RoboCup Rescue 2023 Team Description Paper AutonOHM

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Info

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Video URLs:	https://youtu.be/lefRdaPFHUs
	https://youtu.be/X6P45L14zUI

RoboCup Rescue TDP collection: 2019+: https://tdp.robocup.org/ Pre 2019: https://robocup-rescue.github.io/team_description_papers/

***Abstract*—Team AutonOHM has been participating in the RoboCup Rescue League since 2012. The team focuses on autonomous behavior and exploration for rescue robotics. Our strength lies within implementations like SLAM, navigation, or exploration strategies. Another mainstay is the improvement of hardware for harsh conditions to increase the survivability. Through close contact with the local fire brigade of Nuremberg, the team tries to create solutions that are applicable to disaster scenarios.**

***Index Terms*—RoboCup Rescue, Team Description Paper, AutonOHM, RoboCup Bordeaux 2023.**

I. Introduction

AUTONOHM participated in the RoboCup German Open [1] in 2012 and 2013 with their teleoperated robot Georg. They achieved the second place in 2013, and therefore qualified for the RoboCup World Championship in Eindhoven in 2013, ending up in the 12th spot. In 2014 the team was extended by a second robot called Simon.

Deploying this second, more maneuverable robot for teleoperation and Georg for autonomous operation, resulted in an overall second place at the RoboCup German Open in 2014. Furthermore, a second place in the Best in Class Autonomy Challenge was achieved in this year.

In 2015, AutonOHM participated with the same robots. The major focus of the team laid on increasing the level of autonomy, the quality of robot localization and environment mapping as well as cooperative Simultaneous Localization and Mapping (SLAM). These efforts enabled AutonOHM to win the RoboCup German Open in 2015.

In 2016 the team joined the RoboCup World Championship in Leipzig with a new robot platform (see Fig. 1) capable of driving in rough terrain scenarios [2]. With its new 7-DOF manipulator with three links, the robot enabled AutonOHM to enter the finals. Further developments in the following year concentrated mainly on mechanical improvements of the new platform.

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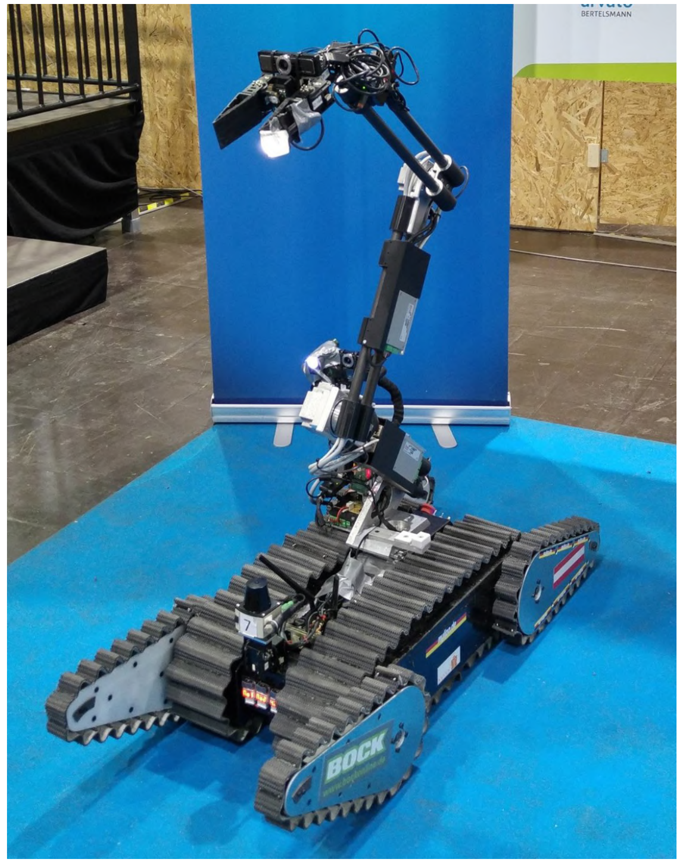


Fig. 1. Robot Schroedi equipped with a 7-DOF manipulator for inspecting points of interest up to a height of 1.5 m and grasping objects. This robot is capable of driving in rough terrains.

At the German Open in Magdeburg in 2017, team AutonOHM achieved the highest score teleoperated in the challenge 'step field' and 'maneuvering center' autonomously and reached the finals. After numerous mechanical defects, an overall 4th place was reached. In the following Best in Class Autonomy challenge, a second place could be achieved.

