Autonomous Tunnel Inspection Robot - MATLAB Virtual Simulation

MECHATRONICS SUBSYSTEM DESIGN PROJECT REPORT

Submitted by

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ABSTRACT

An autonomous robotic inspection system for underground tunnel monitoring is presented as a virtual prototype designed to operate in confined, GPS-denied environments. The system simulates a rugged mobile robot navigating a three-dimensional tunnel while continuously monitoring critical environmental parameters such as methane (CH_4), carbon monoxide (CO), and temperature. Realistic sensor fields with spatial gradients and localized hazard zones are modelled to replicate underground conditions, enabling accurate spatial sampling of safety data during robot motion.

Sensor readings are evaluated in real time against predefined safety thresholds, triggering visual alarms, audible alerts, and event logging to ensure immediate hazard awareness and post-mission analysis. The system integrates navigation, sensing, alarm management, and visualization within a centralized control loop, providing a cohesive and scalable simulation framework. Although currently implemented as a virtual model, the architecture can be extended to real-world autonomous robots for underground inspection, safety monitoring, and hazardous environment exploration.

TABLE OF CONTENTS

Chapter No	Title of the chapter	Page number
1	Introduction	7
2	Literature Review	8
3	Mechatronics System Design Methodology	11
4	Software and Control System Design	15
5	System Integration and Implementation	19
6	Testing and Validation	22
7	Results and Discussion	24
8	Applications, Limitations, and Future Scope	27
9	Conclusion	28
	References	29
	Appendices	32

LIST OF TABLES

Table no	Title of Table	Page number
3.1	Functional Module Description	13
4.1	Environmental Sensor Threshold Values	17
4.2	Simulation Parameters Logged	18
5.1	Logged Mission Data Structure	20
7.1	Sample Logged Hazard Events	26

LIST OF FIGURES

Figure Number	Title of the Figure	Page Number
3.1	System architecture of the autonomous tunnel inspection robot	11
3.2	Three-dimensional glass tunnel model used for robot navigation	12
4.1	Robot navigation path inside the transparent glass tunnel	15
5.1	Robot mission alarm panel indicating detected hazardous conditions	20
7.1	Time-series variation of methane (CH_4) concentration during the robot inspection mission	24
7.2	Time-series plots of carbon monoxide (CO) concentration and temperature during tunnel inspection	25
7.3	Spatial distribution of detected hazardous locations inside the tunnel	25

CHAPTER 1

INTRODUCTION

The Autonomous Tunnel Inspection Robot using MATLAB Simulation is a virtual robotic system designed to perform intelligent navigation and environmental monitoring in underground tunnel environments. The project focuses on enhancing safety by detecting hazardous conditions without human intervention.

Underground tunnels and mines are dangerous due to toxic gases, high temperatures, confined spaces, and poor visibility. Manual inspection in such environments exposes workers to serious risks, including gas inhalation and structural hazards. To overcome these challenges, an autonomous robotic inspection approach is essential.

This project presents a MATLAB-based simulation of a mobile robot navigating through a three-dimensional tunnel. The robot continuously monitors environmental parameters such as methane (CH_4), carbon monoxide (CO), and temperature using virtual sensors. When unsafe conditions are detected, the system triggers alarms and logs the events for analysis.

By implementing the system entirely in simulation, the project enables safe, low-cost testing of autonomous navigation and hazard detection logic before real-world deployment. The developed framework can be extended to practical unmanned ground vehicle applications in underground safety monitoring.

CHAPTER 2

LITERATURE SURVEY

2. Literature Survey

Safe and efficient operation of robots in underground environments requires reliable sensing, navigation, and control mechanisms. Numerous studies have addressed individual challenges such as gas detection, tunnel navigation, and obstacle avoidance. However, most existing works focus on isolated subsystems, while comprehensive simulation-based integration of sensing, control, and visualization remains limited.

The following literature review summarizes key research contributions relevant to the development of the autonomous tunnel inspection robot.

2.1 Research Papers

A. Gas Sensing with Robots in Underground Mines

Mobile robots for gas and environmental monitoring in underground mines typically integrate gas sensors, temperature sensors, and wireless communication systems to reduce human exposure to hazardous zones [3], [7]. Intelligent mine safety monitoring architectures have been proposed to analyze accident causes and implement early-warning mechanisms for methane, carbon monoxide, and other environmental parameters [3]. Autonomous gas-detecting robotic platforms equipped with multi-gas sensors have been reported for operation in post-blast and high-risk mining conditions [7].

Several monitoring systems employ IoT-based wireless networks and embedded controllers to measure methane, carbon monoxide, carbon dioxide, temperature, and humidity, transmitting readings to surface control rooms or cloud-based platforms [1], [4], [5], [8]. Explosion-proof mechanical and electrical design principles are also addressed to ensure safe robot operation in methane-rich environments [11]. Reviews of mine rescue robots summarize tracked and wheeled platforms, sensing payloads, and communication strategies for operation in irrespirable and poorly ventilated conditions [12].

