Development of an autonomous fire extinguishing robot

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Abstract

Robotic systems are being integrated into an ever-growing number of areas of everyday life. They offer many advantages and new possibilities. The use of robotic systems by fire brigades to fight fires at a safe distance to reduce the involved risks is also gaining more importance every year. Most systems are currently used outdoors and are largely controlled manually while maintaining line of sight. Thus, fewer firefighters have to risk their lives in dangerous operations, while they can still extinguish fires effectively. Especially in industrial environments, fires often cause severe damage and can be more dangerous due to chemicals. In this paper, a newly developed modular autonomous robot platform is presented to minimise this risks. This platform was developed to detect and extinguish incipient fires in industrial indoor environments at an early stage. For this purpose, various autonomy functions and hardware modules were developed and tested under real conditions.

1 Motivation

Established fire alarm systems provide an all-round protection for buildings, people and goods. They detect incipient fires and can also effectively extinguish dangerous fires. For the detection of incipient fires, mobile extinguishing robots can make a contribution to fire protection by extinguishing smaller fires automatically and autonomously. During exploration and equipped with early fire detection sensors, the robot is also capable to locally detect fires at their earliest stage [1].

In this paper an autonomous mobile extinguishing robot is proposed to extend existing fire detection and extinguishing systems. This robot is automatically alerted by a central fire alarm system and is sent to the location of the potential fire. It navigates autonomously to the potential fire, detects the fire and extinguishes it automatically. The extinguishing robot is also able to detect initial fires autonomously. It is equipped with sensors for this purpose and patrols autonomously through the environment to detect fires. This paper describes the development of such an extinguishing robot and its evaluation in a fire protection research center.

2 Related Work

The support of firefighters by robotic technology is the subject of current research [2]. Mobile carrier platforms that can assist in firefighting tasks are already commercially available [3][4]. In particular, heavy systems such as the LUF60 and MVF-5, which are powered by diesel engines, have been used several times by different fire departments[1]. These systems are controlled purely manually and support firefighters in fighting fires mainly in outdoor areas but also in underground garages or tunnels. Such systems are usually based on large and heavy tracked mobile platforms equipped with a fire extinguishing system. Extinguishing water is either carried along or supplied via a hose that is towed behind the platform. Autonomous mobile robots for fire detection and extinguishing are subject to active research and not yet commercially available [4]. Detection of fire and smoke using optical methods is also an active field of research [5][6][7].

3 Approach

The development of the autonomous mobile robot took place in the context of the cooperative research project A-DRZ[2] for the establishment of the German Rescue Robotics Center (DRZ[3]) funded by the German Federal Ministry of Education and Research [2].

Within the research project, the use of robot systems is examined in four reference scenarios (fire, chemical substance incidents, collapsed buildings and floods). The developed robot system focuses on the reference scenario “fire”. In particular, the early fire detection and firefighting within industrial production and storage facilities with a high footprint is considered. Typically, these are large halls with defined areas for machines, transport routes and storage areas. Special zones are also often provided for the exclusive use of AGVs[4]. It is assumed that the basic

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[1]https://www.luf60.at/wp-content/uploads/sites/62/2020/10/luf60-referenz-d.pdf
[2]Aufbau des Deutschen Rettungsrobotik-Zentrums
[3]Deutsches Rettungsrobotik Zentrum - www.rettungrobotik.de
[4]Automated Ground Vehicles

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structure of the hall will not change. However, it has to be assumed that people or other temporary obstacles (e.g. boxes, goods, other AGVs) can be within the vicinity of the robot platform while it is moving autonomously.
The aim of the newly developed AGV is to detect, report and suppress incipient fires as early as possible. Especially in industrial environments, small fires can quickly lead to dangerous reactions due to a possible high density of flammable objects or chemicals. The use of the proposed system is intended to prevent the dangers from spreading even without the use of large-scale extinguishing systems. Existing fire protection systems are not to be replaced by the mobile platform.