In 2018, the mechanical design of the robot's drive chain was improved and a new inverse kinematic control for the robot arm was implemented. This improved the control of the robot manipulator drastically and enabled team AutonOHM to score best in most dexterity challenges at RoboCup German Open 2018. The improved drive train allowed the team also to win in hurdles and elevated ramps. With these results, team

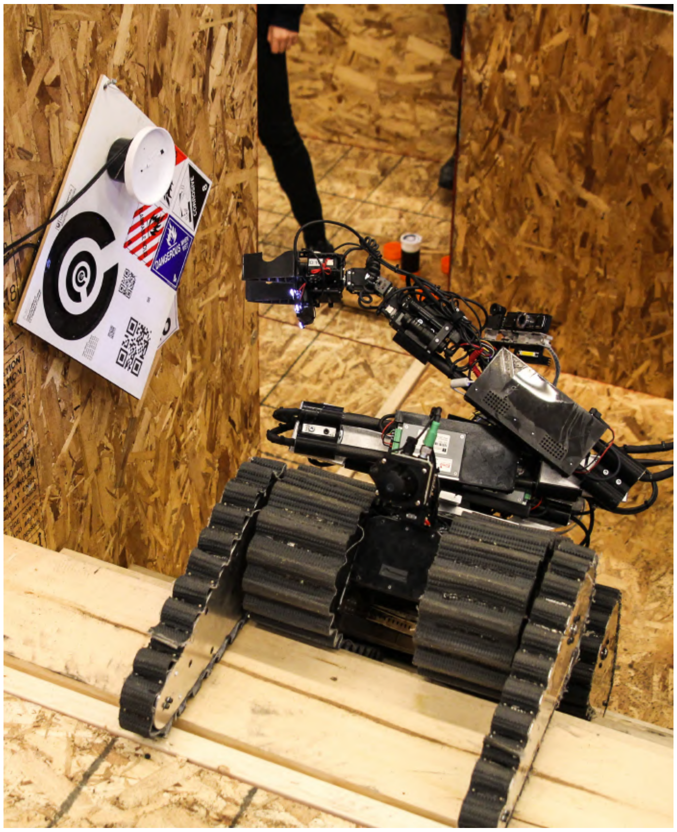


Fig. 2. Schroedi at the finals in Montreal. The image shows Schroedi scoring points for motion, hazard signs, QR-codes and heat signature on a stair obstacle.

AutonOHM advanced to the finals and won the first place.

They also participated at the RoboCup World Championship Montréal 2018. In Canada, the inverse kinematic arm control enabled the team to score best in door opening and allowed good results in most dexterity challenges. Further improvements on the drive train (improved track guide) and the robust self developed SLAM approach enabled the team to score well in the mapping challenges. They reached the finals and scored an overall 5th place. Fig. 2 shows the robot on the stairs in the finals.

The team was also given the opportunity to compete in the World Robot Summit (WRS) challenge in Tokyo, Japan. The team achieved good results in mostly all challenges. It was especially successful in autonomous object recognition and mapping and in mobility challenges. The inverse kinematics allowed the achievement of valuable points in the difficult grasping challenges. AutonOHM reached the finals with these results and scored an overall 3rd place in the Standard Disaster Robotics League. Fig. 3 shows the robot scoring points in the final challenge.

In 2019, AutonOHM participated at the German Open in Magdeburg and the World Cup in Sydney, Australia. In Magdeburg, AutonOHM used nearly the same mechanical setup as in Montréal, however, new autonomous software had been introduced. With the self developed RONA (Source: https://github.com/schmiddey/rona) framework, Schroedi managed the challenges negotiate and crossed

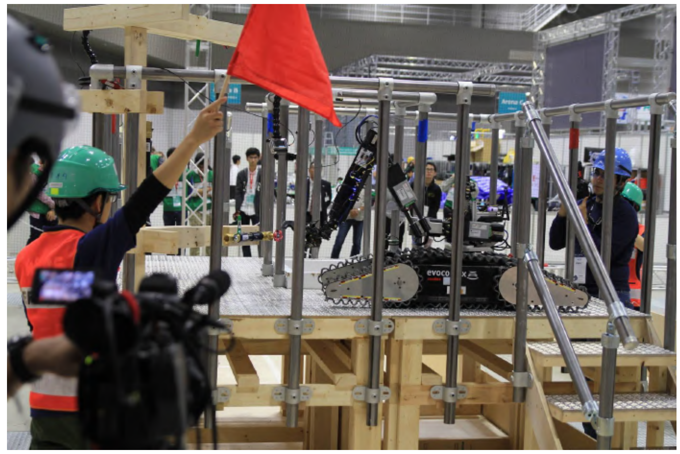


Fig. 3. Schroedi at the finals Tokyo. Image shows Schroedi scoring points by manipulating vents on a stair case. The robot had to climb the stairs up and manipulate levers and vents.

ramps autonomously, wherefore AutonOHM qualified for the autonomy final.

Schroedi performed without faults during the preliminary runs. Its superior mobility capacity and the outstanding manipulator allowed the team to advance also to the mobility, dexterity and the overall finals. AutonOHM won the title again after scoring four victims in the MAN arena and two in the MOB arena. Schroedi also won the best in class mobility final, best in class dexterity final and was placed second in the autonomy final against Team Hector.

