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Literature Review: Gas Concentration Mapping Using UAV with SLAM and Kernel-DM Algorithms.

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ABSTRACT

The increasing consumption of natural gas in Indonesia necessitates enhanced safety monitoring systems for gas infrastructure. This paper presents a comprehensive literature review on gas concentration mapping using Unmanned Aerial Vehicles (UAVs) integrated with Simultaneous Localization and Mapping (SLAM) and Kernel Distribution Mapping (Kernel-DM) algorithms. The proposed system addresses the challenges of gas leak detection in extensive distribution areas by leveraging UAV mobility, SLAM-based accurate localization, and Kernel-DM for generating continuous gas concentration maps. This approach offers advantages in terms of coverage area, obstacle avoidance, exploration efficiency, and real-time monitoring capabilities. The integration of Hector SLAM with GPS and LIDAR sensors provides robust localization in GPS-denied or uncertain environments, while Kernel-DM enables statistical modeling of gas distribution patterns. This review synthesizes existing research, identifies gaps in current methodologies, and proposes an enhanced system architecture for real-time gas concentration mapping in unknown environments.

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1. INTRODUCTION

The global energy landscape is undergoing a significant transformation, with natural gas emerging as a critical transitional fuel in the shift toward cleaner energy sources. Natural gas produces approximately 50-60% less carbon dioxide emissions compared to coal when used for electricity generation, making it an attractive option for countries seeking to balance energy security with environmental sustainability [1]. This transition is particularly evident in developing economies where energy demand continues to grow alongside increasing environmental consciousness. Indonesia, as the world's fourth most populous nation and Southeast Asia's largest economy, exemplifies this trend with its strategic emphasis on expanding natural gas infrastructure to meet rising energy demands while reducing carbon emissions.

Indonesia's natural gas sector has experienced substantial growth over the past decade, reflecting the nation's commitment to diversifying its energy portfolio. Statistical data indicates that domestic natural gas consumption increased at an average rate of 1.1% annually between 2008 and 2018, with domestic production rising by 0.4% per year during the same period [1]. This growth trajectory accelerated notably between 2017 and 2018, with production growth reaching 1.9%, demonstrating increased investment in gas extraction and distribution capabilities. The Indonesian government has identified natural gas as a cornerstone of its energy policy, targeting a 22% share of natural gas in the national energy mix by 2025, up from approximately 16% in recent years [24]. This strategic focus is driven by multiple factors including the abundance of domestic gas reserves estimated at over 100 trillion cubic feet, the need to reduce dependence on coal and oil, and international commitments to reduce greenhouse gas emissions.

The expansion of gas infrastructure has been equally impressive and presents both opportunities and challenges. PT Perusahaan Gas Negara Tbk (PGN), Indonesia's primary gas distribution company and state-owned enterprise, operates over 10,000 kilometers of distribution and transmission pipelines spanning major islands including Java, Sumatra, and Kalimantan [2]. This extensive network represents approximately 96% of the nation's natural gas infrastructure, making PGN the backbone of Indonesia's gas distribution system. By the end of 2019, PGN distributed 988 BBTUD (Billion British Thermal Units per Day) through distribution networks serving residential, commercial, and industrial customers, alongside 2,045 MMSCFD (Million Standard Cubic Feet per Day) through transmission systems connecting production facilities to major consumption centers [2]. The rapid infrastructure expansion has connected previously underserved regions, enabling economic development and improving access to cleaner cooking fuels for households. However, the sheer scale and geographic dispersion of this infrastructure create significant challenges for maintenance, monitoring, and safety management.

This rapid infrastructure development brings inherent safety challenges that require innovative solutions. Gas leaks in production and distribution facilities pose significant risks to public health, environmental quality, and economic assets. Natural gas, primarily composed of methane, is highly flammable and can form explosive mixtures when concentrations in air reach 5-15% by volume. Beyond explosion hazards, methane is a potent greenhouse gas with a global warming potential approximately 28 times greater than carbon dioxide over a 100-year timeframe, making leak prevention crucial for climate change mitigation [22]. Prolonged exposure to high concentrations of natural gas can cause asphyxiation by displacing oxygen, while certain gas processing additives and trace contaminants may present additional health hazards. The economic impact of gas leaks is substantial, representing lost product value, potential liability costs, and damage to infrastructure and surrounding properties.

