is intended, e.g., for manipulating air doors or for moving debris. The paper only includes little detail about customization for mine permissibility.

This paper presents the design of an autonomous robot called *Julius* for use in underground mines. The robot is based on a commercially available platform and is supplemented with an industrial robotic arm for manipulation tasks. Yet, the robot is more compact and maneuverable than some robots mentioned earlier. Since navigation is a prerequisite for everything else, the evaluation experiments focus on mapping and navigation. The remainder of this paper is organized as follows. Section II derives requirements posed by the environment and research objectives, whereas Section III presents the research robot *Julius* and its sensors and actuators to meet those requirements. In Section IV, two underground experiments are described and evaluated. The presented contents are finally summarized in Section V.

II. Requirements

The robot is operated in the local research and educational mine (REM), an old ore mine from the 12th century, and is part of the project *ARIDuA* (Autonomous Robots and the Internet of Things in Underground Facilities, acronym in German), as further explained in subsection II-C. In order to successfully operate, *Julius* needs to fulfill *environment*-, *logistics*-, and *task*-related requirements.

A. Environmental

As in indoor environments, underground mines have no access to GNSSs and, thus, no external referencing system is available. Although the global rotation can be determined by the geomagnetic field, this may be disturbed locally by steel columns or ore bodies. In these cases, one usually trusts in visual odometry, which appears promising in the feature-rich ore veins. Due to darkness, this requires a fine-tuned lighting system on the robot that avoids overexposure and negative effects of specular reflections. Depending on the depth, a seasonally constant temperature from 5 to 15 degrees Celsius prevails and the surrounding groundwater causes maximum humidity (90 to 95 percent). This can lead to condensation water on the sensors and electrical components. Especially with computers that are typically cooled with a plurality of fans, this is to be considered. Accordingly, they must be protected against water and air ingress. In addition, puddles are formed on the ground which absorb infrared (IR) radiation, i. e., IR-B (780 nm to 1.4 μm), and mud leads to wheel slip which interferes with odometry. The rough surface and irregular tunnel cross-sections are especially challenging for mapping and navigation. With uncontrolled roll and pitch movements of the robot, the scanning-plane of laser scanners changes. This has an influence on consistent localization especially with 2D Simultaneous Localization and Mapping (SLAM) methods, calling for visual or 3D methods. The irregular cross-sections may also require 3D collision checking for collision avoidance. The mine's spatial extent requires a long-range operation and thus a high-capacity battery. Operation planning must ensure that the robot does not run out of power midway since charging on site may not be possible when power outlets are kilometers away. Furthermore, the tunnel may become impassable for other devices in case the robot breaks down. Especially in case of emergency, the robot must not hinder an evacuation.

B. Logistics

In order to take the robot underground, it needs to fit into the local pit cage, which limits the robot's dimension to approximately $0.8 \times 1.5 \times 1.8$ meters (w $\times$ l $\times$ h). Since there are rails at REM, ground clearance of the robot has to be at least 13 centimeters. One usage scenario regarding the robot usually includes transporting the robot on a pick-up truck to the mine, down the shaft, preparation time, and multiple experiments. In order to benefit from such a scenario, we estimate a desired operating time of three to four hours. Including decreased battery capacity at low temperatures, battery design capacity should correspond to five hours operating time.

C. Task

The *ARIDuA* project aims to investigate synergies between Internet of things (IoT) and robotics. For this, the interaction between the robot and an IoT infrastructure consisting of Smart Sensor Boxes (SSBs) deployed throughout the mine is examined. Each SSB houses different sensors for environmental monitoring, such as temperature or gas concentration. Collectively, the SSBs form a wireless sensor network (WSN) where SSBs transfer data between each other and to an access point for external usage (for more details see [9]).

Robots can benefit from (georeferenced) IoT infrastructure in GNSS-deprived areas, e.g., by determining a sensor's location to decrease its own localization error. IoT infrastructure can also benefit from robots. To this end, *ARIDuA* examines how the robot might install, rearrange, or remove SSBs underground. Hence, the robot needs some kind of manipulator. As modes of navigation, *Julius* may be operated by remote control, autonomously drive through the mine by following waypoints on a map, or autonomously explore unknown terrain. Maps created by *Julius* might contain locations of mobile and installed SSBs, might be of interest to mine surveyors, and can be used for 3D model creation.