3.1 System design

The platform can be used in different ways depending on the environmental conditions. One possibility is the autonomous exploration of the deployment environment. Waypoints are defined in regions of interest that are examined for potential fires during regular patrols. If a fire is detected, it will be reported and extinguished autonomously. As an alternative to the reconnaissance trips, the platform can also be used as an autonomous hazard prevention system. For this purpose, the robot needs to be integrated into a central fire alarm system to be alerted in the event of a fire. The robot navigates to the reported hazardous area and attempts to localise and fight the detected fire autonomously. In addition, the system can provide alerted emergency services with important visual information about the location.
The framework conditions were elaborated with project partners and are also based on existing systems like the guidelines for AGVs as well as the modularisation concept by Fraunhofer Institute for Communication, Information Processing and Ergonomics (FKIE) [2]. The overall system design is motivated by the high requirements of the intended application scenario. When deployed, the robot has to cover large distances (approx. 500 m) within its operational environment. In order to minimise the time between the alert and arrival at the scene, the robot's drives were dimensioned for a final velocity of approx. 5 m/s. The robot can reach this top speed from a standing start within two seconds. Furthermore, the platform is equipped with extinguishing agent tanks for firefighting and several payload modules. The mobile platform has a maximum payload of 200 kg. During the design phase the firefighting capabilities were defined to be at least 21A[5]. These capabilities were evaluated in various tests inside a fire protection research center.
The developed AGV follows the concept of a modularised design. The overall system is divided into three assemblies: the mobility platform, the module carrier and several payload modules (see **Figure 1**).
All components are linked to one another via defined interfaces. The individual assemblies can be exchanged at will. In particular, the payload modules can even be ex-

[5]DIN EN 3-7 Portable fire extinguishers - Part 7: Characteristics, performance requirements and test methods; German version EN 3-7:2004+A1:2007

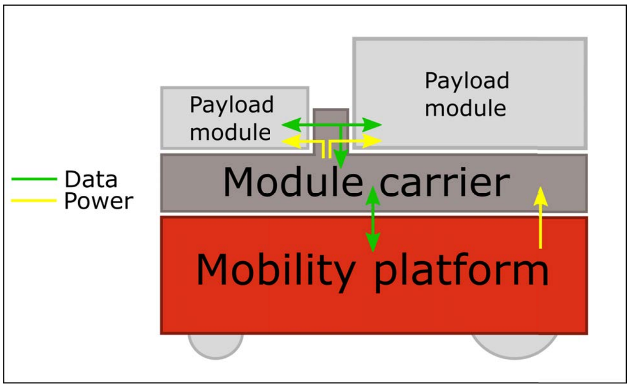

Figure 1 Schematic representation of the modularisation concept

changed during operation. This makes it possible to equip the robot with alternative sensors or actuators within a very short time. Thus, it is possible to refill or replace the extinguishing agent unit after an emergency. Due to the modular design, several payloads can be stored and used when required. The aim of this modularisation concept is to be able to make changes to existing robot systems without requiring any special prior knowledge of the robot.

3.2 Modularisation

A mobility platform represents the basis of the mobile robot. It enables the robot to move and provides energy to the module carrier and the payload modules. For data exchange, the mobility platform is connected to the module carrier via Ethernet. Sensor data is sent from the mobility platform and driving commands are received from the module carrier. The developed mobility platform uses a differential rear wheel drive in combination with free moving omniwheels on an oscillating front axle. A 16-cell LFP[6] battery pack with a capacity of 100 Ah serves as the power source. The mobility platform is controlled by a proprietary control board. In addition, the platform is equipped with a separate certified safety controller to enable safe control of the platform. The safety controller is linked to the actual robot controller and monitors the target velocity of the motors via separate safety encoders. In addition, a 2D safety LIDAR[7] has been firmly integrated into the mobility platform. This LIDAR is monitored by the safety controller and triggers an immediate emergency braking maneuver if the protective field is violated. The protective field range is adjusted depending on the velocity of the robot and, even at top speed, still has enough range to bring the robot to a standstill at a safe distance in an emergency. The maximum protective field range is 9 m while the LIDAR itself has a maximum range of 64 m with a angular range of 275 degrees. The LIDAR was mounted at a height of 200 mm. In addition to the advantages in navigation, this low height is required to reliably detect flat objects or people lying on the floor. Due to the intended use case, situations with high levels of smoke can occur. Since smoke primarily collects at the ceiling of the build-

[6]Lithium Ferrophosphate
[7]Light Detection and Ranging

ing, the low height of the LIDAR maximises the time frame during which its data can be reliably used. The use of the robot in environments that are entirely obscured by smoke is not intended, since safe autonomous navigation can no longer be guaranteed. Alternative localisation approaches (e.g. RADAR[8] or UWB[9]-ranging) were evaluated in order to estimate the position of the robot in manual operation even under thick smoke. In addition to the safety functions, the collected LIDAR data is used for simultaneous localisation and mapping (SLAM). Additional mechanisms have been implemented in the autonomy functions to avoid emergency braking.

