Autonomous mobile robot search strategy for automated compressed air leakage detection

Philipp Richard [1], Satyam Uttamkumar Dudhagara [2], Leonhard Kunz [3], Christiane Ploсiennik[4], and Martin Ruskowski [5]

Abstract: Compressed air is an important work medium for transfer of energy in many industrial processes. The inefficient physical processes used to produce it make compressed air one of the most expensive energy sources in supply systems. Even small leakages can over time result in high energy losses and costs if not detected and fixed timely. In addition, finding leakages in such systems is very time-consuming and expensive as the whole network of pipes must be examined to localize defects. This paper presents the concept of a targeted detection approach for effectively detecting and locating Compressed Air Leakages semi-autonomously through the usage of an Autonomous Mobile Robot as a mobile sensor. It describes how the detection process in an unknown environment can be rapidly accelerated by constraining the search space for the detection of leakages. The process utilizes expert knowledge, object detection and scene interpretation techniques to constrain the search space. The results obtained are integrated into an existing map of the environment and enable targeted repair actions. The evaluation includes an analysis of the individual phases of the approach, proposes further evaluation scenarios, and compares the efficiency of the approach with conventional manual leakage detection.

Keywords: Autonomous Mobile Robot, Compressed Air Leakage Detection, Search Strategy, Object Recognition, Resource efficiency

1 Introduction

Over the last decade, economic, financial, and ecological factors have grown in importance due to the increased urgency in climate action, exerting a significant impact on the industry's evolution. This influence becomes particularly visible when poor environmental performance results in financial penalties. Moreover, the external image and social factor have become more important in the age of social media, especially in relation to economic aspects and carbon emissions. In addition, rising energy prices are themselves a major factor increasing energy efficiency. In response to these challenges, businesses are currently

[1] Technologie-Initiative SmartFactory KL e. V., Trippstadter Str. 122, Kaiserslautern, 67663, Germany, philipp.richard@smartfactory.de, https://orcid.org/0000-0002-5673-4105

[2] Technologie-Initiative SmartFactory KL e. V., Trippstadter Str. 122, Kaiserslautern, 67663, Germany, satyam.dudhagara@smartfactory.de, https://orcid.org/0009-0006-8320-9521

[3] German Research Center for Artificial Intelligence GmbH (DFKI) , IFS, Trippstadter Str. 122, Kaiserslautern, 67663, Germany, leonhard.kunz@dfki.de, https://orcid.org/0000-0002-5175-7906

[4] German Research Center for Artificial Intelligence GmbH (DFKI) , IFS, Trippstadter Str. 122, Kaiserslautern, 67663, Germany, christiane.plociennik@dfki.de

[5] German Research Center for Artificial Intelligence GmbH (DFKI) , IFS, Trippstadter Str. 122, Kaiserslautern, 67663, Germany, martin.ruskowski@dfki.de, https://orcid.org/0000-0002-6534-9057

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exploring methods to increase the effectiveness and sustainability of their production processes. There are many ways to achieve such goals, such as optimizing the use of energy and taking a proactive approach to reducing the need for energy. In addition, identifying inefficient areas and eliminating energy losses, such as those caused by heat transfer from walls, could be alternative strategies. In the industry, Compressed Air Systems (CAS) are essential systems that are used for numerous purposes due to its wide range of applications. The production and use of compressed air is associated with high energy costs, as its production is related to high heat losses, which makes it one of the most expensive forms of energy in production. Studies have shown that compressed air systems can account for up to 10% of total industrial electricity consumption. In addition, leaks in these systems can result in significant energy losses; for example, a single 1 mm hole can result in an energy loss of approximately 3.3 kWh per year, costing approximately $230 annually. Depending on the length, components and environmental conditions of the air system, there can be a high number of leaks that can quickly add up to energy loss and cost. [KÇÖ21]. Despite the high cost and significant energy consumption rate, Compressed Air Leakages (CAL) remain a widespread and often underestimated problem, that leads to significant energy losses and therefore substantial financial losses [DW18]. The costs here sum up the longer a leakage remains undetected. However, identifying and eliminating these leakages is a time-consuming and costly task due to the complex installation of CAS in production halls. Conventional leakage detection methods often require manual inspections by specialist personnel.