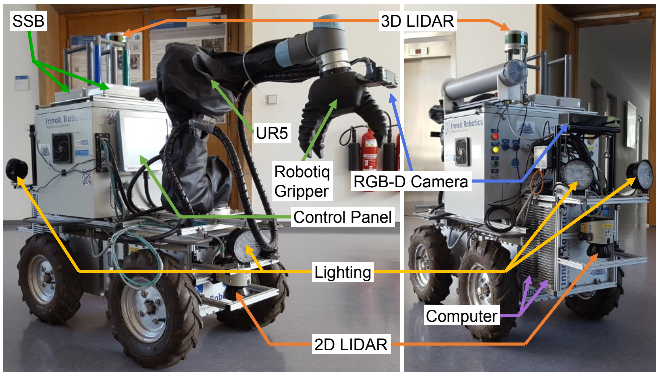
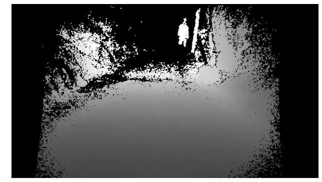
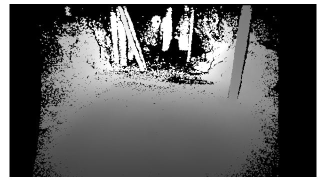


Fig. 2. The research robot *Julius* is equipped with a robotic arm (UR5) and 3-finger gripper (Robotiq). In addition, it carries several optical sensors, i. e., a VLP-16 (top), Kinect ONE (right), SICK LMS (bottom left and right). Two powerful computers (bottom right) and a lighting system are provided. Several SSBs are stored on top of the robot. Network switches, custom electronics, and connectors are stored inside the gray box in the middle.

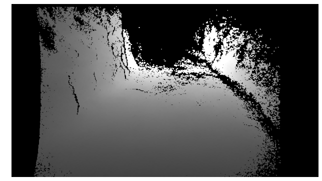
(a) Kinect RGB image.



(b) Kinect depth image of 3(a).



(c) Depth image of mine equipment.



(d) Depth image with absorbed IR.

Fig. 3. Images of Kinect facing forward, tilted downwards. 3(a) The RGB camera is able to see due to the lighting system. 3(b – d) Depth imaging is based on IR projected by the Kinect and therefore independent of visible light. 3(b) Thanks to the depth camera, the sensor detects a person in the dark area in the middle of the picture. 3(c) Also a ladder, people, and a pit prop are visible underground via IR. 3(d) At the right side, a water ditch is absorbing all IR.

The robot will communicate with IoT infrastructure to aid navigation or read data from SSBs. Since *ARIDuA* is a research project, it is desirable for the robot to be, to some extent, modular and easily extensible.

III. Research Robot *Julius*

The research robot presented in this paper is named after Julius Ludwig Weisbach (1806 – 1871). In addition to all aforementioned requirements, the chosen robot should not be built from scratch to obtain replicability. Furthermore, it comprises off-the-shelf sensors, a manipulation unit, computation units, and power supply. Total hardware costs amount to about 96.000 €. *Julius* is depicted in Fig. 2.

A. Robot Platform

Designing a new robot for every new environment or task is not desirable. Therefore, the robot *Julius* is based on a commercial platform developed by *Innok Robotics* [10]. A more detailed description of the adapted platform and its basic equipment can be found in Table I. It consists of four 16 inch wheels, equipped with encoders for odometry, each of which is powered by a dedicated electric motor with 110 newton meters drive torque. This differential drive allows for maximal maneuverability, a property needed in an narrow underground mine, and an operating speed between 0.018 and 0.9 meters per second. The platform has a footprint of circa $142{\times}65$ centimeters, ground clearance of 14 centimeters, and the chassis is IP67 protected. In order to enable use of RGB cameras, the platform is equipped with four LED spotlights. It is desired to obtain a uniform, diffuse lighting instead of a small light cone. As a consequence of these properties, *Julius* is competent to drive in REM.

B. Optical Sensors

In order to autonomously navigate and manipulate IoT infrastructure, *Julius* needs to perceive its environment with appropriate sensors. Optical sensors and their specifications are listed in Table II.