Robotic platforms equipped with gas sensors, cameras, and thermal sensors have also been deployed for disaster surveillance and hazardous gas detection [10], [13], [14]. Coal mine monitoring robots and sensor-based multipurpose mine detection robots further demonstrate practical field implementations [9], [15]. However, most reported systems rely on hardware-centric prototyping, which restricts systematic and repeatable experimentation with alternative sensor layouts, navigation strategies, and alarm thresholds.

B. Tunnel and Mine Inspection Techniques

Inspection technologies for tunnels and mines have traditionally emphasized structural and geological assessment. Automated inspection systems based on mobile mapping platforms integrate LiDAR, cameras, and inertial sensors to generate dense three-dimensional point clouds for defect detection and maintenance planning [16]. Distributed fiber optic sensing techniques enable continuous strain and deformation monitoring along tunnel linings, supporting early detection of structural changes [17]. In mining environments, hyperspectral scanning systems have been proposed to acquire three-dimensional surface and mineralogical information within tunnels, shafts, and galleries [18]. Digital visualization and augmented rock mechanics approaches enhance understanding of underground stress, deformation, and support conditions by overlaying numerical results onto three-dimensional tunnel models [19]. In most cases, the tunnel is treated as a static inspection object, and dynamic hazardous gas accumulation influenced by ventilation conditions along a robot trajectory is not explicitly modelled.

C. Virtual Reality, Digital Twins, and Safety Simulation

Virtual reality and digital twin paradigms are increasingly applied in mining for safety training, planning, and remote supervision [21]. Virtual mine environments allow rapid construction of underground layouts and simulation of human perception and behaviour for safety studies [21]. Digital twin solutions integrate data from equipment, sensors, and process models to support immersive monitoring and decision-making [22].
Industrial studies indicate that digital twins can enhance safety and productivity by incorporating ventilation data, sensor telemetry, and geological information into unified virtual representations [23]. Despite these advances, most systems rely on live sensor data streams or focus primarily on training and visualization. Fully virtual simulation

environments that integrate tunnel geometry, ventilation-dependent hazard fields, robotic navigation, and alarm logic remain limited.

D. Identified Research Gap

Existing robotic gas-sensing systems are predominantly hardware-oriented and provide limited flexibility for systematic testing across diverse hazard distributions, tunnel configurations, and ventilation conditions [7]– [9]. Tunnel and mine inspection techniques emphasize structural and geological analysis without coupling atmospheric hazard evolution to a simulated robotic path [16]– [18]. Virtual reality and digital twin approaches enhance visualization and training but rarely provide a comprehensive simulation-only environment for validating multi-sensor hazard detection and alarm behaviour.

This work addresses these limitations by developing a MATLAB-based virtual mine tunnel inspection framework that integrates voxel-based tunnel modelling, glass-tunnel visualization, spatially varying methane, carbon monoxide, and temperature fields, robotic navigation, and real-time alarm and event logging.

CHAPTER 3

MECHATRONICS SYSTEM DESGIN METHODOLOGY

The proposed system follows a structured mechatronics design approach by integrating mechanical modelling, sensing, control, and actuation within a unified simulation framework. This integration ensures coordinated operation of all subsystems and enables effective monitoring and decision-making in underground tunnel environments.

