RoboCup Rescue 2024 Team Description Paper Hector Darmstadt

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Info

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

***Abstract*—This paper describes the approach used by Team Hector Darmstadt for participation in the 2024 RoboCup Rescue Robot League competition. Participating in the RoboCup Rescue competition since 2009, the members of Team Hector Darmstadt focus on exploration of disaster sites using autonomous Unmanned Ground Vehicles (UGVs).**

We provide an overview of the complete system used to solve the problem of reliably finding victims in harsh USAR environments. This includes hardware as well as software solutions and diverse topics like navigation, SLAM, human-robot interaction and perception. As a contribution to the RoboCup Rescue community, many parts of the used software have been released and documented as open source software for ROS.

***Index Terms*—RoboCup Rescue, Team Description Paper, Urban Search and Rescue, Autonomous Exploration.**

I. Introduction

TEAM Hector Darmstadt (Heterogeneous Cooperating Team of Robots) has been established in late 2008. The team participated in RoboCup Rescue 2009 for the first time. Focusing on autonomy for rescue robot system, the team has a history of highly successful participation in the RoboCup Rescue Robot League competition. The "Best in Class Autonomy" award was awarded to the team in the RoboCup German Open competitions from 2011-2015 and 2018-2023 and in the RoboCup world championships from 2012-2015 and 2018-2019. Furthermore, the "Best in Class Exploration" award has been achieved in 2021-2023 and the "Best in Class Dexterity" in 2021 in the RoboCup world championship. The team also demonstrated that approaches leveraging a high level of autonomy are competitive with teleoperated robots. The team scored the first place in the overall scoring at RoboCup German Open 2011-2014 and 2021-2023. Most notably, it won the world champion title at the RoboCup 2014 competition in Brazil.

Several members of the team participated in the TOTAL ARGOS Challenge as part of Team ARGONAUTS. Here, many software technologies proven in the RoboCup Rescue Robot League were adapted for use in industrial inspection [1], with Team ARGONAUTS ultimately winning the ARGOS Challenge in 2017. Another success was achieved by winning the World Robot Summit Plant Disaster Prevention Challenge in 2018.

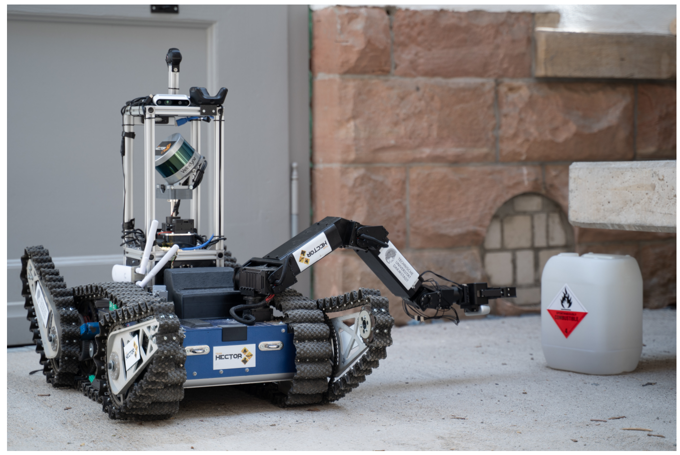


Fig. 1: Asterix rescue robot performing a visual inspection task.

Contributing to an initiative within the RoboCup Rescue community to establish an open source framework for USAR robotics [2], the team has released many of the software modules used to achieve top scores at the RoboCup competition as open source software for ROS to facilitate progress and reduce the need for re-inventing the wheel [3]. Our open-source ROS packages can be found on our Website[1] and GitHub[2].

A. Improvements over Previous Contributions

After we successfully scored the first points for autonomous dexterity in the league in 2023, we aim to improve robustness and versatility of the autonomous capability. Moreover, we plan the challenging integration with autonomous driving to be able to autonomously manipulate objects inside the arena.

Following our successful application of whole-body planning for the traversal of the highly challenging pallet hurdles and crossover ramps, we focus on improvements on robustness to make the execution more reliable. Furthermore, we want to tackle more challenging scenarios such as stairs.