Mining environments are often dark. Here, a depth camera or a camera-light setup can yield image information. Hence, we use a *Kinect* for Xbox One as RGB-D camera at the front of *Julius* right above the aforementioned lighting system. Fig. 3 shows how *Julius* sees the world, once with light as RGB image and three times with IR as depth image. As the *Kinect's* depth imaging may be disturbed by reflective puddles, it may be advisable to tilt the sensor upwards, depending on the environment and use case.

In addition to data from the front-facing RGB-D camera, it is necessary to know (or "see") what the robotic hand could grip. To accomplish that, a second and smaller RGB-D camera (*Asus Xtion*) is mounted on the side of the hand. Although two LED spotlights are at the back of the robot, it is advisable to use a depth camera for manipulation tasks in dimly lit areas like the face of the mine as well.

In order to increase the amount of perceived area, a 3D laser scanner on top of *Julius* provides a continuous 360 degree view. The resulting point cloud enables obstacle detection and mine mapping [11].

With all sensors mounted rather highly and facing outwards, blind spots in the immediate proximity of *Julius* arise as a result. In order to cover these blind spots, the robot is equipped with one 2D laser scanner at each end. The resulting sensor information can be used to detect obstacles like legs or estimate the pathway of the drift.

C. Manipulators

For its manipulation capabilities, the robot is equipped with a robotic arm and hand.

1) UR5: The robotic arm *UR5* is distributed by *Universal Robots*. It is certified for safe human-robot interaction and has six joints, each of which has a working area of $\pm$360 degrees. This provides a workspace with a radius of 85 centimeters. Its own weight of 18.4 kilograms allows for mounting it on the mobile platform. The mass of *Julius* (138 kilograms) is sufficient as counterweight for the dynamics of the *UR5*. Simple communication via Ethernet and

TABLE I

TECHNICAL SPECIFICATIONS OF THE HEROS 444 FG PLATFORM, A MORE DETAILED DESCRIPTION CAN BE FOUND IN THE TECHNICAL REPORT [10].

Type	Name	Description	Communication	Further specifications
Robot platform	Heros 444 FG	4WD, IP67 upgrade, 138 kg weight 0.65 × 1.42 × 1.3 m (w×l×h w/o arm)	Ethernet switch, RC, switches	Battery: Li-ion (NMC), 48 V, 20 Ah capacity
IMU	XSens MTi-30-AHRS-2A5G4	Static acc. 0.2°, 1.0° (roll/pitch, yaw) Dynamic acc. 0.5°, 1.0° (roll/pitch, yaw)	RS-232	Scan rate: 10 kHz Publishing rate: 2 kHz
Lighting system	4×: LED Spotlight	4×: 1200 lm, 27 W, IP67 Beam angle: 60°	None	Not dimmable
Computation	2×: On-Board PC	2×: i7 4×2.7 GHz, 16 GB RAM, 256 GB SSD, Intel HD4600	Gigabit Ethernet, 4×: USB 3.0, 3×: RS-232	IP67/68 connectors, 22 – 90 W

4WD – Four-wheel drive, RC – Radio control, NMC – Nickel manganese cobalt, IMU – inertial measurement unit

TABLE II

SENSOR SET-UP AND CONFIGURATION USED ON THE MOBILE ROBOT JULIUS.

Type	Name	Range [m]	FOV [°]	(Angular) Resolution [°] or [px×px]	Depth accuracy [cm]	Frequency [fps] or [Hz]	Data rate [MB/s]	Connection
Localization camera	Microsoft Kinect One	0.5 – 4.5	70 H 60 V	1920×1080 RGB 512×424 D	±1.8	30	190	USB 3.0
Gripper camera	Asus Xtion Pro Live	0.8 – 3.5	58 H 45 V	1280×1024 RGB 640×480 D	±0.2	30	130	USB 2.0
3D Laser scanner	Velodyne Puck VLP-16	0.5 – 300	360 H 30 V	0.1 – 0.4 H 2.0 V	±3.0	10	8.5	Gigabit Ethernet
2D Laser scanner	SICK LMS 111	0.5 – 20	270 V	0.5	±0.3	50	0.2	Ethernet

FOV – Field of view, V – Vertical, H – Horizontal

availability of robot operating system (ROS) [12] drivers allow integration at the software level. Alternatively, the proprietary URScript language can be used. The arm has a payload of 5 kilograms and usually has an IP54 classification. In order to improve water and dust resistance, it was retrofitted with a rubber "sleeve", which only minimally decreases range of motion.