In Sydney, the robot performed well in the preliminaries. The manipulator and the robust SLAM algorithm allowed good results in both dexterity and mapping challenges. The good results qualified Schroedi for the finals. In Sydney, a new scoring system has been introduced. The robot has to perfom in separated autonomy, dexterity and mobility finals. While the dexterity and mobility stage went well, Schroedi scored rather poorly in the autonomy final, wherefore AutonOHM reached the fifth place.

Due to the pandemic, the championship participation continued with the subsidiary RoboCup event “RoboCup Rescue German Open 2021 – DRZ Edition” at the Deutsches Rettungsrobotik Zentrum in Dortmund.

The team was able to achieve best in class dexterity and the second place in the finals, which drastically differ from the normal final procedure. The teams have to face a simulated chemical laboratory environment. Doors have to be opened, an area filled with smoke and debris has to be traversed and a container and valves have to be closed.

The event again took place in Dortmund in 2022. AutonOHM reached the first place in the event and additionally won Best in Class Dexterity and Mobility. For the first time the stair debris could be won in a championship.

In 2021, the team took part in the WRS Disaster Robotics Category Remote Participation. The videos for this competition were shot in AutonOHMs test site. The results were Best in Class Mobility and Best in Class Exploration and Mapping, both classes that the team competed in.

Since 2014 team AutonOHM uses a self-developed SLAM approach based on the Truncated Signed Distance Function (TSDF) [3], [4], [5]. Over the last years, the team gained expertise in different areas of robotics. This includes 2D and 3D mapping with LiDAR scanners, thermal imaging, sensor fusion, sensor development as well as robot arm manipulation.

Improvements over Previous Contributions

The challenges of 2018 and 2019 revealed a major flaw in the design of Schroedi. The main drive motors where neither fast nor strong enough to compete with the tough international competition, wherefore the whole drive train has been redesigned. The new design consists mainly of better suiting Brushed DC Motors and new worm drives. This results in more torque and a higher maximum speed.

In order to power the motors, the previously used Maxon DEC 50/5 modules had to be replaced. The former motor drivers were only suited for Brushless DC Motors. For this the bottom two boards of the driver stack had to be replaced to support the new Maxon ESCON 50/5 modules. Those modules can be configured to function the same way as the DEC 50/5 modules but facilitate both Brushed and Brushless DC Motors. The top layout of the boards can be seen in figure 4.

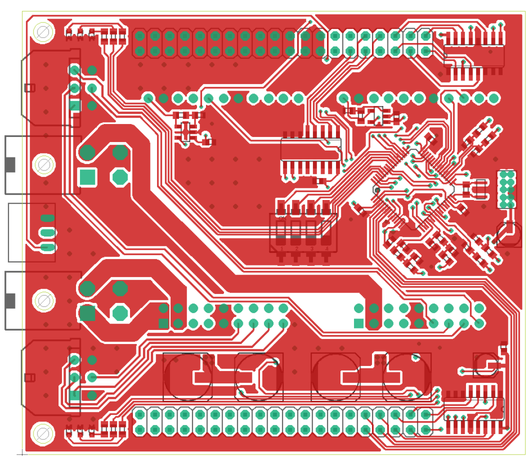


Fig. 4. ESCON compatible motor controller board.

For manipulation tasks a new sensor-board has been developed. It features an Inertial Measurement Unit (IMU), an ambient light sensor as well as Time Of Flight (TOF) sensors. The TOF sensors enable the operator to accurately measure the distance and orientation from objects in front and inside the grippers. Furthermore a targeting LED with low divergence sits at the rotation point of the last Dynamixel XH430-V350 servo to simplify the grasping and rotation of objects. The board also accommodates multiple white LEDs for illumination. The LEDs are dimmable by the operator to suit different lighting conditions. Fig. 5 shows the board without the light diffusion and protection housing.

In 2023, AutonOHM is planing on performing EXP4 Avoid Holes. In order to achieve this, a state machine will be implemented. An Orbbec Astra Stereo S will be fixed to the front of the robot between the tracks. With use of the disparity image and the resulting depth representation, holes can be segmented from traversable terrain.

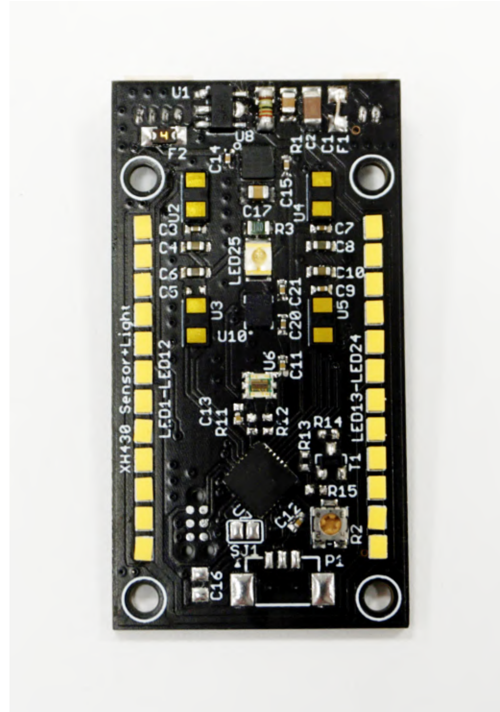


Fig. 5. Sensor board for the end effector.