Regarding the hardware, the established track design lead to several problems. The high friction caused by chain guides resulted in a high current draw of the drive motors. Furthermore,

[1] https://www.teamhector.de/open-source
[2] https://github.com/tu-darmstadt-ros-pkg

the robot occasionally lost its tracks despite the additional guides. For this year, we are working on an improved design with 3D printed treads. We expect to no longer need need chain guides while also improving lateral guidance.

B. Scientific Publications

Participating in RoboCup Rescue plays an important role in our research by 1) motivating research topics, 2) evaluating our research at the competition, and 3) creating data sets for further research. In recent years, we have released several publications with advances related to the RoboCup.

As a basis for the research and development of (autonomous) assistance functions for rescue robotics toward practical applicability, it is crucial to understand the full range of specific requirements and challenges. In [4], we present a novel, comprehensive, and evidence-driven analysis of application requirements and research challenges for (autonomous) assistance abilities derived from a novel model for an integrated function capability based on established technology acceptance models.

We developed a novel method for 3D online radiation mapping using Gaussian Process models [5]. Our proposed method was evaluated at the *ENRICH 2023* robotics hackathon, winning the award for Best Radiation Mapping.

These two publications were awarded as *Best Paper Award Finalist* at *IEEE SSRR 2023*.

We proposed a novel iterative geometric method to predict the 3D pose of mobile ground robots with active flippers [6]. A high accuracy is achieved on uneven terrain by utilizing the ability of signed distance fields to represent surfaces with sub-voxel accuracy.

We proposed a novel actionable semantic mapping and planning approach to create an actionable environment representation, which allows planning of complex behaviors in previously unknown environments [7]. The concept of affordances combined with a scene graph allows robots to autonomously explore environments while a supervisor can intervene and adapt planned tasks.

Previously, we developed a versatile grasping assistance method for supporting the robot operator while grasping arbitrary rigid objects that combines an incrementally segmented 3D truncated SDF scene model with automated grasp pose detection [8]. However, erroneous depth camera registrations can reduce the model quality drastically. To address this issue, we proposed Multi-Cam ARM-SLAM [9] that performs dense localization and mapping in the configuration space of the robot arm using multiple depth cameras while also considering motion of the robot base.

We proposed a flexible framework for virtual projections to increase operator situation awareness, based on a novel method to fuse multiple cameras mounted anywhere on the robot [10]. Moreover, we introduced a complementary approach to improve scene understanding by fusing camera images and geometric 3D Lidar data to obtain a colorized point cloud. The fused point cloud is displayed in the robotics visualization tool RViz which we extended with an overlaid QML-based operator interface[11] using the 2D human-robot-interface tools [12] we have released as open-source ROS(2) packages. The rough terrain at RoboCup Rescue induces fast roll- and pitch-motions on the robot, making state estimation a challenging problem. We propose HectorGrapher [13], a novel, time-continuous SLAM approach for robust and accurate pose estimation and mapping in real-time for challenging terrain. In our follow-up work [14] we extend SDF-based scan lidar registration for localization and navigation with radar under degraded visual conditions such as smoke or fog. For 2D SLAM in USAR environments, Hector SLAM [15] is a robust and efficient solution.

For traversing rough terrain and obstacles as commonly found in USAR scenarios, we proposed a whole-body planner for autonomous mobile ground robots [16], [17] and a highly efficient geometric pose prediction algorithm that is used to plan stability-based paths [18].

II. System Description

A. Hardware

For high mobility and dexterity combined with strong autonomous abilities, Team Hector developed Asterix, which consists of a chassis equipped with main tracks and flippers to carry the modular vision box, manipulator arm and sensor head. In the following, we briefly describe the key hardware components and sensors used for Asterix. A detailed description of the mechatronic system is available in [19].