2) Robotiq Hand: The robotic hand is a *3-Finger Adaptive Robot Gripper* from *Robotiq*. Its fingers can open up to 155 millimeters and the hand can lift between 2.5 and 10 kilograms depending on the type of grasp (e.g., encompassing or fingertip grip). It is equipped with a custom rubber glove to increase robustness and protection against water.

In order to fulfill the goal of manipulating IoT infrastructure underground, *Julius* detects SSBs (e.g., using its gripper camera *Asus Xtion*) and approaches them with the *UR5* and *Robotiq* gripper. Further, the robot is equipped with a specialized sampling device for automated extraction of mountain waters. Both elements can be seen in Fig. 4, Fig. 5 and the video attached to this paper. It is noted, that computer-aided design (CAD) models of all devices are present for the planning process. The environment is represented in an OctoMap. Doing so, the robot uses its manipulator efficiently.

D. Computation

Julius is equipped with two dedicated computers, henceforth referred to as *main* and *utility*. The *main* computer is responsible for the basic processes of the robot, e.g., drive control, receiving most sensor data, controlling the robotic manipulator, and remote control. Algorithms and calculations that are important for basic functions are stored here. In contrast, the *utility* computer covers processes with high computational demand like path planning, image processing, object recognition, or point cloud processing. The two computers are time-synchronized and communicate via ROS.

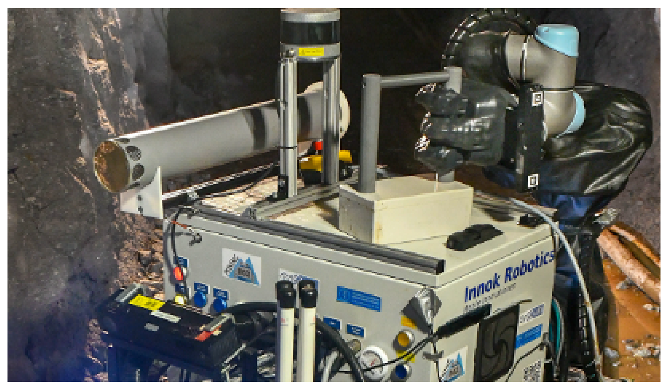


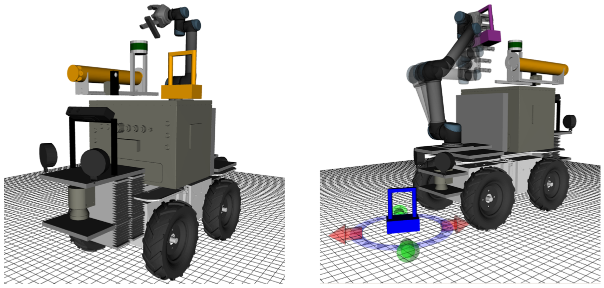
Fig. 4. Research robot *Julius* grasps a sensor box from its top, in order to set it into the mine. This manipulation task is semi-autonomous as a miner provides a suitable target pose via teleoperation. The gray cylinder in the background is a water sample device. Taking those samples may be done fully autonomously in approximately 40 seconds (see attached video).

E. Power supply

Julius's electric engines, computers, and other electric devices require a potent battery. With enabled lighting system, manipulation unit, and sensors, while frequently driving at moderate speed, the battery provides power for approximately six hours operation time in an office environment and approximately four hours underground. The system provides the option to change the battery on site within minutes, which extends operation time underground and prevents a long standstill. For more technical details see Table I.

F. Miscellaneous

Fast and large SSDs in both PCs store maps and sensor data. Due to USB, Ethernet, and other PC interfaces, sensors



(a) Front view, showing robotic arm and hand, LIDARs, lighting, and sensor box (colored orange as it is not part of the robot per se).

(b) Back view, after lifting the sensor station from its top, the robot waits to receive appropriate target pose (blue) from the user.