The module carrier contains a computer for controlling the mobility platform. In addition, the module carrier manages the connected payload modules. ROS[10] messages are used to exchange information between all components.

Payload modules allow the robot to be quickly expanded with additional application-specific sensors and actuators. In addition to the corresponding payload, modules also have an integrated computing unit. This computing unit takes over the measurement of the integrated sensors and publishes the recorded data as ROS messages. Integrated actuators are also controlled with defined ROS messages.

3.3 Mission payload

For the intended application, the developed mobility platform and module carrier are equipped with an extinguishing agent payload, a firefighting monitor payload and a communication payload (see **Figure 2**).

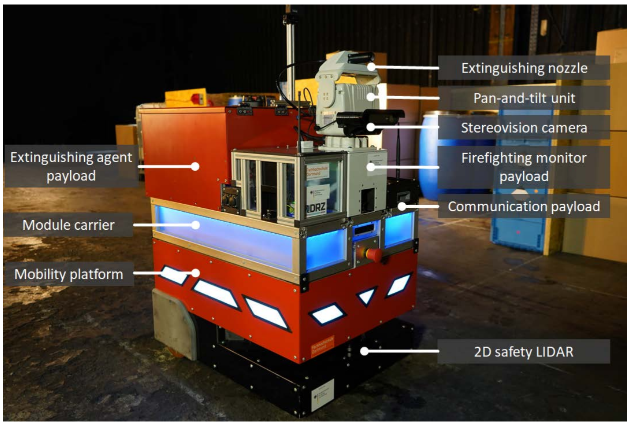

Figure 2 Mobile robot equipped with an extinguishing agent payload, a firefighting monitor payload and a communication payload.

The communication payload provides a highly reliable wireless data connection [8] to fire alarm systems or a situation awareness interface [2]. Two modules are used to extinguish fires. The extinguishing agent payload provides the extinguishing agent and regulates the control of the pressure tanks on request of the firefighting monitor payload. The firefighting monitor combines the capabilities of flame-detection and extinguishing. The robot can be alerted and sent to a fire by linking it to a fire alarm system.

The extinguishing agent payload consists of two adapted fire extinguisher tanks and a compressed nitrogen tank as propellant. In total, the payload can be equipped with 20 kg of firefighting foam and 2 kg of nitrogen. It is possible to exchange the tanks via a maintenance flap in a few simple steps. Equipped with a suitable foam, the payload is able to extinguish Class A and B fires[11]. The propellant can set each tank under pressure (1000 kPa) by individually controlled solenoid valves. Subsequently, the tanks can transfer the agent to the firefighting monitor by a second pair of individually controlled solenoid valves. The status of the solenoid valves can be adjusted and readout via defined ROS messages by an operator or other payload modules (e.g., firefighting monitor payload). The extinguishing capacity of the whole system was determined to be similar to 21A/113B in various standardised fire tests based on DIN EN 3-7.

The firefighting monitor payload combines sensors and actuators. The sensors add the capability to detect and localise flames, while the actuator controls the orientation of the extinguishing agent nozzle. The computing and communication are executed by an Nvidia Jetson Xavier NX. It is connected via an RS422 interface to a pan-and-tilt unit for aligning the extinguishing nozzle and the flame detection and localisation unit. The pan-and-tilt unit has a working range of 180° horizontally and 90° vertically. Detection and localisation are performed by a Stereolabs ZED 2 stereo vision camera. Thermal vision is not implemented due to the resulting strong increase in module costs. The nozzle is connected to the extinguishing agent module via a hose. The flames are detected and localised by the utilisation of an RGB stereo camera. The stereo camera offers good resolution in the range of centimetres in three-dimensional space within a distance of ten metres and sufficient accuracy for repositioning the robot in the decimetre range for objects up to 20 metres. The range of the firefighting nozzle and the corresponding monitor angles were determined empirically. A variety of parameters and indicators are extracted from the RGB image to indicate the presence of fire. The analysis includes static properties such as colour, brightness and size as well as steadiness in position. Based on the analysis, the detection algorithm decides if a fire is present. Furthermore, the distance of a possible fire to the robot is evaluated in respect to the range of the firefighting monitor. The monitor decides whether the fire can already be fought or the robot has to change its position to be able to start the extinguishing process. Resulting movement commands can be transmitted to the mobility platform via the module carrier.