1) Hardware Description of Asterix: Asterix (see Figure 1) is designed to carry the modular vision box developed by Team Hector which is equipped with a continuously rotating lidar, IMU, two RGB-D cameras and the omnidirectional camera. A modular pan/tilt unit with an RGB-D camera and a thermal camera provides additional sensor information.

a) Flippers: For improved mobility, Asterix has four flippers actuated by two flipper motors. To minimize the sensor shadowing caused by the flippers for autonomous operation, one pair of flippers is completely foldable.

b) Manipulator Arm: For manipulation tasks, Asterix has a *ROBOTIS Manipulator-Pro* 6-DOF manipulator arm that is compactly foldable. On top of the gripper, an RGB-D camera, thermal camera and a color camera are mounted in order to perform inspection tasks.

c) LIDAR: The vehicle is equipped with a *Velodyne VLP-16* Lidar attached to a continuously spinning mount. Using this setup, nearly complete coverage of all directions with highly accurate point cloud data is achieved.

d) Thermal Cameras: For victim and heat source detection, the robot is equipped with two *Seek Thermal Compact Pro* thermal cameras. The first one is mounted on the pan/tilt unit and the second one is integrated into the gripper.

e) RGB-D Cameras: An *Intel Realsense D435* RGB-D camera is used for object of interest and victim verification. This camera is mounted on the same pan/tilt unit as the thermal camera. Additionally, two *Intel Realsense D455* RGB-D cameras are mounted on the lidar cage to provide depth data in close proximity of the robot.

f) 360 Degree Camera: An *Insta360 Air* camera is mounted on top of the Lidar cage and is used to acquire visual information from all directions. The robot operator uses a virtual pinhole projection to navigate the robot. Additionally, a 360° panorama projection is used for situational awareness. During detection tasks, the 360-image is used to recognize objects in all directions simultaneously without the need to move a camera.

g) Inertial Measurement Unit: To measure the attitude of the platform, the vehicle is equipped with a 9-DOF inertial sensor which measures accelerations and angular rates and estimates the orientation of the sensor.

h) Wheel/Track Encoders: To measure the translational and rotational speed of the vehicle, it is equipped with encoders measuring track motion. This odometry data is used for low-level speed control.

i) GPS receiver: As the vehicle can optionally be used outdoors too, it can be equipped with a GPS receiver. The position feedback provided by the SLAM system to the map is fused with information from GNSS in this case.

j) Locomotion & Flipper movement: The tracked locomotion of the robot is controlled by a *Teensy 4.0* microcontroller, which is connected to the high-level system via rosserial. The microcontroller unit communicates with the four *Elmo Whistle* motor drivers using CAN to control the brushless AC servo motors (300 W). For controlling the position of the flippers, *CUI AMT21* absolute encoders are coupled to the flipper shafts. Damage to the transmission between motor and flippers is prevented through a slip clutch mounted on the shaft.

k) Computing: For the onboard autonomy of the robot, it has a quad-core and hexa-core Intel NUC equipped.

B. Software

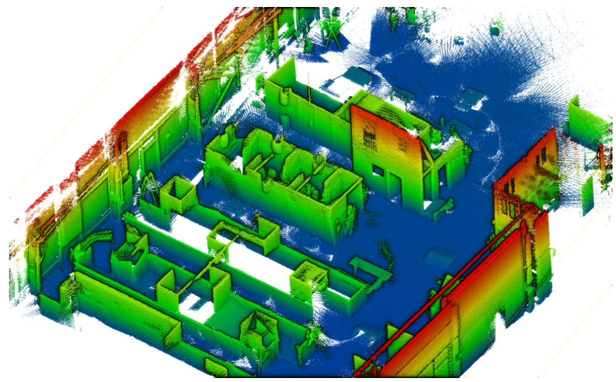
1) SLAM: The Simultaneous Localization And Mapping (SLAM) problem is solved in 3D by using a modified variant of Google Cartographer [20] with a Truncated Signed Distance Function based map representation [13][21] optimized for use with spinning LIDAR data and rough terrain locomotion. Figure 2 shows an exemplary 3D map output.

Additionally, the map is fused with color information of the 360-camera to enable a better semantic understanding of the surroundings [10] (see Figure 3).

The map can be manually or automatically annotated with information about victims and other objects of interest. It can be saved in the GeoTIFF format using the *hector_geotiff* package. This package is available and documented as open source software as part of the *hector_slam* stack for ROS, which is widely used within the RoboCup Rescue League and beyond.