Our paper presents a semi-autonomous robot equipped with specialized sensors to detect CAL in factories. This solution provides efficient and accurate detection of leakages that can potentially lead to significant energy savings. The robot autonomously maps its unknown environment and detects leakages. The search space is constrained using expert knowledge about the placement of pipes, generators and compressed air consumers, as well as optical object recognition and semantic information about its environment. Identified leakages are recorded and provided to a central energy management platform for evaluation and further maintenance actions.

2 Related Work

Today, the industrial standard for detecting CAL relies on manual search methods, typically conducted by specialized companies. These methods involve using handheld devices equipped with ultrasonic sensors to detect high-frequency sounds emitted by escaping air, allowing operators to localize the source of leakages precisely [SG98],[EM12]. While manual techniques offer immediate feedback and high precision, they can be labor-intensive and are prone to human error. To address these challenges, robotic search approaches are being explored. Robots have a wide range of applications, from industrial inspection to human rescue, demonstrating their potential to complement or replace human labor in hazardous or inaccessible environments [WSB19]. Robots are increasingly being used in hazardous environments where human intervention can be risky. These include, for example, detecting sources of gas and odors or the clearance of minefield [Ge97]. Various technological innovations, from visual to sensor-based solutions, have enhanced detection capabilities across different settings. For instance, [Is06] employed Complementary Metal Oxide Semiconductor (CMOS) cameras and gas sensors to detect gas emissions, while [Ma14] integrated Simultaneous Localization and Mapping (SLAM) with gas concentration measurements for indoor gas leakage detection. Light Detection and Ranging (LiDAR)-equipped robots have been used for locating gas leakages along predefined routes [Br20], and patrol robots with high-resolution cameras facilitated remote inspection of gas leakages [YE22]. Other developments address chemical detection and environmental monitoring [Go04]. In the context of compressed air leakage detection, autonomous robotic systems using thermal imaging cameras have been developed for pipeline inspection in thermal power plants [Ib13]. Notably, the AirleakSlam system utilizes SLAM and ultrasonic microphones on robots to precisely locate CAL in three dimensions, offering a proactive approach to leakage detection that can result in significant energy savings [SDS19]. Furthermore, [WCM13] highlights the importance of using different leakage detection methods to effectively identify different sizes. They suggest using pressure-based methods for detecting large leakages quickly and specialized hardware for smaller leakages, even if it requires more time. Combining these methods optimizes leakage detection across a range of sizes, enhancing overall efficiency in leakage management. Detecting and localizing CAL is challenging due to their occurrence in diverse industrial environments, from large production facilities to confined spaces within machinery or infrastructure. [SDS19] highlighted the significance of implementing an efficient robotic search strategy integrating multiple sensors like LiDAR and ultrasonic devices to thoroughly scan confined spaces and accurately identify leakages. The systematic use of robots promises to improve maintenance efficiency on factory floors, underscoring the central role of robotics in modern industrial diagnostics.

3 Search Strategy Approach

To address the challenge of effectiveness and efficiency in compressed air leakage detection, we propose a industrial cost-effective novel approach employing an Autonomous Mobile Robot (AMR) equipped with a suite of sensors. This approach integrates robotics, AI, and sensor technology to automate leakage detection and localization. The AMR, equipped with omnidirectional wheels and navigation algorithms, systematically traverses the environment, gathering sensor data to identify leakages efficiently. The Sensor Suite includes customized ultrasound sensors, LiDAR, and stereo cameras to gather specific data for leakage detection purposes. Additionally, a local expert provides environmental insights or access to piping diagrams, enhancing the accuracy of the detection process. Based on the Automated Leakage Finder (ALF) AMR we have a newly formulated search strategy, which is schematically illustrated in Figure 1 for a single ’search cycle’. The strategy includes systematic navigation based on expert knowledge, the detection of leakage signals in the environment using the sensors and an evaluation logic for the precise localization and identification of leakages. The 'search cycle' can be structured into five phases, which are explained below:

1. **Mapping Phase:** First, the AMR needs a model of the environment in which it can effectively navigate and search for leaks. A current floor plan model, e.g. a building information model, can serve as a basis for this. In addition, the AMR can also independently explore the environment and collect data from the sensors on board to create a comprehensive map itself. This map not only serves as a guide for the subsequent phases, but also enables the thorough exploration of previously unknown, changing or unexplored areas.
2. **Mission Planning Phase:** Once an environment model has been provided or created, the expert can use their knowledge about the compressed air system to prioritize areas for inspection. These areas are selected based on factors such as the probability of containing CAL and the importance of certain sections of the environment. Through strategic deployment planning, resources are allocated efficiently and the effectiveness of the leakage detection process is maximized.
3. **Detection Phase:** After completion of the search setup, the AMR now navigates autonomously and systematically explores the defined areas of interest. The Sensor Suite records sensor data and stores it separately for further analysis to ensure that are potential CAL is recognized.
4. **Localization and Measurement Phase:** Following the detection phase, the AMR carefully analyses the collected data to determine the exact location of the detected

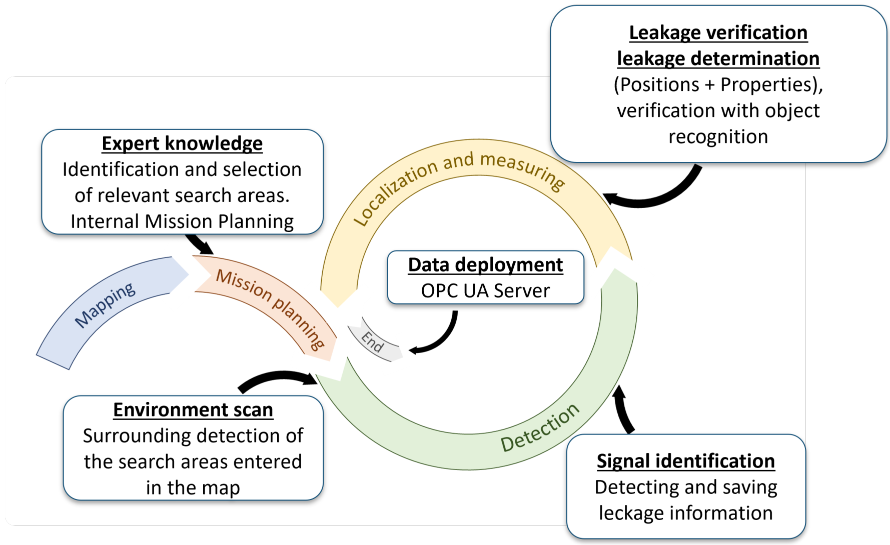

Fig. 1: Search Strategy

leakages. This process involves a comprehensive review, value mapping and leakage determination. During this process, various data sources, such as the position of the robot within the map, the orientation of the sensor suite, measurement values and environmental conditions, are included to filter out outliers and environmental noise.

5. **Data Deployment Phase:** Once leakage have been successfully identified and verified, the information can be integrated into the environment model. The analyzed leakage information can be provided via industry-standard communication and transferred to an energy management platform.

Throughout the process, the search strategy remains flexible and allows for iterative exploration and data collection as required. If necessary, the AMR can repeat the environmental search phase to collect additional data for further analysis. Alternatively, the search can be terminated when a representative report of all potential CAL in the environment is available. This scan cycle can be performed multiple times for environments of interest.

4 Automated Leakage Finder (ALF)

In this chapter, we explain how we have integrated the search strategy into our specific AMR called Automated Leakage Finder (ALF). The following sub-chapters are structured according to the phases of the search cycle (Sec. 3) and each describes the specific techniques and particular features.