As soon as the robot reaches the correct position, the extinguishing process begins. The process starts with an additional flame detection phase for verification purposes and a subsequent calculation of the monitor trajectory. For this purpose, calculated points along the bottom line of the fire are marked and their respective distances to the robot are

[8] Radio Detection and Ranging
[9] Ultra-wideband
[10] Robot Operating System - www.ros.org

[11] DIN EN 2 Classification of fires; German version EN 2:1992 + A1:2004

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determined. For each of these points, the corresponding pose of the firefighting monitor is calculated in order to reach the target point with the extinguishing foam. Afterwards, the extinguishing monitor moves along the different poses to extinguish the fire. If the final pose is reached, it pauses the extinguishing process. During the pause, the fire detection algorithm is carried out repeatedly and the extinguishing success is periodically confirmed for a predefined period of time. If the flames rise again, another extinguishing trajectory is calculated and processed. Eventually, the extinguishing module sends a completion message to the robot. The extinguishing process is illustrated in **Figure 3**.

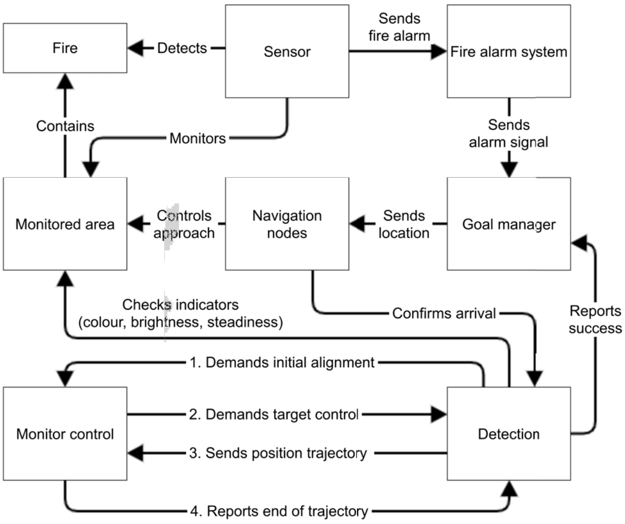

Figure 3 Concept of an autonomous firefighting operation

3.4 Autonomy functions

The foundation of the autonomy functions of the mobility platform is a LIDAR-based SLAM process. For this purpose, the data of the 2D safety LIDAR inside the mobility platform is evaluated to create a two-dimensional occupancy grid map of the environment. The software architecture (see **Figure 4**) of the developed mobile platform is based on the general ROS navigation stack[12] for map creation and navigation. The overall system is divided into several specialized nodes. These nodes are the robot control node, the SLAM node, the global path planning node, the local path planning node and the goal manager. To increase safety, the navigation stack has been expanded to include a preventive collision avoidance (PCA) node.

The controller node takes control of the mobility platform. It accepts velocity commands from other nodes in the system and converts them into corresponding drive control commands. In addition, the controller provides recorded odometry data via ROS messages. The used controller node is implemented on a self-developed microcontroller board that is connected to the module carrier (ROS master) via an Ethernet interface. The ROS version (ROS Melodic Morenia) used does not support microcontroller architectures natively.