2) Mapping: Based on the data from our various depth sensors, including a spinning 3D LIDAR and multiple RGB-D depth cameras, and the localization provided by our SLAM approach, multiple maps are created. A 2.5D elevation map [22] is used for visualization and input for path planning algorithms. (Image-based) detections can be associated with a 3D pose using ray-casts in a 3D map of the environment, which is generated using a modified version of the *octomap* mapping package [23]. A Signed Distance Field (SDF) [24] is used to represent the ground geometry for whole-body motion planning during locomotion.

(a)



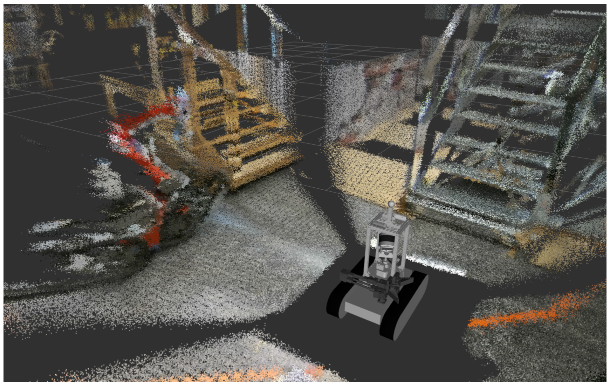
(b)

Fig. 2: 3D SLAM: (a) Top-down projection of the 3D map generated during the mapping task at RoboCup Worldwide 2021 (b) Perspective view of the same map. Note ceiling geometry has been cut from the visualization as otherwise it would obstruct the view.

3) Image Projection: We use a single 360-camera mounted at the top of the robot for operator driving camera and panorama detection camera simultaneously. By flexibly creating views on-demand [10], we use two perspective projections for forward- and backwards-driving cameras and a Mercator projection for 360° object detection (see Figure 4). The viewing direction and zoom of the frontal projection can be controlled with the joystick to simulate a pan-tilt-zoom sensor head without any moving parts or actuation latency, increasing robustness in rough terrain.

4) Victim Detection: Finding human victims under difficult conditions of unstructured post-disaster environments is one of the main goals of RoboCup Rescue. Significant progress in visual object recognition and scene understanding allows us to apply state-of-the-art computer vision methods. To tackle this problem we use a multi-cue victim detection system supporting optical image cues like RGB, thermal and depth images. This complementary information can be used to increase reliability.

Once the detector has recognized a victim or other object of interest this detection is forwarded to the *hector_object_tracker* which keeps track of known objects and updates this model based on positive and negative evidence.



(a)

(b)

Fig. 3: (a) 3D point cloud captured by the VLP-16 Lidar with fused color information from the 360 camera (b) Same scene as captured from an external camera for reference.

Fig. 4: Two fish-eye images are streamed from the omnidirectional camera (top-left), which are converted to perspective (bottom-left) and Mercator projection (right).

The separation of object detection and modeling enables the flexible integration of different sensory sources for various classes of objects. The position and pose of each object is tracked using a Kalman Filter. The *hector_object_tracker* is the only interface between perception and control, e.g. for the creation or modification of tasks or the manipulation of model state due to operator interaction.

A comprehensive overview of our approach to semantic mapping using heterogeneous sensors such as thermal and visual cameras can be found in [25].

a) Thermal- and Depth-Based Victim Detection: In addition to visual victim detection, we use a thermal and also an RGB-D camera to verify vision-based hypotheses.

In most cases, images provided by the thermal camera are very helpful for identifying possible victim locations. As a drawback of a thermal camera, the thermal images often contain not only victims but also other warm objects, such as radiators or fire, so that thermal and visual recognition systems will deliver complementary information.

To further reduce false-positives, we use point clouds from the RGB-D camera to evaluate the environment of the victim hypotheses. False-positive victim hypotheses can be identified by the shape of the environment or by missing depth measurements at the victim location.

b) Hazmat Sign Detection: Hazmat symbols give important information to first-responders regarding the dangers they are facing at a disaster site. By correctly detecting and mapping hazmat signs, first-responders can prepare for toxic chemical substances that may contaminate the mission environment. We developed a hazmat sign detection based on YOLACT [26] which is tuned and trained with the possibly encountered hazmat signs in rescue scenarios. We run the detection on a panorama projection of the 360 camera for maximum coverage of the robot's surroundings. Detections are used as input for the *hector_object_tracker* as described above for the victim detection case.