4.1 Mapping

To gain a thorough understanding of the environment, SLAM (Simultaneous Localization and Mapping) implementation is crucial. Various techniques, including LiDAR- , RGB-D-, graph-based-, and feature-based SLAM, are available for mapping in robotics. LiDAR SLAM creates 3D maps, RGB-D SLAM combines color and depth data, graph-based SLAM represents the environment as a graph, and feature-based SLAM detects visual features. Visual SLAM, chosen for its cost-effectiveness, robustness in diverse environments, and non-intrusiveness, utilizes off-the-shelf cameras [Ch22]. We implemented a Robot Operating System - Version 2 (ROS2)[6]-based visual 2D-SLAM solution using the SLAM Toolbox[7] to generate a global map with inflated boundaries, preventing collisions. Alternatively, locally provided maps can be integrated into the robot's navigation system after conversion to a compatible 2D format. Assigning a world frame to the environment facilitates navigation in subsequent phases and serves as a reference for leakage localization.

[6] Robot Operating System (ROS), https://www.ros.org/, Accessed on July 18, 2024.
[7] Slam Toolbox, https://github.com/SteveMacenski/slam_toolbox, Accessed on July 18, 2024.

4.2 Mission Planning

This stage comprises two sub-stages: leveraging expert knowledge to identify high-priority areas and devising an efficient coverage path. RViz[8], a user-friendly interface, allows experts to mark areas of interest on a generated map using the Nav2[9] AMR navigation stack as can be seen in Fig. 2. A custom RViz panel enables experts to input location coordinates as polygon corners, visualizing these areas on the map. The panel also initiates mission planning by publishing a '/clicked_point' topic onto marked polygons, signaling exploration commencement. This integration facilitates site identification and mission planning, utilizing expert knowledge through a user-friendly RViz interface. After initiating mission planning, an efficient coverage path planner or sweeping path planner is utilized to generate paths for designated polygons. Adapted from the 'Grid based coverage path planner[10]', this process calculates optimal paths within each polygon, ensuring comprehensive coverage while minimizing unnecessary movement. Prioritizing paths along the longest edge of each polygon reduces turns, conserving energy and time. Once exploration in a polygon is complete, the planner selects the next closest polygon, ensuring systematic coverage. Generated paths are broken into waypoints spaced according to sensor reach, guiding the robot through designated areas. This integrated approach optimizes resource utilization and maximizes coverage, enhancing leakage exploration effectiveness and efficiency.

4.3 Detection

During the detection phase, a special waypoint publisher acts as the initiator, publishing predefined waypoints planned by the coverage path planner as goals to the robot's navigation system, which is integrated with the Nav2 stack. As these waypoints are published, they guide the robot through the designated regions of interest. Once the robot reaches a designated waypoint, it executes a scan cycle as a ROS2 *action* using the 'perform action at waypoint' feature of the Nav2 stack to identify potential leakages in the environment. Equipped with ultrasound sensors on a pan and tilt system, the robot examines the environment for readings surpassing predefined thresholds, indicative of potential leakages. The sensor suite collects important data, including signal strength, which allows conclusions to be drawn about the size of the leak, LiDAR distance measurements to the leakage and visual data from onboard cameras. These data sources offer a multifaceted perspective of the surroundings, facilitating comprehensive leakage detection. The gathered data is vital for identifying and locating possible leakages accurately. To achieve comprehensive coverage, sensors are strategically placed on a pan-tilt turret, allowing the robot to systematically scan its surroundings. At each waypoint, the robot conducts multiple scan cycles, covering the entire 360-degree range. This meticulous process ensures thorough exploration and detection of any anomalies.

[8] Rviz, https://github.com/ros-visualization/rviz, Accessd on July 18, 2024.