3.1 Overall System Architecture

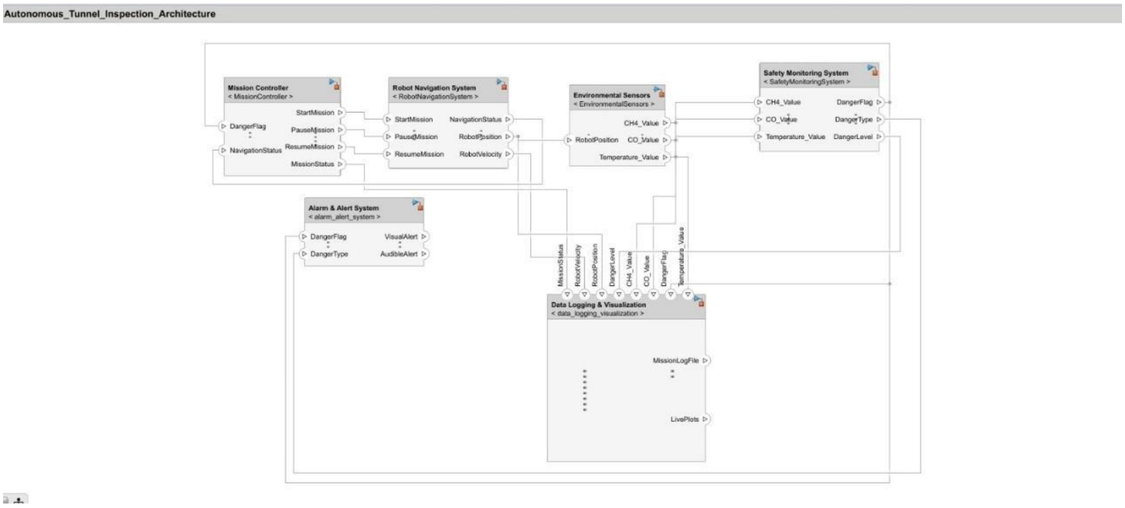

Fig 3.1 System architecture of the autonomous tunnel inspection robot

Figure 3.1 presents the overall system architecture of the autonomous tunnel inspection robot developed using a mechatronics design approach and implemented entirely in the MATLAB simulation environment. The system is organized into interconnected functional subsystems including the mission controller, robot navigation system, environmental sensing unit, safety monitoring system, alarm and alert module, and data logging and visualization block. The mission controller supervises the overall operation by issuing start, pause, and resume commands based on navigation and safety status. The robot navigation system generates robot position and velocity information, which is continuously fed to the environmental sensors for spatial sampling of methane (CH_4), carbon monoxide (CO), and temperature values. The safety monitoring system evaluates sensor data against predefined thresholds to determine hazard conditions. Upon detection of unsafe conditions, danger flags and hazard types are transmitted to the alarm system and mission controller, enabling visual and audible alerts as well as mission control actions. Simultaneously, all key parameters are recorded by the data logging and visualization module for real-time monitoring and post-mission analysis within MATLAB.

3.2 Mechanical Model

Figure 3.1 illustrates the three-dimensional tunnel geometry representing the mechanical subsystem environment for the autonomous robot. The tunnel is modelled using a voxel-based carving technique, in which discrete volumetric elements are systematically removed to create a continuous and constrained underground passage. This method enables accurate spatial representation of confined tunnel conditions, including bends and curvature encountered in real underground environments.

As shown in Fig. 3.1, a smooth mesh-based tunnel surface is generated along the robot's centreline using spline interpolation combined with circular cross-sections. The tunnel is rendered as a transparent glass structure to enhance visualization, allowing clear observation of the robot's motion and sensor interactions within the tunnel. The resulting mechanical model ensures that the robot remains physically constrained within the tunnel boundaries while navigating complex curves and loops, thereby providing a realistic and controlled simulation environment for safety and navigation analysis.

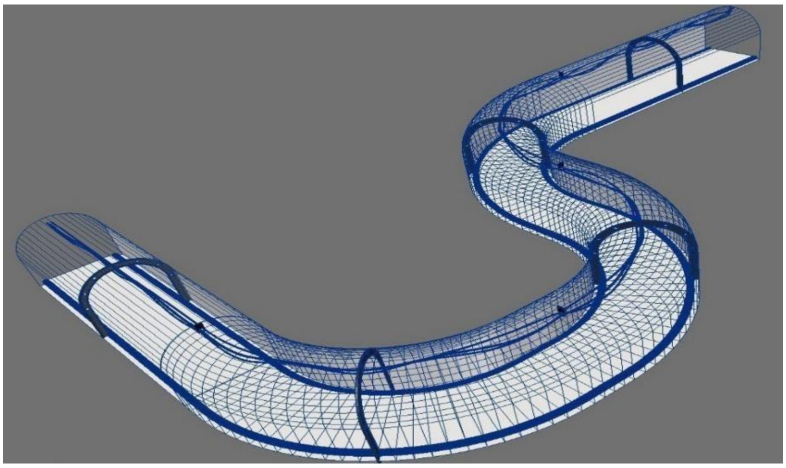

Figure 3.2 Three-dimensional glass tunnel model used for robot navigation

3.3 Sensing System

The sensing subsystem simulates environmental monitoring within the tunnel using virtual sensor fields. Three primary parameters are modelled:

- Methane (CH_4) Concentration: Simulated with spatial gradients and localized high-concentration pockets to represent combustible gas accumulation.

- Carbon Monoxide (CO) Levels: Modelled to reflect toxic gas presence in underground environments.
- Temperature: Simulated with depth-dependent gradients and random variations to mimic thermal conditions inside tunnels.

Sensor values are continuously sampled at the robot's exact three-dimensional position. Areas outside the tunnel are masked to ensure that sensor readings are only obtained within valid tunnel regions. This spatial sensing approach closely resembles real-world sensor behaviour and allows accurate hazard detection.

3.4 Control Logic

The control subsystem is responsible for decision-making and safety enforcement. A threshold-based logic compares real-time sensor readings with predefined safety limits for CH_4, CO, and temperature. When any parameter exceeds its threshold, the system immediately transitions into a danger state.

In the danger state, visual alerts, audible alarms, and warning indicators are activated. Simultaneously, the hazardous event is logged with time, location, and sensor values for post-mission analysis. Once the alert sequence is completed, the control logic resumes normal operation, allowing the robot to continue its inspection mission. This deterministic control strategy ensures fast and reliable hazard response.

Table 3.1 Functional Module Description

Function Name	Role in System	Subsystem
path_navigation()	Generates robot inspection path	Planning
robot_platform()	Updates robot position	Actuation
environment_tunnel_model()	Provides sensor readings	Sensing
safety_monitor()	Evaluates hazard condition	Control
mission_controller()	Decides alert action	Decision
safety_alert_system()	Triggers alarms and logging	Safety

3.5 Actuation System

The actuation subsystem governs the movement of the robot through the tunnel. The robot follows a predefined three-dimensional path generated using spline interpolation to ensure smooth and continuous motion. At each simulation step, the robot's position is updated along the path based on a fixed time interval, simulating constant-speed traversal.

The robot's motion is synchronized with sensing and control operations, ensuring that environmental data is captured accurately at each location. Visual indicators, such as a moving robot marker and path traces, provide real-time feedback of the robot's position and operational state. This coordinated actuation approach enables effective inspection coverage of the entire tunnel.