5) Navigation: To handle the challenges posed by the rough terrain in the rescue arena, the path planning algorithm uses a real-time feasible pose prediction heuristic to plan stable paths based on the predicted contact points of the robots support polygon. Whereas traditional approaches are limited to binary traversability classification or handcrafted traversability estimations to be able to compute paths in real-time, our approach takes into account both the robot using the Unified Robot Description Format (URDF) and the raw 3D structure of the ground.

Furthermore, we implement an alternative path planning algorithm based on the Legged Locomotion Libary (L3) [27]. This planner uses the ARA* algorithm on a state lattice that directly encodes the robot's motion feasibility during state generation. A 2.5D traversability map is utilized to evaluate the cost of each state transition, determined by the convex hull of connected robot footprints. Additionally, a heuristic lookup table is computed to determine the optimal orientation to overcome obstacles effectively.

A 2.5D heightmap is used to represent the ground geometry. It is generated online from lidar and depth camera data. The two RGB-D cameras mounted on the cage fill blind spots of the lidar to cover the close proximity of the robot with a high update frequency.

The planned path is executed by a blind LQR-controller, which uses a kinematic motion model to minimize the expected path tracking error [28]. The resulting velocity commands are sent to the motor controllers.

6) Motion Planning: More challenging obstacles like high steps or steep ramps might only be traversable by adjusting the robot kinematics while driving. Flipper joints can be used to keep stable contact with the ground and the manipulator arm shifts the robot's center of mass. We use an optimization-based motion planner to generate joint trajectories that enable the robot to autonomously overcome such obstacles [16], [17].

The motion plan is based on a prediction of the robot-terrain interaction with a Signed Distance Field (SDF) representation of the ground [6].

7) Manipulation: We use the manipulation framework *MoveIt* as our interface to control the manipulator arm. We efficiently solve the inverse kinematics problem by formulating it as a nonlinear-least-squares optimization problem and solving it with *Ceres*[3]. The arm can be controlled by either direct tele-operation or by planning to desired states. During tele-operation, the operator directly sets goal poses for the inverse kinematics using the gamepad. The closest solution is chosen for a smooth execution and self-collision constraints are obeyed. In a separate mode, the robot base can be moved while keeping the end-effector at a fixed position in world coordinates.

8) Object Inspection: The assistance capability for object inspection allows the robot arm to be moved automatically so the gripper's camera directly looks at a point of interest. This tool consists of two key elements: a user interface implemented as an RViz plugin and a sampling-based planning of the arm configuration.

The user interface facilitates the intuitive selection of points of interest within the 3D scene. These points are visualized as arrows, indicating both the position and orientation the robot should adopt to focus on a particular object. Setting these arrows is user-friendly, as collision checks with the perceived environment, such as point clouds, automatically position the arrow within the scene. Figure 5 depicts an illustrative representation of this interface.

Following the selection by the operator, a sampling-based planner determines a suitable pose for the robot's arm. The generated pose ensures that the camera points to the object, aligning with the given direction while also guaranteeing the absence of collisions. Additionally, the Octomap representation [23] of the environment is used to verify the visibility. Lastly, the collision-free reachability from the current to the computed arm configuration is verified.

C. Communication

An Ubiquiti UAP-AC-M UniFi[4] access point is used for high-bandwidth wireless communication. Both 2.4 GHz 802.11b/g/n or 5 GHz 802.11a/n/ac operation are possible. For distributing the network to multiple robot computers, the access points use relayd provided by the OpenWrt firmware to create a wireless bridge. The used SSID is "rrl_hector_darmstadt".

D. Human-Robot Interface

To enable seamless sliding autonomy control from pure teleoperation to full autonomy, an advanced user interface on top of existing ROS tools has been developed.