II. SYSTEM DESCRIPTION

The software architecture of the robot is based on the Robot Operating System (ROS) [6]. The chassis of Schroedi has been developed in cooperation with the RoboCup Rescue Robot Team of the Carinthia University of Applied Sciences Villach [7]. With its chain wheel drive and four flippers, it is able to handle complex obstacles like stairs and step-fields. The robot arm is capable of inspection and manipulation tasks like opening doors. The system will be remote controlled and additionally in most of the maneuvering challenges autonomously as well.

A. Hardware

The robot's hardware is designed for robust long term missions in disaster areas and will be described in this section.

a) Leveling Platform: The leveling platform consists of two servo drives which are able to align the laser scanning plane horizontal with two degrees of freedom (Figure 6d). The orientation of the chassis is measured with an IMU, which is mounted inside the chassis. An Arduino board receives the data from the IMU and calculates the required angles of the axes to keep the scanning plane aligned horizontally. Both servo drives are directly connected to the Arduino board. The leveling platform is an independent system on the robot.

b) Sensor Head: The sensor head is used to orientate different sensors with a single platform (Figure 6a). Two servo drives are used to pan and tilt the sensor head. It is equipped with an infrared camera, an RGB camera with auto focus and an RGB-D camera. All sensors are calibrated to each other by an extrinsic and intrinsic matrix. The sensor head is mainly used for visual inspection. Victims can be located quickly using different visual sensors. Figure 6a illustrates the sensor head with its sensors. During the challenges of 2018, the former Optris infrared camera has been exchanged with a SeekThermal device. The team also added LED lights below to illuminate dark areas.

c) Motor Controller: Team AutonOHM developed a custom motor controller: The robot is equipped with four Brushed DC Motors for the main drive and four Bushless DC (BLDC) Motors for the flippers (see Fig. 6b). The four controllers, based on Maxon EC amplifier DEC modules 50/5 for the Flippers and Maxon Escon 50/5 for the main drive, are integrated into a compact motor driver stack. The stack consists of four NXP KV31 based slave boards, each of which controls two motors. The Atmel Atmega328 based master board, which also includes the required power supplies and galvanic isolation, connects the stack via USB to the ROS-System.

d) Manipulator: Sometimes victims are not directly reachable for the mobile robot, e.g. a victim is located behind an obstacle. For such cases, the mobile platform needs an inspection arm to improve victim localization abilities. Schroedi is equipped with a 7-DOF robot arm. To achieve higher compactness of the manipulator without reducing the operation range, it has three links instead of two compared to most existing robot arm configurations. (see Figure 6f).

The Tool Center Point (TCP) holds audio sensors, a CO2 sensor and a gripper (see Figure 6e). Due to its 7 degrees of freedom the robot arm is able to fulfill complex inspection and manipulation tasks. The maximum payload is limited to 0.5 kg when it is fully extended. The robot arm can reach objects within a distance of 1.5 m. The manipulator can be controlled teleoperated with a game pad controller or autonomously. In order to search for life signs, it is equipped with a microphone, a CO2 sensor and a thermal camera. The SeekThermal thermal cameras where added to the system. Their small design and low weight made it possible to use such a device on the gripper, as well as on the sensorhead. A speaker enables the operator to talk to a potential victim. The current design is depicted in Fig. 6e.

e) Drive train: After a mechanical breakdown during the RoboCup German Open Finals in 2017, the mechanical parts of the drive train had to be improved. The shaft-hub connections were optimized from a form-fit connection with a feather key to a force-fit connection using a clamping set. The advantage of the new concept (see Figure 6c) is higher stability even if alternating and bunting loads occur. The drive train is designed to overcome slopes of 45° as well as 15° slopes with an additional load of 50 kg. In 2022 further improvements were made to the drive train. The advantage of the new drive train is the optimised transmission and the use of DC motors. The results are more torque and higher maximum speed.

