

Development of a Mobile Service Robot with UWB Localization for Hazard and Air Quality Detection in Multi-Room Facilities

Abstract— Environmental hazards such as undetected fires and toxic gas exposure remain a persistent threat in multi-room facilities, as illustrated by incidents like the Kartalkaya Hotel fire and Microtel Inn carbon monoxide leak. Conventional fixed sensors often fail to provide comprehensive, real-time detection and intervention across large or complex spaces. We propose and assess the feasibility of a novel autonomous mobile robot capable of both detecting and responding to fire and gas hazards through real-time localization, air purification, and user alert systems. An autonomous robot simulator was developed for evaluating navigation, localization, and gas detection in structured environments. The system displayed advanced path-finding capabilities in 3 distinct settings while continuously testing CO exposure. Overall, the robot traversed ~53 cells in 749 steps with a UWB median error of 0.437 cells (25th 0.43, 75th 0.44) with an 80% source detection rate. These results demonstrate reliable hazard modeling, bounded UWB error, and reproducible performance across layouts, establishing a flexible platform for validating safety-critical sensing and multi-sensor fusion in autonomous systems.

I. INTRODUCTION

In recent years, the increasing risk of environmental accidents such as undetected and human-caused fires or prolonged toxic gas exposure have highlighted the need for intelligent and autonomous systems capable of fast detection and intervention. High profile accidents such as the Kartalkaya Hotel fires in Turkey or the undetected carbon monoxide leaks at the Microtel Inn in West Virginia USA, tragically illustrate the neglect in this area and how the lack of rapid hazard localization and around the clock environmental control result in avoidable casualties. The conventional solution to this problem is using stationary fire detectors and some air quality monitors; however, their immobility, dependence on placement and susceptibility to negligence limit them from being sufficient solutions to the problem in large, multi-room facilities.

Mobile robots have been proposed as critical tools for search and rescue (S&R) missions due to their ability to operate in dangerous and uncertain environments [1]. The combination of mobile robots and sensors also allows automatic supervision of environmental parameters, such as hazardous materials or air quality, in real-time across large areas [2]. Even though robot-assisted environmental monitoring is not new, its application has mostly focused on detection alone without direct mitigation [3].

The mobile robot olfaction (MRO) is a branch of robotics that combines gas sensors with the flexibility of mobile robots [4]. The MRO has become popular especially in monitoring of potentially hazardous conditions in recent

years [4]. The field of MRO considers two main tasks: gas source localization (GSL) and gas distribution mapping (GDM). GSL's purpose is to find the chemical sources that caused the gas [5]. GDM's purpose is to build a map of the distribution of the chemical in the environment [5].

This paper presents an extended MRO design that combines ultra wideband (UWB)-based indoor localization, air quality sensing, fire detection and industrial-level filtration to detect and react to fire- and gas-related hazards inside enclosed buildings. In contrast to other solutions, this robot is not only able to detect and localize environmental threats but also to commence real-time purification and alert procedures as an active responder, not a passive observer. Additionally, through a mobile device app the system aims to provide a mobile alerting system through the user's device. In sum, the device aims to provide continuous surveillance in terms of air quality and gas leaks, combined with strong filtration and autonomous operation for hazard monitoring, detection and response through a single system.

The UWB-based localization system has been chosen because of its precise localization ability compared to other strategies such as wall-following. Moreover, UWB systems are comparatively economical and easier to install than other alternatives such as LiDar and visual SLAM technologies. Even though the need for anchors is a downside of UWB technologies, the reduced need for a facility map and technical knowledge from the user for initialization, differentiates the UWB technology from its alternatives.

Our proposed system uses modular high efficiency particulate air (HEPA) and activated carbon filters, offering both fine particulate filtration and the adsorption of toxic gases. The filters in the system are arranged in a Corsi-Rosenthal box (CR box) configuration. Previous studies have shown that this box arrangement has lower airflow resistance, higher airflow rates, and particle removal rates that exceed most commercially available portable HEPA filters [6]. The CR box design also outperforms single filter configurations by up to 2.6x clean air delivery rate (CADR) [7].

In the first part of our study, we aimed to research the feasibility and usage potential of the smart air quality, fire detection, and prevention system proposed in this paper. TO achieve this goal, as proposed in the experiments section of this paper, we developed a localization, mapping, and gas detection simulator. In the second part of our study, we built a prototype for our system. The aim for this second part of the study was to confirm our feasibility evaluation and simulation results from the previous part of the study.

A. Related Works

In recent years, autonomous mobile robots have been getting increasingly prevalent in the S&R field, especially in hazardous indoor environments. Even though previous studies have mainly emphasized features such as gas detection, remote sensing, and terrain navigation, none combined both detection and intervention capabilities in a modular system.