[3]https://github.com/tu-darmstadt-ros-pkg/ceres_ik_moveit_plugin
[4]https://ubntwiki.com/products/unifi/unifi_mesh

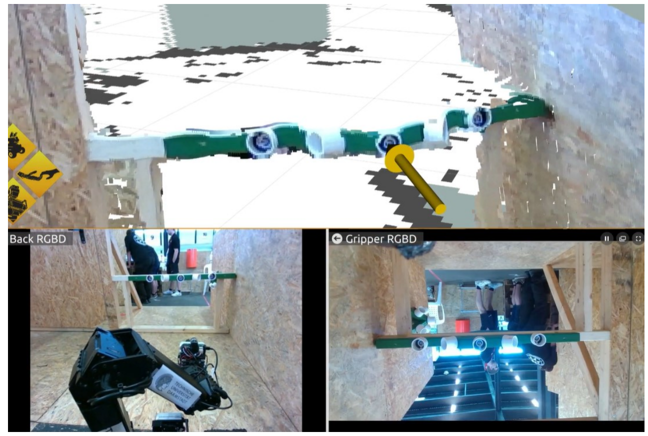


Fig. 5: Using our assistive capability for object inspection, the operator can interactively choose a point and direction to look at, indicated by the yellow arrow. The robot's arm autonomously moves into position. The resulting camera images can be seen at the bottom.

a) Mission Definition and Control: For defining autonomous or semi-autonomous behaviors, the FlexBE (Flexible Behavior Engine) approach developed within the scope of the DRC is used [29]. Using FlexBE, basic robot capabilities can be modeled via states and complex behaviors can be composed via the GUI by drag and drop. FlexBE supports selecting the desired autonomy level of the robot at runtime, making it very well suited for flexible control with an adjustable level of autonomy.

b) Monitoring and Human Supervision: As a basis for our operator interface, we use the open source robot visualization tool *RViz* which allows us to make use of the many integrated and publicly available visualizations of common robot sensor data. To augment the visualization of pre-processed 3D sensor data, we render a 2D operator interface on top of *RViz* using our open-source packages *hector_rviz_overlay*[5] and *qml_ros_plugin*[6]. The combination of the 3D visualization of the robot's world model with an overlaid 2D operator interface enables the control of the robot in a simple and intuitive fashion [11]. For the visualization and control, we use techniques from popular video games to facilitate a quick onboarding process for new operators who will find themselves familiar with the interaction design. Figure 6 shows a screen capture of this UI.

c) (Semi-)Autonomy: Autonomous and semi-autonomous behaviors can be executed using the overlaid 2D operator interface where complex actions can be hidden behind simple configurable buttons. During the execution, the interface will display the current status of the active action and allows to cancel the action at any time. These buttons can be added and modified at runtime by experts, allowing for a quick adaptation of the interface to the needs of the particular mission. Related actions can also be grouped in directories for quick access which has proven useful during stressful situations in past RoboCups.

[5]https://github.com/tu-darmstadt-ros-pkg/hector_rviz_overlay
[6]https://github.com/StefanFabian/qml_ros_plugin

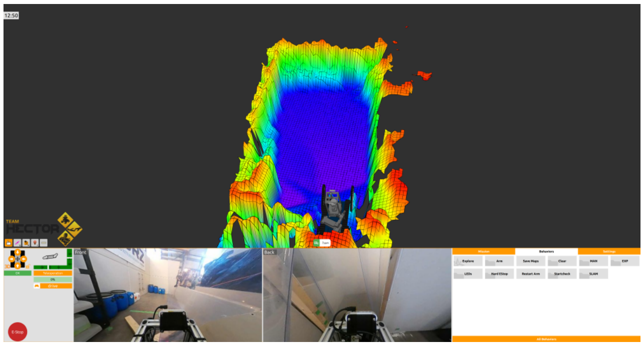


Fig. 6: Team Hector User Interface: Scene from the RoboCup German Open 2021 Finals.

d) Teleoperation: In case supervisory control is not sufficient, the robot can be fully teleoperated using a game pad. In this case, the operator uses the aggregated world model generated from sensors onboard the robot and video streams to obtain situation awareness via the user interface. Common actions can be triggered using the joystick where the operator can switch between a driving mode which controls base movement and flipper position and a manipulation mode for controlling arm and gripper. Common movements like folding/unfolding the arm or positioning the flippers for driving are easily accessible as separate behavior buttons. The motion is only executed as long as the button is pressed, so the operator is always in control. Our teleoperation software is available as open-source[7].

e) Efficient Data Transmission: In disaster scenarios, wireless connection to the robot is typically degraded by environmental factors such as thick walls or metal structures. In these situations, it is critical to establish an efficient communication channel with the robot to effectively transmit data for operation.