B. Software

The following section demonstrates the algorithms and software of AutonOHM for the RoboCup Rescue League.

a) Low Level Control: The low-level control of Schroedi is responsible for the basic control of actors and the access to the sensor signals. The commonly known robot middleware Robot Operating System (ROS) is responsible for the communication [6]. The software is structured in nodes, each containing a single executable. The exchange of information between these ROS nodes is realized by ROS data types, e.g., messages, services or actions, via TCP/IP. On the startup of the robot, different checks are applied to the sensors and actors. If tests fail – e.g., a sensor cannot provide data in sufficient cycle time, or an actor does not provide feedback, the startup aborts and the operator of the robot is informed.

b) Localization and Mapping: A self developed Simultaneous Localization and Mapping (SLAM) approach *ohm_tsd_slam* is used to generate a map of unknown environment with a 2D laser scanner. Information like the location of victims or points of interest is stored according to this map. A major feature of *ohm_tsd_slam* is that multiple robots can create a map together. Additionally, robust localization is guaranteed by the use of a Random Sample and Consensus (RANSAC) approach [8].

c) Victim Detection: Vital signs are detected with the help of different sensors. A sensor head is used to orientate the sensors independent of the robot base. The sensor head uses video-, thermal- and RGB-D cameras for virtual perception. A CO2 sensor is mounted on the TCP of the manipulator of the robot to detect breathing. An approach for the automatic detection of heated objects was developed to allow a faster sensor check as well as to improve the object detection during exploration missions [9]. Parts of the developed software are free to use and open access via [10].

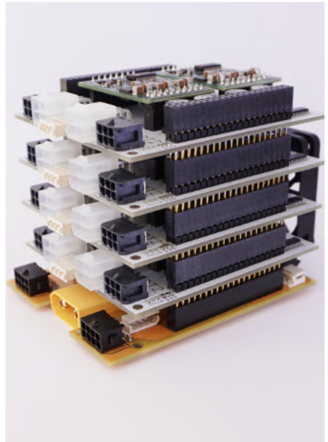
d) Navigation: For autonomous navigation, the ROS package RONA (Source: https://github.com/schmiddey/rona) is used. It contains path planning based on the A* algorithm and is suitable for single and multi-robot path planning [11]. Additionally, the package contains basic implementations for path control. Also, it includes an implementation for frontier-based exploration. In contrast to the common ROS navigation stack, RONA is lightweight and needs less parametrization.

The robot can be operated with a state machine called Robot Statemachine (RSM) which offers an aided control that can be used by simple GUI commands [12]. It enables sending the robot to explore or follow given waypoints autonomously and execute special routines when reaching a goal (see Figure 7). The RSM encapsulates navigation and exploration packages and interfaces them via plugins. For example the ROS navigation package and the package explore_lite are interfaced, so that the robot can explore areas fully autonomously.

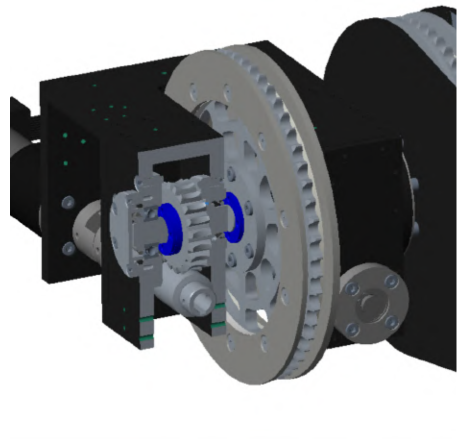
The provided GUI offers control over the extended safety mechanism for driving the robot by multiplexing all generated movement commands and only forwarding the desired one. Sending a manual command by e.g. joystick to the robot or pushing a button called the “Software Emergency Stop” in the GUI instantly halts the robot.

The exploration allows running a task when reaching goals, like tilting a sensor to improve the generated map. This can also be done for waypoint navigation.A Number of modes can be set, that determine the order in which the waypoints are visited and the pattern of repetition. Waypoints can be placed at the robot’s current position or by placing an interactive

(a) Sensor head with IR-Camera, RGB-Wide-Angle-Camera, 3D Structured-Light-Sensor.

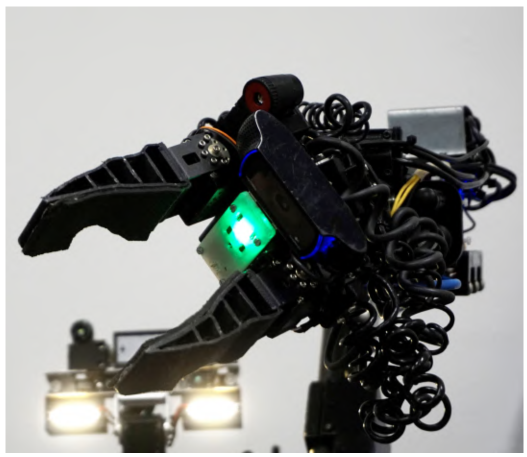


(b) Motorcontroller set up for the main drives and flippers.

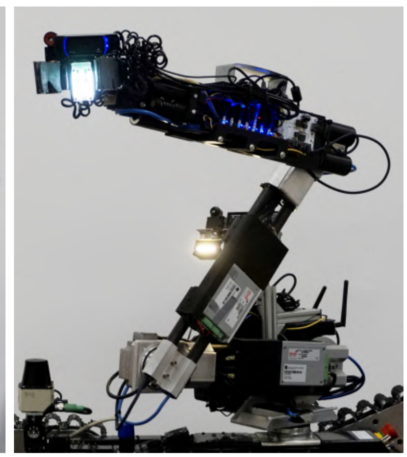


(c) Drive train in detail.