In previous studies, Novotny et al. proposed a modular mobile platform for performing general search and rescue (S&R) operations in disaster areas [1]. Although their design prioritized locomotion ruggedness, modular subsystems, and remote data collection, it did not address environmental monitoring or air quality response. Likewise, Rahmaniar and Wicaksono demonstrated a CO-monitoring robot through the MQ-7 sensor for detecting carbon monoxide levels in home environments [3]. Even though the robot from their study was able to transmit sensor readings through Wi-Fi, it lacks localization or intrusion of any type. Another study by Rofiq et al. built upon this idea by proposing a mobile robot with onboard gas sensors for autonomous CO monitoring and audible alerts [8]. This study demonstrated the viability of using gas sensors in mobile robots. However, it did not offer localization or on the spot air treatment.

Some more recent studies by Chiu et al. [9] and Singh et al. [10] incorporated PM 2.5 filtering and detection technologies into mobile robots. However, these studies did not address toxic gas, fire, or smoke detection. Moreover, these studies incorporate a wall-following strategy and a light-seeking strategy through LDR sensors, respectively. Differentiating them from our system that uses UWB devices to achieve source localization.

Platform and software integration has also been previously explored in autonomous mobile robots, most notably in robot vacuum cleaners. There are commercial air-purifying robots available that have explored the topic; however, to our knowledge, they do not typically have the capacity to autonomously detect, locate, and respond to emergent hazards like fires, toxic gases, or smoke plumes in unfamiliar environments. Further, no known project integrates UWB-based localization with carbon monoxide filtration and air quality stabilization in mobile form.

B. Contributions

This work offers the following contributions to the presented problem:

- 1) We propose a system that integrates hazard detection and intervention systems in one mobile robot. This novel robot includes an UWB anchor system for positioning and multi-gas sensing through multiple environmental and gas sensors for an efficient hazard detection system combined with a double Corsi-Rosenthal box shaped filtering with industry grade HEPA and activated carbon filters for mobile filtration.
- 2) We propose using a UWB system for mapping and localization. Through the usage of this UWB mapping system we are able to detect the exact location of the gas-source and alert the user immediately. This system has

the potential to be crucial in undetectable accidents such as a CO leak.

- 3) We propose using a real-time data visualization and alert system through a mobile app. If data such as air quality, event triggers and robot location are streamed to a mobile interface, the user can be directly notified through their mobile device and can receive specialized data for different areas in a large facility.

II. PROPOSED SYSTEM

This section introduces the proposed system design. For the data collection system, the robot uses 7 analog outputs from various sensors: MQ-2 for smoke and flammable gas detection, MQ-7 for carbon monoxide detection, IR Flame detector for flame detection, and 4 Sharp GP2Y0A21YK0F sensors for distance data. The digital environmental sensors ENS160-BGLM and BME680 provide air quality data for the system. The robot uses two NEMA 17 42BYGH stepper motors each connected to a TMC2208 motor driver. The Arctic Bionix P140 fan used in the Corsi-Rosenthal box is connected to a 15A 400W PWM supported MOSFET switching module. A Qorvo DWM1001-DEV board will be used as the UWB receiver in the robot. The system will be powered through a 5200 mAh 3S 50C LiPo battery.

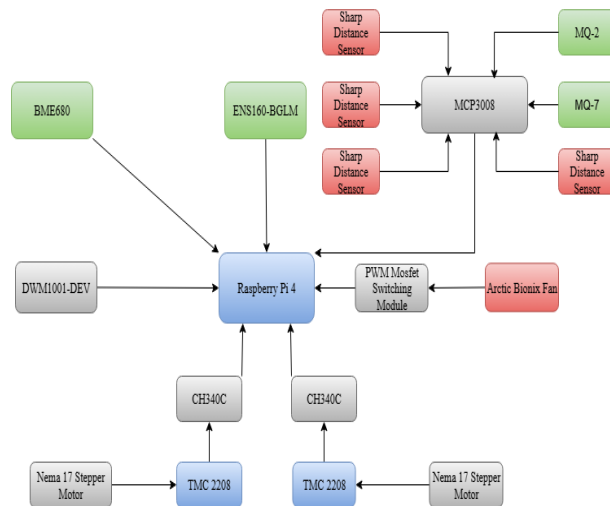


Fig 1. The proposed system presented as a box diagram

III. ROBOT DESIGN / IMPLEMENTATION

A. Chassis Design

The robot chassis that can be seen in Fig. 2 was designed specifically to support an autonomous mobile robot that has air quality, fire, and hazardous gas detection and purification capabilities. A commercial platform was not preferred to directly meet the design constraints for this system specifically. The main constraint faced during the design process was enabling constant airflow in and out of the robot. To solve this constraint, airflow was allowed from all four sides of the robot through holed surfaces. The air outtake was enabled from the top of the chassis through a fan. Another constraint in the design process was the size of the air filters used. To enclose the rectangular filters used in the robot, a rectangular shaped chassis was preferred over

circular ones used in most commercial mobile robots. The robot was designed to use two wheels and a ball caster for all-directional movement. The upper face of the chassis is sectioned off for each filter. The chassis was designed with the computer aided design (CAD) software Onshape and will be printed with PLA filament for the prototype.