[12]http://wiki.ros.org/navigation

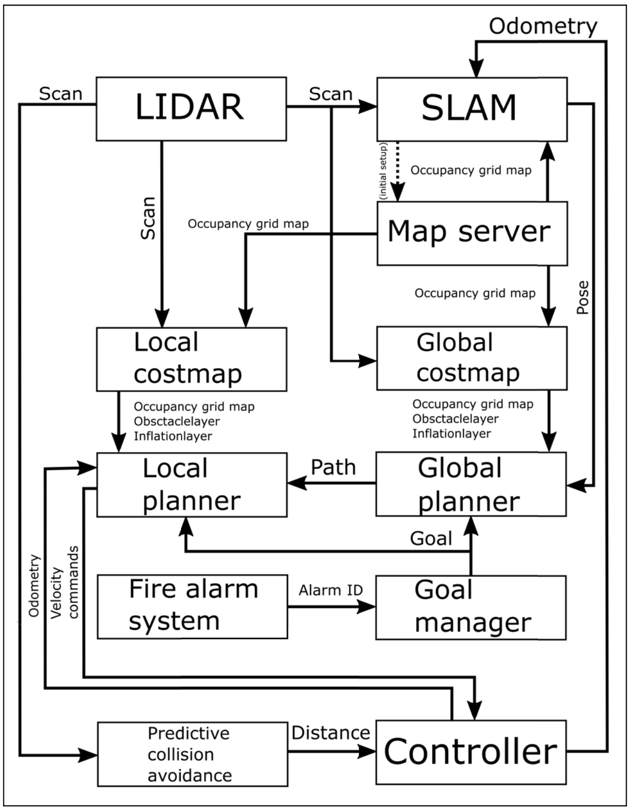

Figure 4 Overview diagram of the implemented navigation stack

For this reason, a simplified protocol[13] is used to communicate with the ROS master of the module carrier. The motor drives are connected to the control board via a CAN[14] interface. The controller node is based on a self-developed control system architecture for controlling the drive's motors. Both differential drives and Mecanum drives are supported [9].

The SLAM node is used to generate a two-dimensional environment map and to localise the mobility platform within this map. To generate this map, the data of the integrated safety LIDAR is evaluated. In the planned deployment scenario, it is intended to record a map of the environment during the initial setup of the system. Temporary obstacles are registered in a global and local costmap during use. System resources can thus be saved, since the environment does not have to be mapped continuously. Operating the system in environments with significant environmental changes can result in an unreliable localisation. In these cases, continuous mapping is a possible alternative. The used SLAM node is based on an efficient implementation of a sparse-dense mapping (SDM) framework [10] to generate maps of the environment and a scan-matching algorithm [11] for localisation within a given map. The initially recorded map of the area is made available via a map server and used as the basis for localisation via scan matching.

The global planner node[15] is responsible for calculating a

[13]http://wiki.ros.org/rosserial
[14]Controller Area Network
[15]http://wiki.ros.org/global_planner

path within the entire environment map from the robots position to a given destination. To generate a valid plan, the occupancy grid map provided by the map server (or SLAM node) and an overlaid global costmap is used. The global costmap basically corresponds to the original environment map and assigns a defined cost factor to each cell of the occupancy grid map. These costs correspond to the probability of an obstacle at the given position. If a cell is marked as occupied, that cell is assigned the maximum cost and bypassed when planning a feasible path. Additional layers are overlaid on the global costmap data to ensure that the physical dimensions of the mobility platform and those of unknown possible obstacles are taken into account when planning a path. The obstacle layer uses the LIDAR data to capture deviations of the captured data from the initial map of the environment (see **Figure 5**). Obstacles are determined using ray tracing and noted on the costmap with the maximum costs. Thus, in addition to changes in the environment, temporary obstacles are also taken into account when planning the path. The inflation layer distributes the cost of a cell to its neighboring cells within the costmap. The maximum radius and scaling factor of this distribution can be adjusted. This ensures that the cost of crossing a cell with the robot footprint increases the closer the robot is to an obstacle. When configuring the parameters, the maximum rotation radius of the mobility platform was taken into account. The path planner considers the cost of the cells within the global costmap during path planning. Configuring the additional layers of the costmap ensures that the robot can reach a goal without colliding with any obstacles. As soon as a goal is set by the goal manager node, the global planner node calculates a path from the current robot position to the goal. Since the costmap is continuously updated during the navigation, it can be recognised if an originally valid path cannot be traveled due to a new obstacle. If the robot is unable to navigate around an obstacle without straying too far from the calculated path, the current plan is discarded and a new plan is determined. If no valid plan can be determined for the current situation, the navigation will be aborted for safety reasons.