CHAPTER 4

SOFTWARE AND CONTROL SYSTEM DESIGN

The complete system is implemented entirely in the MATLAB environment, providing an integrated platform for modelling, simulation, visualization, and data analysis. MATLAB enables seamless coordination between path planning, sensing, control logic, and user interaction, making it suitable for developing and validating autonomous inspection systems.

4.1 Path Generation Using Spline Interpolation

Figure 4.1 illustrates the spline-based path generation used for robot navigation inside the glass tunnel environment. The inspection trajectory is formed by combining straight sections, smooth curved portions, and a looped region into a single continuous path, with spline interpolation applied to predefined waypoints to remove sharp discontinuities. This results in a smooth curvature profile that enables stable robot motion and near-uniform speed throughout the inspection process. The generated spline path closely follows the tunnel centerline, allowing the robot to safely negotiate complex tunnel geometries while maintaining smooth and controlled movement within the confined environment.

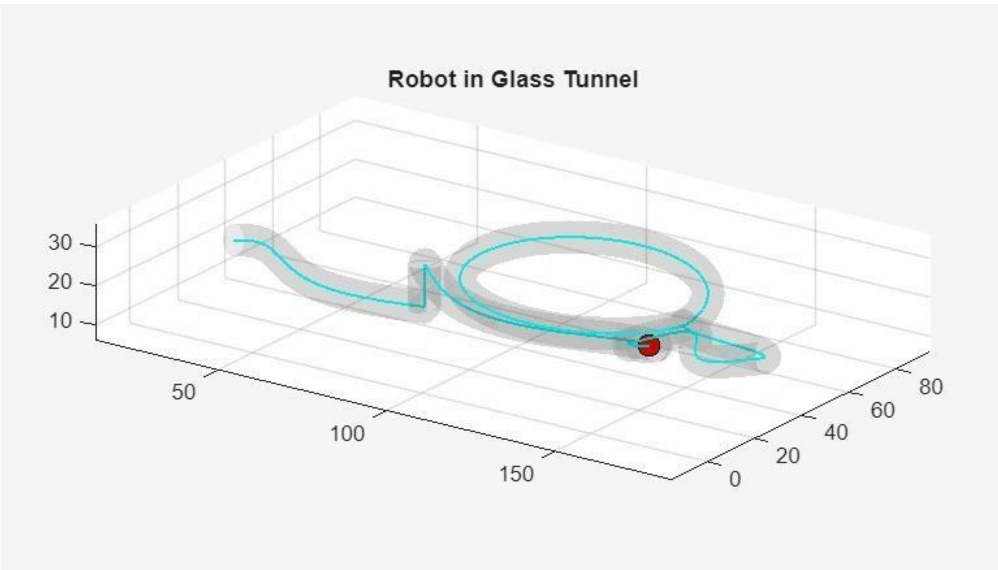

Figure 4.1 Robot navigation path inside the transparent glass tunnel

4.2 Voxel-Based Tunnel Carving for Spatial Constraints

A voxel-based modelling technique is employed to construct the tunnel environment. The three-dimensional workspace is discretized into volumetric elements, and tunnel regions are carved by selectively activating voxels around the robot's predefined path. This method ensures that the tunnel geometry closely follows the robot's trajectory while maintaining spatial constraints. The voxel model also serves as a mask that restricts sensor readings to valid tunnel regions, preventing unrealistic data sampling outside the tunnel.

4.3 Sensor Field Generation with Gradients and Localized Danger Pockets

Environmental sensing is simulated using three-dimensional sensor fields representing methane (CH_4), carbon monoxide (CO), and temperature. Each field includes smooth spatial gradients combined with random noise to replicate real underground conditions. In addition, localized high-intensity regions, referred to as danger pockets, are introduced along selected tunnel locations. These pockets simulate hazardous gas accumulation and temperature rise, enabling realistic testing of the system's hazard detection capabilities.

4.4 Real-Time Robot Position Updates

The robot's position is updated in real time along the predefined path at each simulation step. The current position is displayed within the three-dimensional tunnel visualization using a moving marker. This continuous position update ensures accurate spatial correlation between robot location and sensor readings. The synchronized update mechanism provides a realistic representation of robot motion during inspection.

4.5 Alarm Logic Based on Sensor Thresholds

A threshold-based control logic continuously evaluates sensor readings obtained at the robot's position. Each sensor parameter is compared against predefined safety limits for methane concentration, carbon monoxide levels, and temperature. If any parameter exceeds its threshold, the system identifies the condition as hazardous and immediately triggers an alarm state. The logic supports multiple simultaneous hazard conditions and records the specific cause of the alarm.

Table 4.1 Environmental Sensor Threshold Values

Sensor Parameter	Symbol	Threshold Value	Unit	Hazard Type
Methane	CH_4	300	ppm	Explosive gas
Carbon Monoxide	CO	30	ppm	Toxic gas
Temperature	T	45	°C	Thermal hazard

4.6 Audio-Visual Alert Mechanisms

Upon detection of a hazardous condition, the system activates both visual and auditory alerts. Visual warnings include flashing of the robot marker, warning text display, and colour changes in the alarm panel. An audible buzzer sound is also generated to simulate emergency alerts. These audio-visual indicators ensure immediate hazard awareness and mimic real-world safety alert systems used in underground monitoring.