Fig. 5. URDF model of *Julius* visualized in *rviz* during the task of deploying a sensor box. Lifting the box from its start pose on top of the robot (5(a)) is done autonomously, while providing a target pose is done via teleoperation (5(b)) using Interactive Markers.

can easily be exchanged. Via WiFi and Bluetooth-like receivers, *Julius* communicates to other PCs or remote controls. Communication to the SSBs is accomplished via Bluetooth Low Energy (BLE). In addition to the native remote control, a second, redundant controller connected via Bluetooth-like technology and communicating via ROS safeguards against failures. This controller can operate up to 10 meters away from the receiver. However, as with all other communication, the operating distance is limited to line-of-sight.

G. Simulation

To simulate and test algorithms, many of the robot's components already provide existing models in the Unified Robot Description Format (URDF). We added URDF models of custom or missing parts. The result can be seen in Fig. 5. In simulation software Gazebo [13], every sensor has its own Gazebo sensor plugin and within ROS it does not matter whether real or virtual sensors publish their data. The results of a former project [11] allow for creating a virtual model of REM in which a virtual *Julius* can drive and test algorithms.

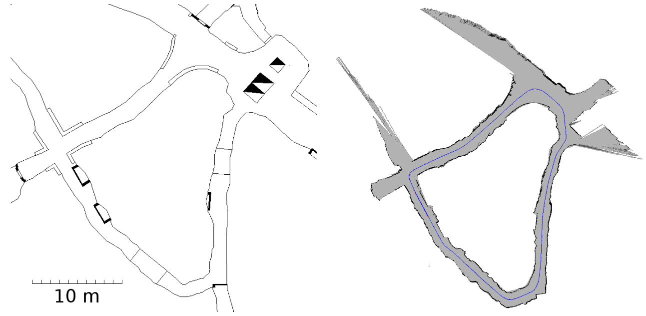
IV. Evaluation of Test Drive

In order to test *Julius*'s ability to map its surroundings and autonomously navigate in an already known map, we separately tested mapping and autonomous driving at two separate areas in the REM: First, mapping at a well-developed educational trail called "Lehrpfad" and, second, mapping and autonomous driving at a drift called "Wilhelm Stehender Süd". Since obtaining an accurate ground truth in underground mines is not trivial, the authors will present a quantitative evaluation in a future paper.

A. Mapping Educational Trail "Lehrpfad"

The educational trail *Lehrpfad* can be visited by the general public. Fig. 6(a) depicts a part of *Lehrpfad* as CAD mine plans.

1) Setting: The area of operation is approximately 75 meters long. The ground is flat and effectively has no major surface irregularities. In addition, the whole trail is well lit and allows for driving a loop in a short amount of time.



(a) CAD mine plans.

(b) Grid map by RTAB-Map [14].

Fig. 6. Maps of the research mine's educational trail *Lehrpfad*. 6(a) CAD mine plans created by mine surveyors. 6(b) 2D occupancy grid map created by RTAB-Map [14] while driving remote controlled through *Lehrpfad*.

2) Experiment: With all sensors operating, *Julius* was controlled remotely by one team member closely following the robot. The test drive went off without problems as expected and after approximately five minutes the robot reached its starting point again. During the drive, RTAB-Map [14], also used in former project [7][11], created the 2D occupancy grid map depicted in Fig. 6(b).

3) Results: Fig. 6 shows both the mine plans and the created 2D occupancy grid map. Thanks to a detected loop closure [15], the error could be minimized and the created map is quite close to the mine plans.

B. Autonomous Driving "Wilhelm Stehender Süd"

The operation area for the autonomous test drive is located at *Wilhelm Stehender Süd* depicted in Fig. 8(a).

1) Setting: The part of the drift where the test drive took place is approximately 150 meters long and is, in contrast to *Lehrpfad*, bumpy, muddy, and without light. Beforehand, *Julius* was driven remotely operated along the drift to create the 2D occupancy grid map depicted in Fig. 8(b).

2) Experiment: Waypoints were added manually to the priorly created map via a graphical user interface (GUI). The global path planning is done by the ROS navigation stack while the local path planning is done by timed elastic bands, or more specific, the ROS package *teb_local_planner* [16]. While the RGB-D camera is used for navigation, the 3D laser scanner is used for obstacle avoidance. The autonomous drive was monitored by team members. Fig. 7, a screenshot of the attached video, shows a glimpse of all layers taking part during navigation.