(d) Leveling platform



(e) Current End-effector with thermal imager, sensorboard, and RGB-Camera.



(f) 7-DOF manipulator for inspecting points of interest up to a height of 1.5m and grasping objects.

Fig. 6. Mechanical components and sensor concepts of Schroedi.

marker in RViz. For every waypoint a different routine can be chosen which enables autonomous inspection tasks with different objectives.

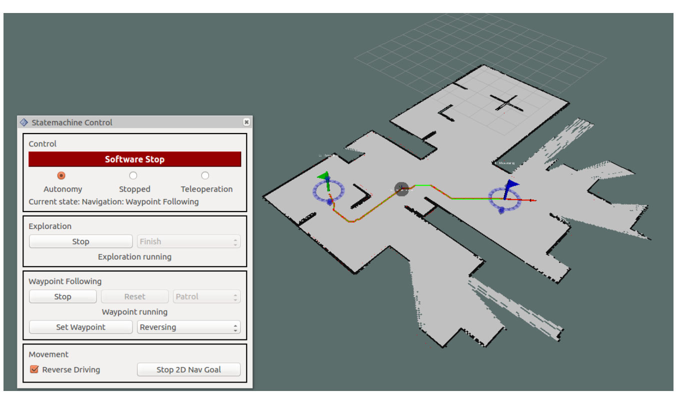


Fig. 7. Statemachine for waypoint following.

e) Point of Interest Search: For a real disaster scenario, the generated map is searched for wall segments. At first, points which change their state from free cells to occupied cells are extracted.

In this set of points the wall finder searches for straight lines using RANSAC [8] algorithm. The Occupancy Grid Map is a 2D map, so straight lines are interpreted as walls. The wall finder locates both sides of a wall. Based on the extracted walls, target poses (points of interest) are computed and inspected by the robot. This improves the robustness of finding potential victims.

f) Exploration: Schroedi can explore unknown environments based on laser scan sensor data. The sensor data is processed by the Frontier Exploration approach, presented by Yamauchi [13]. This algorithm uses the occupancy grid map to find regions which the autonomous robot has not seen before. The frontier algorithm searches for frontiers between free cells and unknown cells. These frontiers must fulfill some conditions, e.g., the frontier must be as wide as the robot. Additionally, the frontiers are sorted and prioritized based on their size and the navigation distance to the robot. Although the exploration does not rely on user interaction, a user can define areas in the map, which are prioritized higher, to enhance the

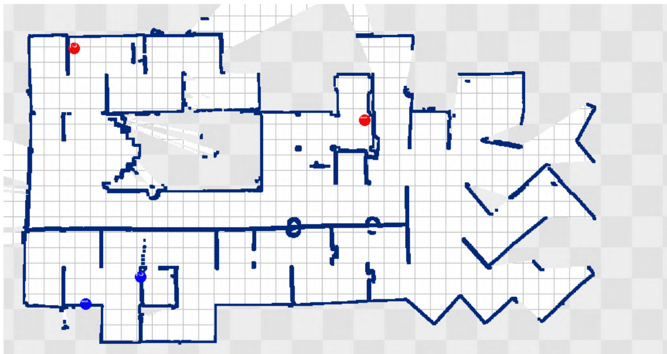
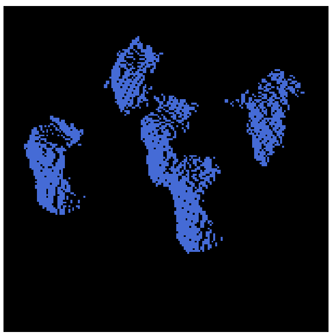


Fig. 8. Map generated by the ohm_TSD_slam



(a) Extracted pipestar represented in a PointCloud. Pipe detection is realised with PCL [15] [8].

(b) Found pipes are marked with green lines in RGB image. Realised with [16].

Fig. 9. Perception for autonomous manipulation.

performance in exploration.

g) Arm control: The complexity to solve the inverse kinematic problem rises with the number of joints, and with their configuration. The manipulator of Schroedi has seven joints – shown in Figure 6f. Joints 2 to 4 are parallel which results in redundancy and joints 5 to 7 build a spherical wrist. To solve the inverse kinematics problem there is a combined analytical and iterative solution implemented. The orientation problem of the end-effector is solved analytically due to the spherical wrist. The positioning problem of joints 1 to 4 is solved with an optimization algorithm based on [14]. The solution is stable near singularities and considers joint limits. The end-effector is controlled manually with a gamepad controller. To solve tasks autonomously the arm uses the input data of two 3D-cameras (see Figure 9a and 9b).

C. Communication

For network communication, the frequency of 5 GHz has been chosen. The used channel can be adjusted as needed. Another frequency of 446 MHz is used for two-way radio communication between team members in the setup phase. Table I shows all used frequencies and their transmission power.