4.7 Continuous Logging of Danger Events

All detected hazard events are logged continuously into a comma-separated values (CSV) file. Each log entry includes the simulation step number, robot position coordinates, sensor readings, detected hazard type, and a timestamp. This logging mechanism supports post-mission analysis, safety auditing, and system performance evaluation. The log file serves as a permanent record of hazardous occurrences during the mission.

4.8 Synchronized Control Loop Operation

The entire system operates within a centralized control loop that synchronizes sensing, visualization, control decisions, and actuation. At each iteration, the robot's position is updated, sensor data is sampled, alarms are evaluated, and visual displays are refreshed. This synchronized operation ensures consistent system behaviour, real-time responsiveness, and reliable decision-making throughout the inspection mission.

Table 4.2 Simulation Parameters

Parameter	Symbol / Variable	Value	Description
Number of Simulation Steps	numSteps	200	Total number of robot motion and sensing iterations
Path Dimension	path(k,:)	3D	Robot position in X, Y, Z coordinates
Logging Frequency	—	Every step	Data logged at each simulation iteration
Control Loop Type	—	Sequential	Motion → Sensing → Safety → Logging

CHAPTER 5
SYSTEM INTEGRATION AND IMPLEMENTATION

All subsystems of the proposed autonomous tunnel inspection robot are integrated into a single MATLAB-based simulation environment. This unified framework enables coordinated interaction between tunnel geometry, robot navigation, sensor modelling, control logic, visualization, and data logging. The integrated approach ensures consistency, real-time responsiveness, and reliable system behaviour throughout the inspection mission.

5.1 Robot Navigation inside a Transparent Glass Tunnel

The robot operates within a three-dimensional tunnel modelled as a transparent glass structure. The tunnel geometry is generated using voxel carving and smooth mesh techniques, allowing complex curves and loops while maintaining spatial continuity. The transparent glass representation enables clear visualization of the robot's movement and internal tunnel structure. The robot follows a predefined path constrained entirely within the tunnel boundaries, ensuring realistic navigation through confined underground spaces.

5.2 Sensor Sampling at the Robot's Exact 3D Location

Environmental sensor values are sampled directly at the robot's instantaneous three-dimensional position. This precise spatial sampling ensures that methane (CH_4), carbon monoxide (CO), and temperature readings accurately correspond to the robot's location within the tunnel. Sensor fields are masked outside the tunnel region, preventing invalid readings and reinforcing physical realism. This tight coupling between position and sensing enables accurate hazard detection and spatial correlation.

5.3 Real-Time Alarm State Updates in the User Interface

Figure 5.3.1 illustrates the real-time alarm panel of the user interface, which continuously displays live sensor readings such as methane (CH_4), carbon monoxide (CO), and temperature along with the current system status. When any sensor value exceeds its predefined safety threshold, the interface immediately updates to a DANGER DETECTED state, highlighted using prominent warning text, colour-coded values, and flashing danger indicators. This real-time visual feedback ensures continuous situational awareness for the operator and enables rapid identification and response to hazardous conditions during the robot's inspection mission.

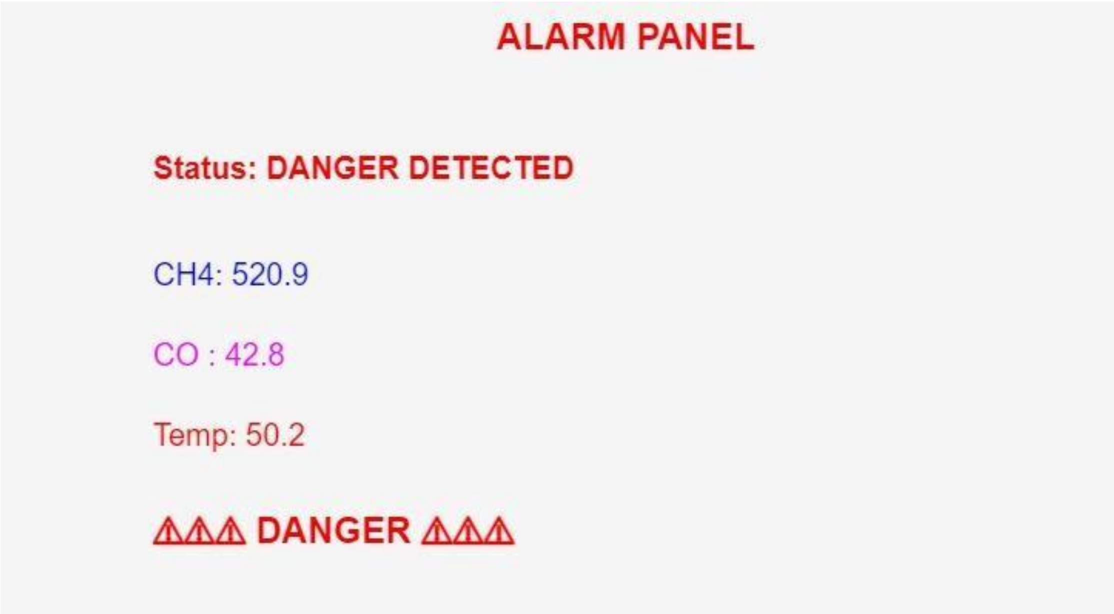

Figure 5.1 Robot mission alarm panel indicating detected hazardous conditions

5.4 Hazard Event Recording with Time and Location Information

Each detected hazard event is recorded automatically with detailed metadata, including the robot's position coordinates, sensor values, detected hazard type, and timestamp. Events are logged into a structured CSV file, allowing systematic post-mission analysis and documentation. This logging mechanism enables traceability of hazardous zones and supports performance evaluation of the inspection system.