The local planner[16] is responsible for local path planning. In this case, a new local path is determined on the basis of the determined global path and the local environment of the mobility platform. This path is then followed by the mobility platform. In order to achieve this, the local planner sends driving commands to the controller of the mobility platform. Similar to the global planner, the local path is determined using a local costmap. This is based on a smaller section of the known occupancy grid map of the area, centered at the mobility platform's center of rotation and is also overlaid with an obstacle and inflation layer. In addition to the local costmap, the system parameters of the mobility platform are also known. This involves the type of drive, the physical dimensions of the mobility platform and the maximum velocity and acceleration values. Thus, the node is able to plan the most time efficient path while controlling the platform safely around all obstacles. The odometry data of the controller is used

[16]http://wiki.ros.org/teb_local_planner

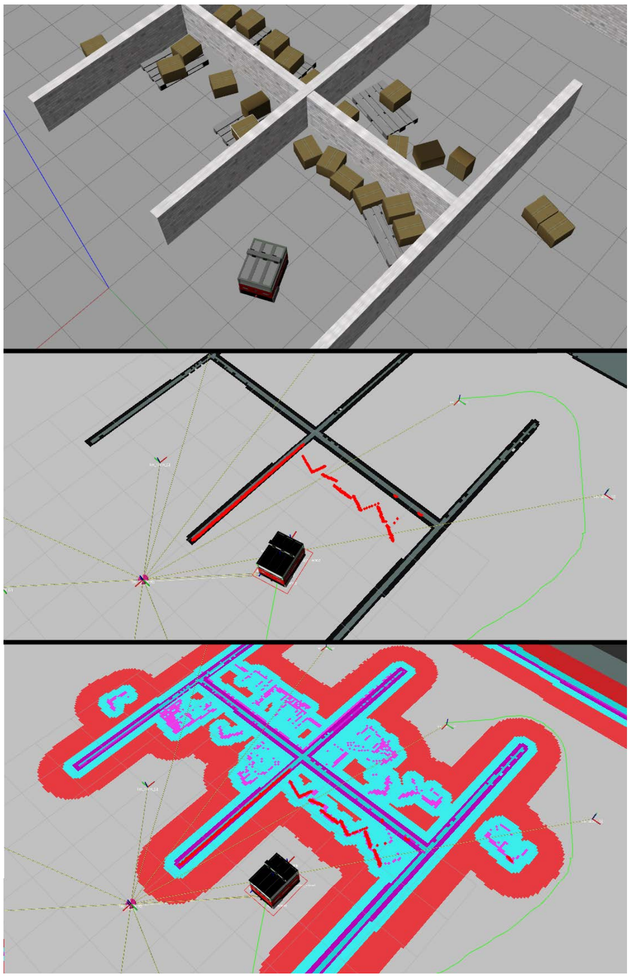

Figure 5 Simulated environment (top), occupancy grid map (center) and global costmap (bottom)

as additional feedback during navigation. The node can thus register whether the robot was able to successfully implement the transmitted driving commands and can make appropriate corrections if necessary. This is of particular value because the robot throttles its maximum velocity due to the received predictive collision avoidance data. During the navigation, the local costmap and the local path are constantly updated. If the local planner is unable to calculate a valid path within the local costmap, the navigation is aborted and a new global plan is requested from the global planner.

The goal manager is linked to the local fire alarm system and manages the goals of the mobility platform in case of an alarm. The fire alarm system is connected to various fire detectors. These fire detectors are installed within the operational environment and monitor regions of interest. The positions of these fire detectors are known to the goal manager and are referenced to the origin of the environment map. Each fire detector is assigned an appropriate target pose of the mobility platform. At this target pose, the mobility platform is at a safe distance from a possible hazard and is able to get an overview of the surroundings via an equipped fire detection payload module.

If a fire detector is triggered, the fire alarm system reports the corresponding detector ID and the goal manager starts

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the navigation to the preset destination by transmitting the corresponding goal to the planners. If several detectors are triggered, they are processed in the order in which they were reported. When a reported target is reached, the goal manager waits for clearance from an operator or the equipped firefighting monitor payload module. If a fire location is outside the reach of the firefighting monitor payload module after it reached its destination, it is possible to define new sub goals using payload modules or operators in order to approach the hazardous area. If no fire was detected at the destination, the firefighting monitor payload module notifies the goal manager which in turn transmits the next destination to the path planner. If there is no further destination in the queue, the home position of the mobility platform is approached and the robot switches to an idle state until the next alarm.

The predictive collision avoidance node is an additional security measure of the mobility platform. During the autonomous or manual operation of the platform, collisions and heavy braking maneuvers should be avoided to protect people and property. For this purpose, a node was developed that observes the robot's environment and, taking the robot parameters into account, determines the distance to the nearest obstacle (see **Figure 6**).