TABLE I
NETWORK COMMUNICATION FOR ROBOTS AND OPERATORS.

Frequency	Band	Power(mW)
5.0 GHz - 802.11ac	adjustable	< 500 (adjustable)
446 MHz		500

D. Human-Robot Interface

For mobility and maneuvering challenges, the robot is controlled by a gamepad. The controlling is similar to computer games and allows easy adaptation. Important information is displayed in the main driving or manipulation camera feed. The operator can choose between forward and reverse driving mode or manipulation mode. The gamepad commands are mapped according to the selected mode and the main camera feed is set to either the driver camera or the manipulator camera. The manipulator camera is mounted above the gripper. In manipulation mode, a small camera image displays the driver camera to help the operator in difficult manipulation challenges.

To set up the robot for a mission, several measures have to be accomplished, for instance, powering up the drives and enabling the panning of the laser scanner. A checklist and basic training for team members and contributors minimize errors during the start-up phase.

III. Application

A. Set-up and Break-Down

Due to pressure of time in competition, setup and handling of the robots and the operator station needs to be efficient. The network is powered by an uninterruptible power supply and can operate for several hours without external power. Router, antenna, power supply and an additional Monitor are mounted inside an Peli Air Case 1615 for easy transportation. The operator uses a laptop computer to communicate over the network with the robot. The robot is ready to run within a few minutes. Because of the robot's weight of more than 70 kilograms and the operator station, the set-up needs to be done by at least two persons.

B. Mission Strategy

In the classic rescue competition, Team AutonOHM focused on multi-robot systems: One robot is not enough to fulfill the various tasks in RoboCup Rescue as well as in a real disaster scenario. Therefore several robots should help task forces to search for victims. For RoboCup Rescue one robot was controlled teleoperated while a second robot performed autonomous exploration and victim detection. With this former mission strategy, the amount of possible points per mission was doubled.

Since the competition changed in 2016, the team focuses on the evolution of one robot, capable of coping with any terrain or challenge in RoboCup, WRS or at a real rescue scenario. In the setup phase, the team tries to score as many multipliers as possible, using the carried sensors and its manipulator. The robot's software enables it to perform in some challenges autonomously, for instance MAN1, MAN2, MAN4 or the exploration and mapping challenges.

Fig. 10. Robot Schroedi and the fire brigade of Nuremberg.

C. Experiments

Team AutonOHM tested different sensors for different scenarios: Optical sensors could fail in an environment containing smoke or dust. Besides optical sensors, ultra sonic range finders and RADAR sensors are tested to guarantee perception in such an environment. This is why the fusion of different sensors is necessary to provide enough robustness [17]. During a research project with the Deutsche Bahn (German Railway), where a shunting locomotive was automated, experiences were made [9]. Since 2014 team AutonOHM collaborates with the local fire brigade of Nuremberg, testing sensors suitable for zero sight areas due to smoke.

D. Application in the Field

Since 2013 team AutonOHM has been cooperating with the fire brigade of Dettelbach, Germany as well as in Nuremberg, Germany in order to discover the requirements for human-robot collaboration (see Figure 10). The acceptability of the fire-fighter depends on their age and their experience with computer technology. The robot should increase its durability and battery life to perform well in a real disaster scenario. Also, signal shielding from a concrete dam or steel-girder constructions can cause errors and should be concerned. In August 2016 a workshop took place in cooperation with the fire brigade No. 3 in Nuremberg. Different techniques using different cameras and laser scan mapping were demonstrated. The laser scan maps allow the incident commander to direct his men for finding victims in time. This will save lives in the future [18].

IV. Conclusion

The mobile robot Schroedi is starting in his seventh competition year. The track lead fixed one of its major issues, the loss of the track. In the competition season of 2019, only the low speed while maneuvering to the different test arenas in the RoboCup finals caused problems. The hardware update will take care of this problem. The new drivestrain will be tested extensively in the competitions of 2023.

With a finally stable and fast chassis, team AutonOHM will include more autonomous software. In 2019, several challenges where driven autonomously already. This will be extended in 2023 with traversability, 3D mapping, exploration and autonomous 3D object recognition.

Appendix A
Team members and Their Contributions

Team AutonOHM consists of several students and research assistants of the TH Nuremberg Georg Simon Ohm. The following list is in alphabetic order:

- Tim Engl — Mechanical Design
- Niklas Kohlisch — Perception, Electronic Design
- Stefan May — SLAM
- Leon Pinzner — Perception, Autonomy
- Thomas Sander — Mechanical Design
- Serge Tene Tene — Perception, Electronic Design
- Johannes Vollet — Electronic Design