Table 5.1 Logged Mission Data Structure

Log Field	MATLAB Variable	Description
Step Index	k	Current simulation step
Robot Position	robotPose	Robot's 3D coordinates (X, Y, Z)
Sensor Readings	sensorData	CH_4, CO, Temperature values
Danger Flag	dangerStatus	Binary hazard indication (0 = Safe, 1 = Danger)

5.5 Final Overview of Detected Danger Zones

At the completion of the mission, a final overview visualization is generated to highlight all detected danger zones within the tunnel. The tunnel geometry and robot path are displayed along with markers indicating the locations of hazardous events. This overview provides a consolidated representation of risk-prone areas, assisting in safety assessment, planning of corrective measures, and future inspection strategies.

5.6 Validation of Integrated System Performance

The successful interaction between tunnel geometry, sensor modelling, control logic, and visualization validates the effectiveness of the integrated system. The simulation demonstrates smooth data flow and synchronized operation across all subsystems. This integration confirms that the proposed framework is capable of supporting autonomous inspection tasks and can serve as a foundation for real-world robotic implementations.

CHAPTER 6

TESTING AND VALIDATION

Testing and validation were carried out to ensure the correctness, reliability, and robustness of the autonomous tunnel inspection system. Multiple test cases were designed to evaluate navigation accuracy, sensor reliability, alarm responsiveness, data logging integrity, and visualization consistency within the MATLAB simulation environment.

6.1 Verification of Robot Path Containment

The robot's navigation path was tested to confirm that it remained completely within the tunnel boundaries throughout the mission. This was verified by constraining the robot's coordinates within the voxel-defined tunnel volume and visually inspecting the robot's trajectory inside the transparent tunnel mesh. No instances of boundary violation were observed, confirming accurate path generation and spatial constraint enforcement.

6.2 Validation of Sensor Threshold Detection Accuracy

Sensor validation focused on ensuring that hazardous conditions were detected only when sensor values exceeded predefined thresholds. Artificial danger pockets with elevated methane (CH_4), carbon monoxide (CO), and temperature values were injected at known tunnel locations. The system accurately detected these conditions at the correct spatial positions, demonstrating reliable threshold-based hazard identification without false positives in safe regions.

6.3 Alarm Activation and Reset Behaviour

The alarm system was tested for correct activation, duration, and reset behaviour. Upon detecting hazardous sensor values, the system immediately triggered visual warnings, flashing indicators, and audible alerts. After the alert sequence was completed, the alarm state reset correctly, allowing the robot to resume normal operation. Repeated hazard encounters were handled consistently without system instability.

6.4 CSV Logging Reliability

The data logging subsystem was tested by analysing the generated CSV log file after mission completion. Each hazard event was correctly recorded with the simulation step number, robot position, sensor readings, hazard type, and timestamp. No missing or duplicate entries were found, confirming reliable and continuous logging of danger events.

6.5 Visual Validation of Danger Locations

Final validation involved visually comparing detected danger points with the original sensor field distributions. The plotted danger markers aligned accurately with high-intensity regions in the sensor maps, confirming correct spatial correlation between sensor data and detected hazards. This visual inspection verified the overall integrity of sensing, detection, and visualization subsystems.

CHAPTER 7

RESULTS AND DISCUSSION

Figure 7.1 illustrates the variation of methane (CH_4) concentration measured along the robot's inspection path during the simulation. As shown in Fig. 7.1, the CH_4 levels remain within normal limits for most sections of the tunnel, with distinct spikes occurring at specific locations corresponding to predefined hazardous pockets. These sharp increases indicate the robot's successful detection of elevated methane concentrations only in critical regions, validating the accuracy of the sensor modelling and spatial hazard representation within the tunnel environment.

Figure 7.2 shows the combined variation of carbon monoxide (CO) concentration and temperature along the inspection trajectory. As depicted in Fig. 7.2, both CO and temperature values exhibit stable behaviour in safe regions, while noticeable peaks occur in hazardous zones where predefined thresholds are exceeded. The synchronized rise in CO and temperature confirms the system's ability to detect multiple environmental hazards simultaneously. The absence of false alarms in non-hazardous regions demonstrates the robustness and reliability of the threshold-based detection logic used in the simulation.