3) Results: Fig. 8 shows the mine plans and the created 2D occupancy grid map of the operating area. In Fig. 8(c), both maps are put on top of each other. They partially do not match. No loop closure was possible during this experiment and, therefore, the errors could not be minimized. According to the maps, highest errors occur at rotation estimations. Despite using an inaccurate map, *Julius* was able to safely navigate autonomously from waypoint to waypoint.

C. Summary and Discussion

The created map of *Lehrpfad* is visually quite close to the original mine plans. The trail was flat, the environment

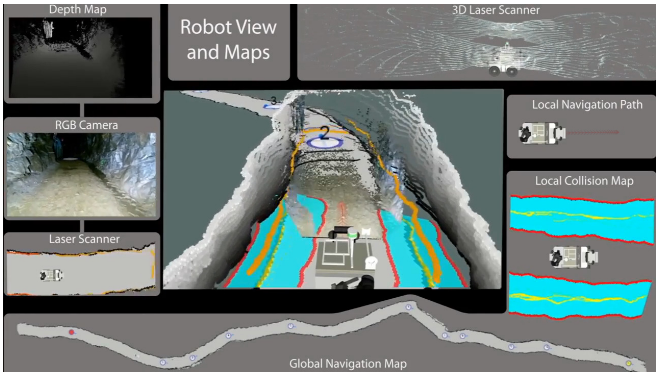
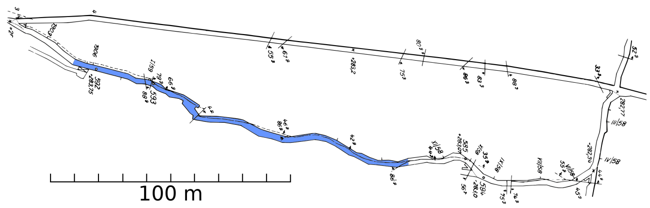
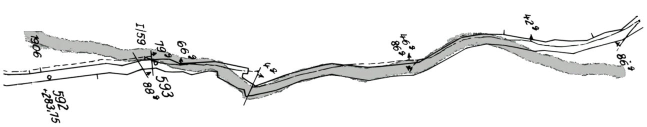


Fig. 7. Sensor data received during the drive: RGB and depth image of the Kinect are shown at the top left, points received by the laser scanners are shown at the bottom left and top right. In addition, the planned local path and local collision map are depicted at the right. At the bottom, the occupancy grid map, set waypoints, and *Julius*'s position are shown.



(a) Ground truth mine plans. The marked area is the area of operation.

(b) 2D occupancy grid map created by RTAB-Map [14].



(c) Overlay of both maps. Instead of matching the starting position, they are displaced in a way to show a large mutual segment.

Fig. 8. Maps of *Wilhelm Stehender Süd* and their comparison. 8(a) Mines plans created by mine surveyors used as ground truth. 8(b) 2D grid map created while driving remotely controlled through *Wilhelm Stehender Süd*. 8(c) The overlay of both maps reveals errors in rotation estimations.

well lit, and a loop closure was possible. All that enabled a creation of a map that approximates the mine plans well.

Without these favorable conditions, ground truth mine plans and the grid map diverge in the second experiment. Slip due to mud, an odometry model based on 2D, IMU issues due to magnetic interferences and gyroscope drift, and no loop closure might all cause the translations and especially rotations to be estimated inaccurately. With help of GNSSs, these shortcomings typically could have been compensated.

Nonetheless, the maps created by the robot are sufficient for localization and path planning. *Julius* was able to navigate autonomously from waypoint to waypoint using a local path planner and appropriate sensor equipment.

V. Conclusion and Future Work

This paper presents the design of an autonomous, agile, and compact robot equipped with a robotic arm for underground environments. In order to handle prevailing harsh conditions, a robotic platform including IMU and lighting was retrofitted with two RGB-D cameras, laser scanners, a robotic arm, and a 3-finger gripper. The manipulation unit is specially protected against environmental influences.

Based on these results, future work includes further and more challenging navigation tasks. Furthermore, it is planned to implement exploration of unknown terrain and using the gripper camera for tasks like driving backwards or perceiving an additional perspective of the scene. In addition to a 360 degree laser scanner, it is aimed at including omnidirectional cameras as well. When project *ARIDuA* progresses, *Julius* has to proof its manipulative capabilities and, in this context, how the navigation might be improved using IoT infrastructure.

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