Appendix B
Lists

TABLE II
SCHROEDI

Attribute	Value
Name	Schroedi
Locomotion	tracked
System Weight	77kg
Weight including transportation case	90kg
Transportation size	0.8 x 0.5 x 0.5 m
Typical operation size	1.2 x 0.5 x 0.5 m
Unpack and assembly time	15 min
Startup time (off to full operation)	10 min
Power consumption (idle/ typical/ max)	60 / 200 / 800 W
Battery endurance (idle/ normal/ heavy load)	240 / 120 / 60 min
Maximum speed (flat/ outdoor/ rubble pile)	1 / 1 / - m/s
Payload (typical, maximum)	3/ 10 kg
Arm: maximum operation height	155 cm
Arm: payload at full extend	0.5kg
Support: set of bat. chargers total weight	2.5kg
Support: set of bat. chargers power	200W (100-240V AC)
Support: Charge time batteries (80%/ 100%)	90 / 120 min
Support: Additional set of batteries weight	2kg
Cost	EUR 26,000

TABLE III
OPERATOR STATION

Attribute	Value
Name	Operator Station
System Weight	22.5kg
Weight including transportation case	22.5kg
Transportation size	0.84 x 0.47 x 0.28 m
Typical operation size	0.84 x 0.47 x 0.7 m
Unpack and assembly time	1 min
Startup time (off to full operation)	1 min
Power consumption (idle/ typical/ max)	90 / 130 / 230 W
Battery endurance (idle/ normal/ heavy load)	6 / 4 / 2 h
Cost	EUR 4,600

TABLE IV
HARDWARE COMPONENTS LIST

Part	Brand & Model	Unit Price	Num.
Drive Motors	Maxon RE40	EUR 379	4
Motor Encoder	Maxon MR 500 Ticks	EUR 92	4
Motor Gear	Maxon GP 42 C	EUR 241	4
Motor Controller	Internal Development	EUR 200	1
Flipper Motors	Maxon EC max 40 70 W	EUR 490	4
Flipper Motor Encoder	Maxon MR 512 Ticks	EUR 92	4
Flipper Motor Gear	Maxon GP 42 C	EUR 248	4
Motor Drivers	Maxon DEC 50/5	EUR 57	8
Power Supply	Internal Development	EUR 35	2
	M3-ATX-HV 6-34V DC/DC (95 W)	EUR 57	2
	Internal Development	EUR 50	1
	DCDC-NUC	EUR 59	1
Batteries	mylipo HV - Lipo 4100mAh 22,2V 6S 35C/70C	EUR 73	8
Servo Motors Chassis	Robotis Dynamixel MX28-T	EUR 175	4
Servo Motor Controller	USB2AX	EUR 34	1
Main Computing Unit	Mini-ITX PC, MSI H110I Pro, Intel i7 6700T, 16GB RAM	EUR 700	1
Additional Computing Unit	Intel NUC7i7DNKE	EUR 600	1
Micro Controller	Arduino Micro	EUR 18	1
WiFi Router	Netgear Nighthawk R7000	EUR 150	1
WiFi Bridge	Netgear N900	EUR 60	1
IMU	XSense Mti-620	EUR 780	1
	Bosch BNO055	EUR 15	1
Cameras	Orbbec Astra Stereo S	EUR 180	1
	Asus Xtion Live Pro	EUR 150	1
	Genius Widecam F100	EUR 30	1
	Logitech C920	EUR 80	1
Infrared Camera	Seek Thermal Compact-Pro FF	EUR 500	1
	Seek Thermal Compact	EUR 250	1
LRF	SICK TIM-571	EUR 2500	1
Microphone	Rode VMMICRO VideoMicro	EUR 40	1
CO_2 Sensor	DFRobot SEN0220	EUR 70	1
7-axis Robot Arm	Harmonic Drive(HD) CHA-17A-100-E	EUR 2,400	1
	HD FHA-14C-100E	EUR 1,600	2
	HD FHA-11C-100E	EUR 1,500	1
	Robotis Dynamixel XH430-V350-R	EUR 230	4
Motor Drivers	Elmo MC Gold DC Whistle	EUR 600	4
Servo Motor Drivers	USB to RS485	EUR 45	1
UPS	OpenUPS	EUR 115	1
UPS Battery	Hacker TopFuel LiPo 35C Power-X 5000mAh 4S MTAG	EUR 95	1
Battery Charger	Voltcraft V-Charge 200 Duo	EUR 80	1
Rugged Operator Laptop	Lenovo Thinkpad P52	EUR 3,500	1

TABLE V
SOFTWARE LIST

Name	Version	License	Usage
Ubuntu	18.04	open	Operation System
ROS [6]	melodic	BSD	Middle Ware
PCL [15]	1.8	BSD	ICP
OpenCV [19], [20]	3.2.0	BSD	Haar: Victim detection
OpenCV [16]	3.2.0	BSD	LBP: Hazmat detection
Qt4	4.8	GPL	GUI
ohm_tsd_slam	melodic		Multi-Robot SLAM
MoveIt!	melodic	BSD	Robot arm control
TRAC-IK	v1.4.0	BSD	Inverse kinematic

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