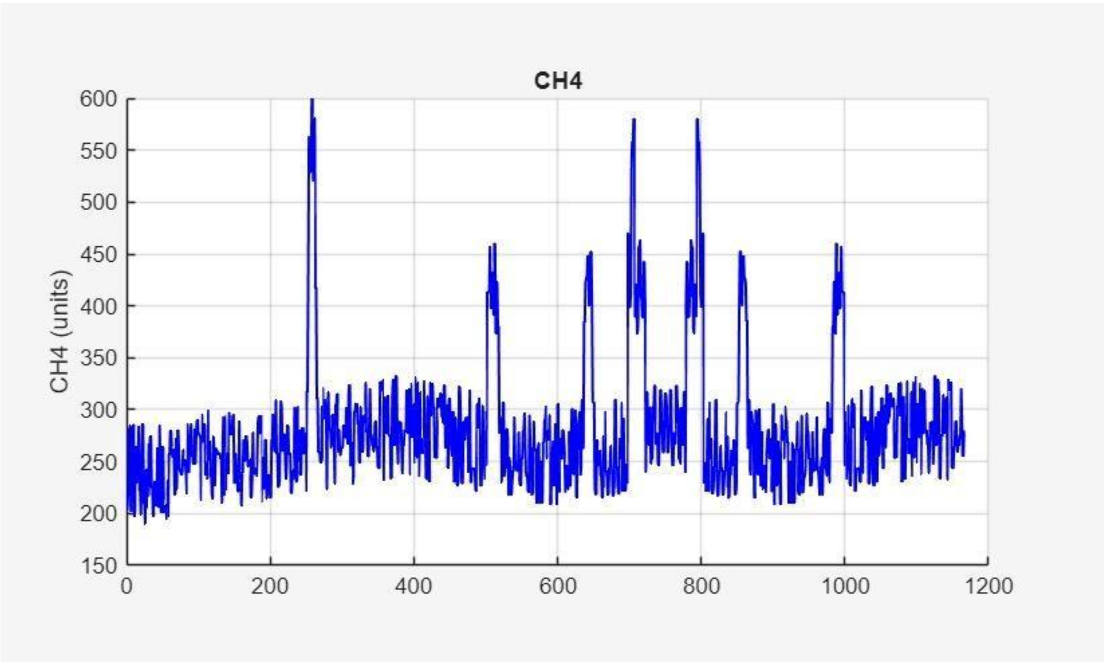

Figure 7.1 Time-series variation of methane (CH_4) concentration during the robot inspection mission

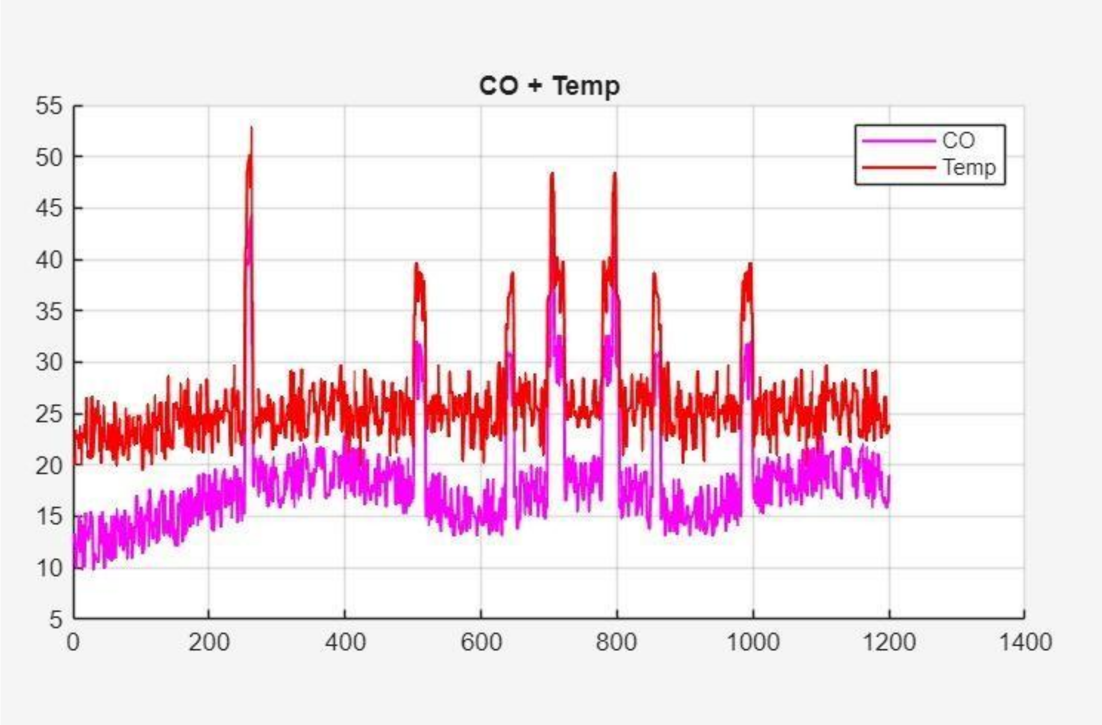

Figure 7.2 Time-series plots of carbon monoxide (CO) concentration and temperature during tunnel inspection

Figure 7.3 illustrates the alarm visualization and alert response during hazardous conditions detected by the autonomous tunnel inspection system. As shown in Fig. 7.3, visual indicators such as flashing robot markers, warning messages, and color-coded status displays provide immediate feedback to the operator upon detection of unsafe conditions. In addition, an audible buzzer is activated to reinforce hazard awareness, closely simulating real-world emergency alert systems. The alarm mechanism consistently activates and resets in accordance with sensor threshold conditions, ensuring reliable alerting while maintaining uninterrupted mission continuity.