[9] Nav2, https://navigation.ros.org/, Accessed on July 18, 2024

[10] PythonRobotics, https://github.com/AtsushiSakai/PythonRobotics?tab=readme-ov-file#grid-based-coverage-path-planning, Accessed on July 18, 2024

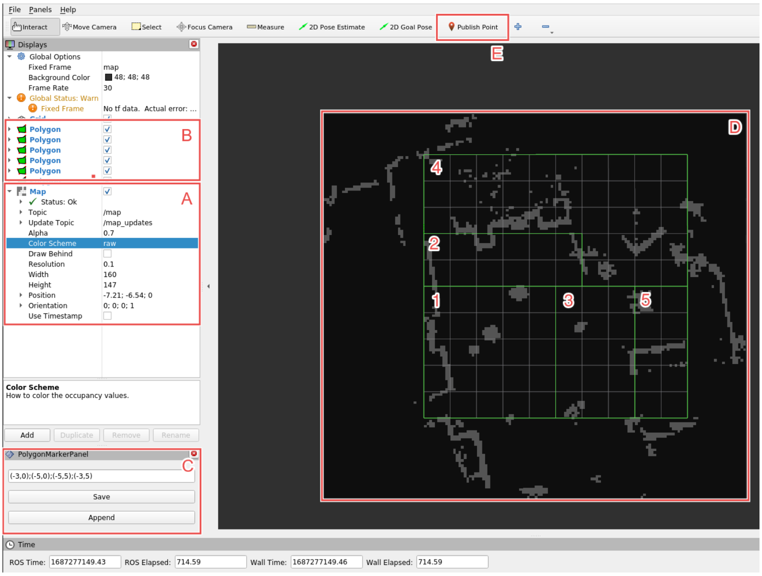

Fig. 2: User interface for the introduction of expert knowledge and the individual selection of areas of interest for leak detection. A) Map topic; B) Polygon topics; C) Polygon marking panel; D) Map with designated polygons in green; E) Publish point feature to assign initial search polygon

4.4 Localization and Measurement

In this phase, collected leakage data undergoes comprehensive processing. Outliers are identified and removed, while information from multiple waypoints regarding the same leakage is consolidated. To precisely identify the source of each leakage, objects are detected in images using a pre-trained 'you only look once' version 4 (YOLO v4[11]) deep learning network. While the involvement of worker expertise, in the mission planning step constrains the overall search space, the search space at each stopping point includes still a 360° x 180° spherical scan of the robot's surrounding. Since the directional microphone as main sensor to detect leakages needs a narrow focus point to distinguish sounds from larger distances, cameras offer a much faster wide-angle scan of the complete environment at a stopping point. A spatial localization of the components belonging to the compressed air system, and specifically weak points like pipe junctions, can significantly restrict the scanning area at a stopping point of the robot. Thus, the scanning time can again be reduced significantly through a restriction of the search space. The angular location of potential leakages relative to the robot's position is determined through the orientation of the turret and the robot itself. By precisely tracking the orientation of both the turret and the robot, the system can accurately ascertain the angular position of any detected anomalies. This spatial information along with the robot's world pose is instrumental in localizing potential leakages within

[11] YOLOv4, https://arxiv.org/abs/2004.10934, Accessed on July 18, 2024.

Fig. 3: Concept of our AMR - ALF

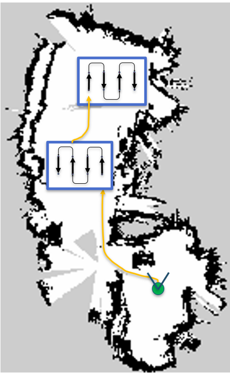

Fig. 4: Map with Search Polygons

the environment. The compiled information includes 3D coordinates of potential leakages within the global map's frame, along with their corresponding properties.

4.5 Data Deployment

The final phase involves transmitting leakage information using an Open Platform Communications Unified Architecture (OPC-UA) server, a preferred industrial communication protocol. This ensures seamless transfer of data from the AMR to any necessary destination. Upon reviewing the results, the search cycle can be concluded. However, if further exploration is required, the process can be repeated with adjusted sector priorities, maintaining efficiency while adapting to evolving requirements.

5 Experiment and Evaluation

To evaluate the effectiveness and performance of our ALF system, we conducted a standard test of the implementation of the concept in controlled environments within the Energy technologies and applications in production (ETA) Lab[12]. The ETA Lab resembles a typical factory floor layout. It consisted of various structures such as pipes, machinery, and tools where CAL may occur. The standard experiment was designed to assess ALF's ability to search and scan for leakages in mapped environments and thus its ability to follow the desired path and cover all regions of interest. The focus for the evaluation criteria should be the system's effectiveness in terms of both accuracy and speed in identifying leakages within the specified environment.