Situation awareness through a 3D representation of the environment is crucial for teleoperation. Elevation maps are an efficient and wide-spread representation, but the common ROS message type for elevation maps, *grid_map_msgs/GridMap*, takes up a lot of bandwidth during transmission. We developed a compression tool[8] that ensures the stable transmission under restricted network conditions. By converting the map to a JPEG image and using the ROS *compressed_image_transport* plugin, we achieve a compression rate of $< 5\%$ of the original size.

III. Application

A. Set-up and Break-Down

The standard system setup consists of one or more robots capable of autonomous or teleoperation via a laptop computer. All the control equipment easily fits into a standard backpack. The robots can be carried by two persons.

To start a mission, the robots and the laptop have to be switched on, and the operator can connect to the robots via WiFi.

[7] https://github.com/tu-darmstadt-ros-pkg/hector_teleop

[8] https://github.com/tu-darmstadt-ros-pkg/hector_grid_map_compression

B. Mission Strategy

As a focus of our research is reducing workload for operators and leveraging synergies between intelligent onboard systems and operators, pure teleoperation is only employed in case of failure of autonomous components. As during previous competition participation, autonomous operation is the desired control modality, possibly switching to a supervised autonomy mode for complex manipulation tasks that benefit from a human operator's superior cognitive and sense-making abilities.

C. Experiments

Robot systems are tested against subsets of standard NIST ASTM standard test methods that are reproduced in our lab. This includes a random maze, stairs and some of the proposed manipulation tasks. Importantly, testing of all system software components in simulation is a first class concept that is used to full extent by the team. Using the gazebo simulator, robots can be simulated within arbitrary disaster scenarios, allowing to evaluate performance and identify issues before costly and involved tests with the real system are performed. The *hector_nist_arenas_gazebo* ROS package allows the fast and user-friendly creation of simulated disaster scenarios using elements of the NIST standard test arenas for response robots. Additionally, we use the test facilities of the German Rescue Robotics Center for larger scale experiments.

D. Application in the Field

We work tightly together with first responders in various research projects to bring our work to real world application. As part of the German Rescue Robotics Center [30], we investigate the application of ground robots in scenarios for 1) fire, 2) collapse, 3) flooding and 4) CBRN accidents. In the aftermath of the 2021 European floods, two team members and a robot were deployed in Erftstadt, Germany as part of the Robotic Task Force, led by the German Rescue Robotics Center. In February 2022, a large fire in Essen, Germany destroyed 39 apartments in a large apartment building. As the building was in danger of collapsing, large parts could not be accessed by human first responders anymore. Two team members deployed a rescue robot to explore the building and create 3D maps as part of the fire investigation [31].

IV. Conclusion

In this team description paper, we provide an outlook towards the RoboCup 2024 competition. We focus on highly reliable 3D mapping, autonomous rough terrain negotiation and automated perception of objects of interest. These capabilities have been already demonstrated in previous RoboCup competitions and will be further improved for participation in RoboCup 2024.

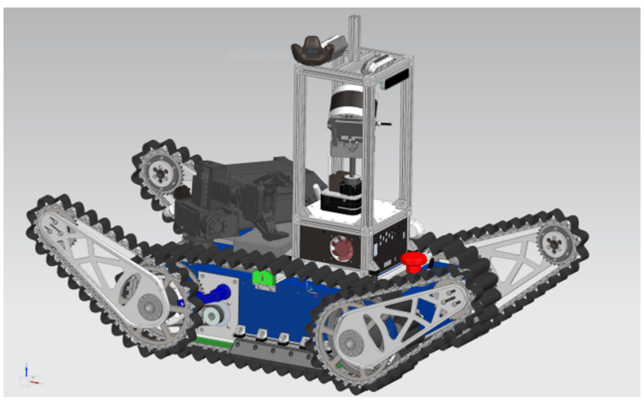
Appendix A
Team members and Their Contributions