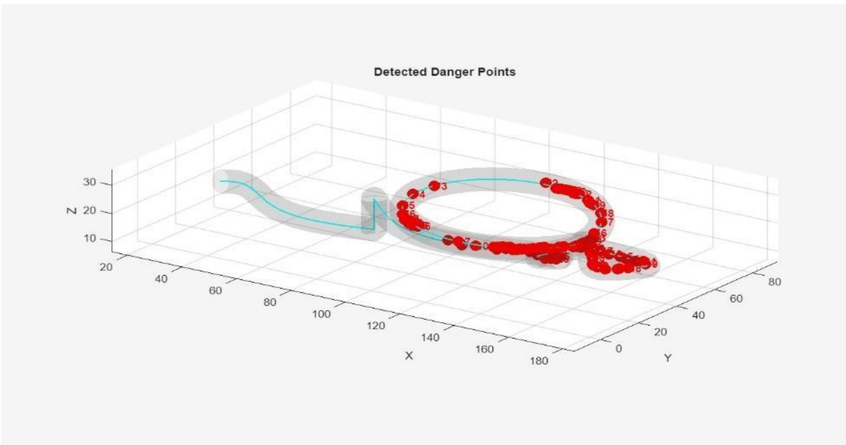

Figure 7.3 Spatial distribution of detected hazardous locations inside the tunnel

Post-mission analysis was facilitated through effective danger mapping. All detected hazard locations were plotted within the tunnel geometry, providing a clear spatial overview of risk-prone zones. This visualization enables better understanding of environmental risk distribution and supports planning of safety interventions.

Overall, the results confirm that multi-sensor monitoring significantly improves situational awareness compared to single-parameter systems. By simultaneously evaluating gas concentration and temperature, the system provides a more comprehensive assessment of underground safety conditions.

Table 7.1 Sample Logged Hazard Events

Step No.	X	Y	Z	CH_4 (ppm)	CO (ppm)	Temp (°C)	Hazard
57	4.2	1.8	0.9	345	22	41	CH_4
103	6.1	2.3	1.2	210	38	44	CO
149	7.8	3.0	1.4	190	18	48	Temp

CHAPTER 8

APPLICATION, LIMITATIONS, AND FUTURE SCOPE

Applications

The proposed system has potential applications across various safety-critical and industrial domains. In underground mine inspection, it can assist in early detection of hazardous gases and thermal anomalies, reducing the need for human entry into dangerous areas. Pipeline monitoring applications can benefit from the system's ability to inspect confined passageways for gas leakage and overheating. The simulation framework is also suitable for disaster response training, allowing emergency teams to study hazardous scenarios in a virtual environment. Additionally, the project serves as an effective educational and research tool for teaching robotics, sensing, and autonomous system design.

Limitations

Despite its effectiveness, the current system has certain limitations. The navigation strategy relies on predefined paths and does not include real-time SLAM or obstacle avoidance capabilities. All sensors are simulated, which may not fully capture real-world noise, drift, and environmental uncertainty. Furthermore, the system does not include a wireless communication model for transmitting data to remote monitoring stations, limiting its real-time operational realism.

Future Scope

The system can be enhanced in several ways to increase its practical applicability. Integration with ROS and deployment on real robotic platforms would enable hardware validation of the developed algorithms. Artificial intelligence and machine learning techniques can be incorporated for anomaly detection and predictive hazard analysis. Implementing SLAM-based navigation would allow autonomous exploration in unknown tunnel environments. A real-time web-based dashboard can be developed for remote monitoring and control. Additionally, hardware deployment using platforms such as Raspberry Pi or NVIDIA Jetson would support real-world testing and field applications.

CHAPTER 9

CONCLUSION

This project presents a comprehensive MATLAB-based simulation of an autonomous robotic safety inspection system designed for underground environments. By integrating tunnel modelling, virtual sensor monitoring, alarm handling, real-time visualization, and data logging, the system demonstrates a practical and scalable approach to autonomous inspection. The simulation results validate the effectiveness of multi-sensor hazard detection and integrated control logic. The developed framework provides a strong foundation for future research and real-world implementation of autonomous safety robots in hazardous underground environments.

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Appendix A: MATLAB Simulation Implementation

This appendix presents the complete MATLAB implementation used to simulate the autonomous tunnel inspection system described in this report. The script mission_glass_optimized.m integrates tunnel modelling, robot navigation, environmental sensing, alarm handling, visualization, and data logging into a single executable framework. A voxel-based method is used to generate a confined tunnel geometry, followed by smooth mesh construction using spline interpolation for realistic visualization. The robot follows a continuous spline-based path while sampling methane (CH_4), carbon monoxide (CO), and temperature sensor fields modelled with realistic gradients and hazard pockets. A real-time user interface provides live sensor plots, alarm visualization, and audible alerts when safety thresholds are exceeded, with hazard events logged for post-mission analysis. Supporting functions for tunnel mesh generation and geometric processing are also included, making the appendix a complete reference for the simulation framework