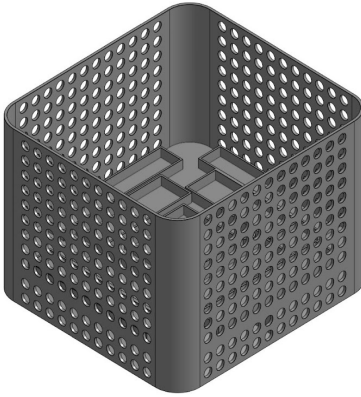


Fig 2. The proposed chassis design rendered in Onshape 2025

B. Circuit Design

The circuit was designed from the circuit design software KiCad. The previously mentioned proposed system will be presented as a circuit design in Fig. 3. For each of the sensors used in the system a separate sensor board was preferred.

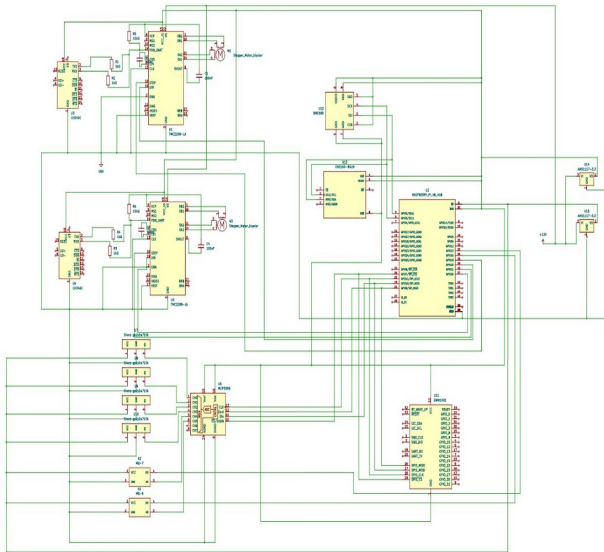


Fig 3. The wiring diagram that encompasses every system component in the robot represented by schematics. (KiCad 2025)

C. Software Design

The robot software focuses on two features: movement and data collection. The Raspberry Pi 4 gathers data from every sensor and communicates with the tracking app through a Flash server. The data gathered from environmental sensor is compared to Occupational Safety and Health Organization’s (OSHA) Permeable Exposure Limits (PEL) to initiate tasks like filtration or movement. The data from the Sharp distance sensors are used to stop movement and reroute when

obstacles are present. The user sets up UWB anchors in various rooms. The Raspberry Pi gathers initial location data from these anchors. The microcontroller is tasked with initializing the switch between rooms periodically, so the Raspberry Pi always has the data for the robot’s location and destination. The mapping and routing is based on the data gathered by the DWM1001-DEV UWB module. The distance from other UWB anchors is calculated to receive the exact location data of the robot. This data is used for path-finding and source location to alarm or warn the user of the hazardous situation.

IV. EXPERIMENTS

A simulator was designed to test the usage potential and the capabilities of the system proposed in this paper.

A. Localization & Mapping & Detection Simulations

A Python-based simulator that combines occupancy-grid planning with a stochastic carbon monoxide (CO) dispersion model and sensing modules was developed on Gazebo to evaluate the proposed movement and localization frameworks. Three layouts -a long hallway, a multiroom plan, and a serpentine maze- were modeled with randomly placed, diffusing carbon monoxide (CO) pockets. 5 separate simulations were conducted for each scenario. The median values for these 5 trials were used in the results and discussion sections of this paper. MQ-9B-like sensing was emulated with 55 ppm (warning) and 200 ppm (alarm) thresholds, Gaussian noise, IIR filtering, and with optional Kalman correction. An eight-ray feature sensor provided structural awareness, while Ultra-Wideband (UWB) anchors delivered noisy range measurements refined via Gauss-Newton trilateration. Robot behaviors included cautious hallway traversal, plume-seeking under warning, and immediate stop at alarm. In each trial, the robot was tasked with reaching a goal location with increased CO levels while continuously monitoring those CO levels. To approximate gas propagation accurately a Gaussian pocket model with diffusion and drift was used. The identified target data for this simulation are telemetry, heatmaps, animated trajectories, and UWB error traces. The target data will provide insight on quantitative and visual analysis of the robot’s real-life performance.