[12] TU Darmstadt ETA Lab, https://www.ptw.tu-darmstadt.de/eta-fabrik/startseite/index.de.jsp, Accessed on July 18, 2024.

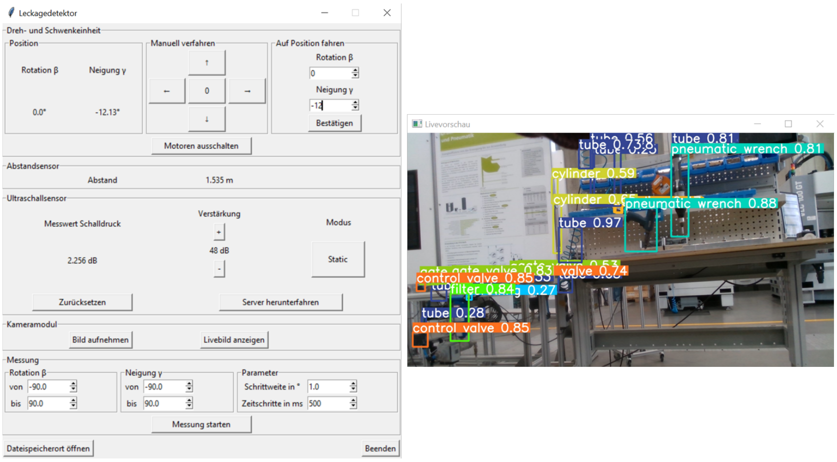

Fig. 5: Graphical User Interface (GUI) to perform a manual scan cycle with detected and identified potential sources of leakage

5.1 Components Test

In our testing setup, the cornerstone is the AMR Robotino® 4.0, a versatile platform from Festo Didactic known for its adaptability and robustness. Its omnidirectional wheels, powered by Dunkermotoren motors and encoders, ensure agile and precise movement crucial for navigation. Integrated with an Intel RealSense D435i stereo-depth camera, it enables visual SLAM implementation. This AMR serves as the backbone of our solution, enabling efficient navigation and inspection tasks. We enhance its capabilities with advanced sensors like Remote Sensory Check ultrasound sensor, TeraRanger Evo 60m LiDAR, and a Delock USB 2.0 IR camera for visual data. These sensors, along with the IMU, encoders, and communication modules, augment perception and enable data fusion with external systems. Strategically affixed via a pan-and-tilt turret mechanism, these sensors provide comprehensive coverage and multi-modal sensing capabilities, as illustrated in Fig. 3. This integrated setup forms a robust testing framework for evaluating our robotic system's performance in mapping, localization, and leakage detection tasks.

5.2 Testing and Evaluation

In our experiment, we aimed to assess the capabilities of our robotic system in mapping, localization, and sweep path planning for efficient navigation and inspection tasks. Initially, we focused on the mapping phase, where we employed the RealSense Camera equipped with point cloud functionality to capture detailed spatial data of the environment. Through the utilization of RViz, a robust visualization tool, we monitored and analyzed Robotino's autonomous exploration and mapping activities. With the mapping completed, we transitioned to the localization phase, where precise localization of Robotino within the mapped environment was achieved. Subsequently, we launched the localization modules to validate Robotino's ability to determine its position accurately. Moving forward, in the sweep path planning phase, we utilized predefined polygons from the local expert to plan optimal paths for Robotino to traverse and inspect specific areas within the environment as represented in Fig. 4. By employing a sweep path planner, we generated efficient paths that covered the designated sectors effectively. The execution of the experiment confirmed the system's ability to navigate and inspect the environment comprehensively. Our experiment yielded valuable insights into the resilience and effectiveness of our robotic system for mapping, localization, and sweep path planning in unexplored areas. To test the detection and identification of leakages, an isolated test for only the sensor suite was done. Using a custom python based GUI tool a manual scan by controlling the pan and tilt turret over a 2D area in front of it. The ultrasonic sensor, camera and LiDAR gather important information from the direction in which they are pointed and are used later for analysis. The GUI for the 2d scan as well as detected sources of leakages can be seen in Figure 5. While the scan cycle wasn't automated or directly integrated and was only tested in isolation with predetermined sources of leakage and information, this lays the groundwork for AMRs in the search for CALs.