Many students and researchers at TU Darmstadt contribute to the team. The following list is in alphabetical order:

- Frederik Bark — Semantic Perception
- Marek Daniv — Perception
- Kevin Daun — 3D SLAM
- Stefan Fabian — Navigation, User Interface
- Simon Giegerich — Navigation
- Erik Kohler — Mechanical Design
- Jonathan Lichtenfeld — SLAM, Perception
- Martin Oehler — Motion Planning, Calibration
- Aljoscha Schmidt — Manipulation
- Konstantin Stute — Motion Planning, Perception
- Jonas Süß — Mapping, Mechanical Design
- Tim Unverzagt — Software Development
- Martin Volz — Mapping, Perception
- Nathalie Woortman — Mapping

Appendix B
CAD Drawings

CAD renderings of our robot platform Asterix are provided in Figure 7.



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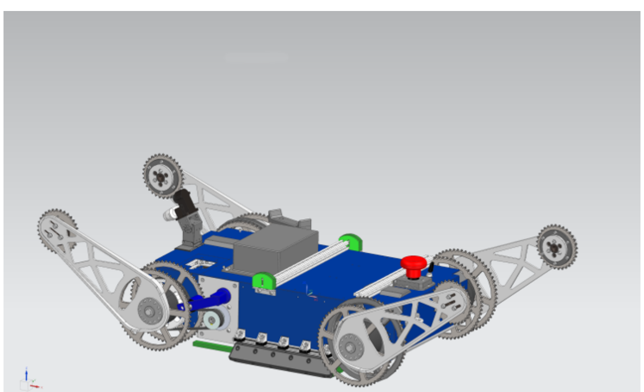

(b)

Fig. 7: CAD renderings of Asterix.

Appendix C
Lists

An overview of the used hard- and software is provided in the Tables I, II, and III.

TABLE I: Asterix UGV

Attribute	Value
Name	Asterix
Locomotion	tracked
System Weight	58kg
Weight including transportation case	63kg
Transportation size	0.9 x 0.7 x 0.8 m
Typical operation size	0.72 x 0.51 x 0.6 m
Unpack and assembly time	30 min
Startup time (off to full operation)	1 min
Power consumption (idle/ typical/ max)	100 / 300 / 2000 W
Battery endurance (idle/ normal/ heavy load)	90 / 60 / 30 min
Maximum speed (flat/ outdoor/ rubble pile)	1.2 / 0.8 / 0.5 m/s
Payload (typical, maximum)	10 / 20 kg
Arm: maximum operation height	0.85m
Arm: payload at full extend	2.0 kg
Support: set of bat. chargers total weight	4.0kg
Support: set of bat. chargers power	1,200W (90-240V AC)
Support: Charge time batteries (80%/ 100%)	30 / 40 min
Support: Additional set of batteries weight	2.6kg
Cost	30000 USD

TABLE II: Operator Station

Attribute	Value
Name	COTS Notebook
System Weight	3 kg
Weight including transportation case	3 kg
Transportation size	0.6 x 0.35 x 0.1 m
Typical operation size	0.6 x 0.35 x 0.1 m
Unpack and assembly time	1 min
Startup time (off to full operation)	1 min
Power consumption (idle/ typical/ max)	50 / 100 / 300 W
Battery endurance (idle/ normal/ heavy load)	10 / 5 / 4 h
Any other interesting attribute	Any Linux notebook can be used
Cost	2000 USD

Acknowledgment

Research presented in this paper has been supported in parts by the LOEWE initiative (Hesse, Germany) within the emergenCITY center and by Nexplore within the AICO Collaboration Lab. We thank the department of computer science at Technical University of Darmstadt for the continuous support.

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TABLE III: Software List

Name	Version	License	Usage
Ubuntu	20.04	open	OS
ROS	noetic	BSD	Middleware
PCL [32]	1.10	BSD	Pointcloud processing
OpenCV [33], [34]	4.2	BSD	Hazmat detection
MoveIt	1.1.8	BSD-3	Manipulator Motion
Ceres Solver	1.14.0	Apache 2.0	SLAM, IK

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