V. RESULTS

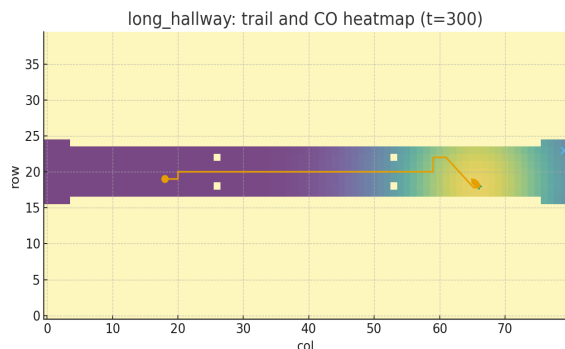


Fig 4. The robot’s path-taking in a long hallway with a CO pocket represented by the localization simulation’s output.

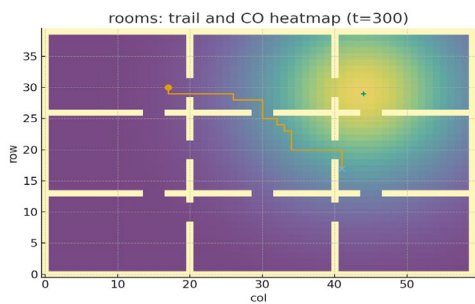


Fig 5. The robot's path-taking in a multi-room facility with a CO pocket represented by the localization simulation's output.

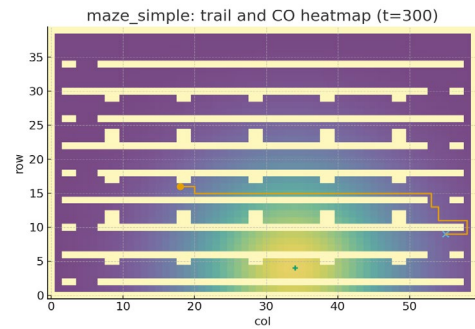


Fig 6. The robot's path-taking in a serpentine maze with a CO pocket represented by the localization simulation's output.

Three figures - Fig.4, Fig. 5, and Fig. 6- represent paths taken by the robot in a long hallway, partitioned rooms, and a serpentine maze, respectively. The colored background indicates CO concentration at $t=300$. The robot's trail is highlighted in orange. Robot behaviors include cautious hallway traversal, plume-seeking under warning, and immediate stop at alarm. Simulation outputs include telemetry, heatmaps, animated trajectories, and UWB error traces. In the serpentine maze plume detection occurred later than the other two cases because of narrow corridors limiting exposure, whereas, in the multi-room environment the robot encountered larger unblocked areas which led to a faster source detection. In the serpentine maze the robot traversed ~ 60.1 cells in 913.4 steps on average with a UWB median error 0.434 cells (25th 0.43, 75th 0.44) and a standard deviation of 0.012. The WARN and ALARM states were triggered 79.2% and 4.2% of the time, respectively. The UWB source localization rate in a maximum of 1000 steps was just 60%. On the other hand, in the multi-room layout it traversed ~ 50 cells in 571 steps on average with a UWB median error of 0.44 cells (25th 0.44, 75th 0.44) and a standard deviation of 0.007. The source localization rate in a maximum of 1000 steps was 100%. In the long hallway, the robot traversed ~ 57 cells in 805.8 steps on average with a UWB median error of 0.438 cells (25th 0.43, 75th 0.44) and a standard deviation of 0.018. The WARN and ALARM states were triggered 5.2% and 0.14% of the time, respectively. The source localization rate in a maximum of 1000 steps was 80%.

VI. DISCUSSION

The simulation results indicate that the proposed framework has the capabilities to navigate through complex settings while continuously testing CO levels. Integration of

filtering methods, such as the Kalman-based estimation, proved to be crucial in reliable threshold detection under stochastic noise. The robot identified the gas source in 80% of the cases demonstrating the effectiveness of the proposed UWB localization system. The data also shows that environmental topology strongly affects the amount of time the system takes to identify the CO pocket. As a result of the multi-room environment having the lowest median steps taken, it can be inferred that, while open environments accelerate detection, constrained mazes delay it. These findings align with previous studies such as Albertin et al. (2025) on adaptive robot localization through UWB detection [11] and make our proposed system highly applicable for our aim of providing multi-room facilities for air quality and hazardous gas detection and purification.

The results highlight the advanced capabilities of the simulator that combine path planning, environment modeling, and adaptive autonomy within a unified and reproducible framework. Beyond verifying plume-seeking behavior by simulation, the system is flexible for use across a variety of sources, settings, dissimilar gas types, or airflow-informed dispersion models. As a result, the framework becomes an effective testbed for the development of autonomous inspection and safety robots that deploy in hazardous environments.

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