5.3 Further test scenarios

To ensure comprehensive evaluation and validation of our ALF system, additional methodologies have been defined to thoroughly assess its performance across various settings:

1. **Polygon Shape Variation:** The adaptability of ALF to different industrial environments will be evaluated by adjusting the shape and size of search polygons. This test aims to simulate various industrial layouts, enabling us to observe how the system optimally scans different geometric complexities. These variations will help us understand the flexibility of the AMR to navigate and perform in environments that mimic real-world irregularities and structural variations.
2. **Waypoint Distance Variation:** By altering the distances between waypoints, we can gauge the efficiency and thoroughness of the coverage. This testing will help us determine the optimal waypoint spacing that balances thorough scanning with time and energy efficiency. The results will inform us of the best practices for setting waypoint parameters under various conditions, ensuring both precision and effectiveness in the system's operational procedures.
3. **Sensor Sensitivity Testing:** Adjusting the sensitivity thresholds and scan parameters of the sensors will help evaluate the detection accuracy and minimize false positives. This testing is crucial for fine-tuning the system to differentiate between actual leakages and environmental noise or false signals, thereby enhancing the reliability and robustness of ALF in detecting compressed air leakages.
4. **Environmental Complexity:** To assess the robustness and adaptability of ALF in complex environments, we plan to introduce variable obstacles and modify the layout within the testing areas. This will include:

(a) Prepared Testing Areas: Designated test zones will be prepared with known leakage sources and varying environmental conditions to systematically evaluate ALF's performance. These areas will mimic real-world conditions with added complexities such as temporary obstructions, varying air flows, and different types of surfaces that could affect sensor readings.

(b) Controlled Leakage Scenarios: Leaks of different sizes and pressures will be introduced in a controlled manner to assess the system's sensitivity and accuracy. By having predefined leakage parameters, we can accurately measure the system's response time and precision in localization.

(c) Comparative Analysis: The results from ALF will be compared against known benchmarks and traditional leakage detection methods. This will not only validate the effectiveness of the system but also highlight areas of improvement and advantages over conventional approaches.

These tests will be carried out in collaboration with various partners in the KI4ETA project, leveraging their distinct industrial settings to ensure that ALF is well-tested under diverse conditions. The outcomes of these tests will help us refine the system further, ensuring it is robust, adaptable, and capable of operating efficiently in any industrial environment.

6 Conclusion and Future Work

In this paper, we presented an automated approach for the detection and identification of compressed air leakages in industrial environments using an AMR. By integrating detection sensors specifically adapted for this use case in combination with evaluation algorithms, our system significantly accelerates the detection of compressed air leakages and increases resource efficiency compared to conventional methods based on handheld devices. The results of preliminary tests performed with individual components of the system have shown promising results, highlighting the potential for significant energy savings, reduction of financial losses and minimization of environmental impact. In the framework of the KI4ETA project, our future work will focus on testing the entire system in various scenarios to validate its effectiveness in real-world conditions. We have meticulously outlined a series of comprehensive test scenarios that will evaluate the system's performance across different environments and situations. These tests will aim to refine the system further and ensure its robustness in varying industrial contexts. A major focus of our future work will be integrating object recognition more deeply into the system. By embedding expert knowledge through advanced techniques like knowledge graphs, we aim to enable automatic searches along compressed air systems, improving the robot's ability to autonomously derive missions and tasks. This will enable the robot to identify and recognize critical objects and areas of interest autonomously, streamlining the search process, and making it more efficient. In summary, this research provides a solid foundation for the use of robots in the detection of compressed air leakages. The integration of AI-based analytics, object recognition and expert knowledge will be crucial to make the system smarter and more adaptable to complex industrial environments and ultimately improve the ability to proactively save energy and align with global sustainability goals.

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