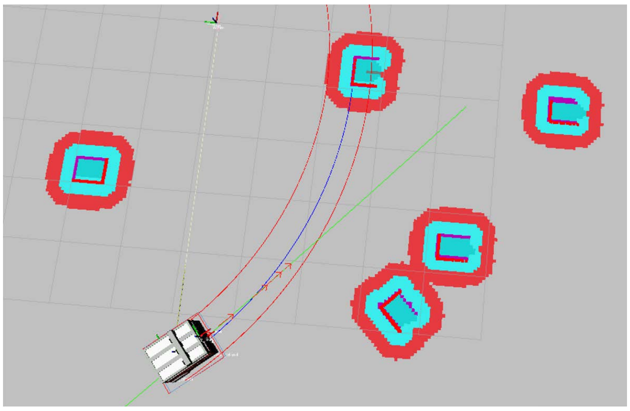

Figure 6 Predictive Collision Avoidance (PCA). Predicted search area (red) and minimal distance to possible collision (blue)

In addition to the LIDAR data, the current velocity, direction of travel and the dimensions of the mobility platform are included in the determination of relevant obstacles. The current trajectory of the mobility platform is determined via the current velocity and direction of travel. The curvature of the search area is defined via the calculated trajectory while the width is based on the robot dimensions and can be configured if necessary. During the search for an obstacle, only laser trajectories within the search area are considered. If there is an obstacle within the search area, the shortest distance between the mobility platform and the obstacle is calculated, taking the curvature of the search area into account. Due to the path geometry and the LIDAR position, parts of the search area may be shadowed due to objects outside the search area. In this case, the lowest visual range is assumed to be the minimum safe distance. This distance is then transferred to the controller. Based on this value, the allowed maximum velocity of the mobility platform is reduced. By reducing the velocity, the protective field size of the safety LIDAR can also be reduced via the active protective field adjustment of the safety controller. The goal here is to ensure the safety of the system while maximising the velocity while driving.

4 Experimental evaluation

The capabilities of the developed robot system and the equipped payload modules are regularly tested under real conditions within several test setups. The focus in these experiments was on the essential capabilities of the system, such as navigation, localisation, collision avoidance, communication between the robot and the fire alarm system, error-free detection of flames as well as precise localisation and successful extinguishing of fire sources. Therefore, a reproducible, realistic and changeable test environment was developed.

For each setup, two rectangular shaped rooms were built. In each room, different objects (e.g., plastic barrels or cardboard boxes) and a fire pan filled with flammable liquid as a fire source were randomly placed. Each room has a flame detector linked to a fire alarm system and an entrance position known to the robot. One such configuration can be seen in **Figure 7**. The robot is aware of the map of the entire scenario. The robot's starting position is randomly determined in the test hall.

Figure 7 Experimental test setup for autonomous fire extinguishing

The fire pan is ignited in a randomly selected room. The fire event is immediately detected by the built-in flame detectors and forwarded to the fire alarm system. The system transmits the corresponding identification number of the triggered flame detector to the robot, which navigates along the optimal route to the associated room entrance. Once on site, the corresponding room is scanned by the firefighting monitor. The fire is detected, localised and extinguished eventually. After extinguishing, the firefighting monitor waits for validation by the flame detectors of the fire alarm system and reports the extinguishing success to the mobility platform.

During the execution, obstacles unknown to the robot are placed in the approach path or previously possible paths are completely blocked. The position of the fire is changed in each run and switched between rooms.

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Figure 8 shows a few excerpts from the autonomous firefighting tests[17] and the tests for the robot's extinguishing capacity.

Figure 8 The developed robot platform during autonomy tests (left) and evaluation of extinguishing capacity similar to DIN EN 3-7 (right)

5 Conclusion

The developed system was able to successfully complete the test scenarios. The alarming by the fire alarm system as well as the navigation to the corresponding rooms took place without errors. On the approach, unknown obstacles were avoided without collision and blocked routes were recalculated in real time. The fire detection algorithm reliably detected and localised the fires. Due to the precise localisation and correct trajectory calculation, the extinguishing process was completed successfully at all time. In addition, the communication and coordination between the systems worked flawlessly. The extinguishing process started when the robot came to a standstill and the robot started the return journey to its home position after the reported extinguishing success. The tests were successfully repeated several times in different setups. The system described in this paper shows that an autonomous mobile robot platform is a useful addition to established extinguishing systems. The presented autonomous robot makes it possible to detect and fight locally limited and smaller fires successfully.

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