Recent incidents underscore the urgent need for improved leak detection and monitoring systems. In July 2019, an oil and gas pipeline leak along the North Coast of Java Island was reported by Pertamina to SKK Migas (Special Task Force for Upstream Oil and Gas Business Activities) and the Ministry of Energy and Mineral Resources [3]. This incident, occurring in a region with dense industrial activity and significant population, highlighted vulnerabilities in pipeline integrity management and the challenges of detecting leaks in offshore or difficult-to-access locations. Similarly, in January 2020, a natural gas pipeline leak occurred in a residential area of Depok City, West Java, causing widespread concern among residents who reported strong gas odors [4]. This incident particularly emphasized the proximity of gas infrastructure to populated areas and the potential health hazards from excessive natural gas inhalation, including headaches, dizziness, nausea, and in severe cases, loss of consciousness. These events, while successfully managed without major casualties, reveal critical gaps in current monitoring capabilities and response protocols. They demonstrate that despite regulatory frameworks and safety procedures, the existing inspection and monitoring systems may not provide adequate coverage or sufficiently rapid detection of leaks to prevent hazardous situations from developing.

Traditional manual inspection methods for detecting gas leaks, while still widely employed, are increasingly inadequate for the scale and complexity of modern gas distribution networks. These conventional approaches typically involve trained personnel using handheld gas detectors to inspect pipelines, connections, and facilities at regular intervals or in response to reported concerns. The fundamental limitations of this approach are numerous and significant. First, the limited coverage of large geographical areas within reasonable timeframes means that vast sections of pipeline networks may go uninspected for extended periods, creating windows of vulnerability where leaks can develop and persist undetected. Manual inspections of PGN's 10,000+ kilometer network, for instance, would require enormous human resources and time to achieve even minimal coverage frequencies. Second, difficulty accessing hazardous or restricted locations such as pipeline segments crossing rivers, dense forests, swamps, or industrial facilities limits the comprehensiveness of manual inspections. Third, manual detection methods provide insufficient spatial resolution in gas concentration measurements, typically offering only point measurements at specific locations rather than continuous spatial distributions that would enable better understanding of leak sources and plume behavior. Fourth, delayed response times to potential leak incidents result from the reactive nature of scheduled inspections and the time required to dispatch inspection teams to suspected leak locations. Finally, high operational costs associated with manual monitoring, including personnel salaries, equipment maintenance, transportation, and safety measures, make frequent comprehensive inspections economically challenging, particularly for organizations managing extensive infrastructure networks.

These limitations necessitate an automated, efficient, and comprehensive approach to gas leak detection and concentration mapping. The ideal solution would combine wide-area coverage capability with high spatial resolution, real-time or near-real-time monitoring, access to difficult terrain, cost-effectiveness for routine deployment, and the ability to generate actionable intelligence for maintenance and emergency response. Emerging technologies in autonomous systems, advanced sensing, and data processing offer promising pathways to address these requirements. Unmanned Aerial Vehicles (UAVs), also known as drones, have emerged as particularly attractive platforms for gas detection applications due to their mobility, ability to access difficult terrain, relatively low operational costs compared to manned aircraft, and capacity to carry various sensor payloads [14][15]. However, realizing the full potential of UAV-based gas detection requires integration with sophisticated algorithms for navigation, mapping, and data interpretation.

This research proposes a UAV-based gas concentration mapping system that integrates advanced robotics and sensing technologies to overcome the limitations of traditional inspection methods. The system architecture consists of four key technological components working in concert. First, the UAV platform provides aerial mobility enabling extensive area coverage and access to difficult terrain including elevated pipelines, remote locations, and hazardous environments. Modern hexacopter configurations offer excellent stability, redundancy for safety, and sufficient payload capacity for sensor integration while maintaining flight times of 20-25 minutes sufficient for practical survey missions. Second, SLAM (Simultaneous Localization and Mapping) algorithms enable accurate localization in GPS-uncertain environments, which is crucial given that GPS signals may be degraded or unavailable in certain operational contexts such as dense urban areas, forested regions, or near large structures. SLAM technology allows the UAV to build accurate maps of unknown environments while simultaneously determining its precise location within those maps, providing a foundation for georeferencing gas concentration data. Third, Kernel-DM (Kernel Distribution Mapping) algorithms generate continuous gas concentration distribution maps from discrete sensor measurements. Rather than representing gas concentrations as isolated point measurements, Kernel-DM creates smooth, continuous spatial distributions that better reflect the physical behavior of gas plumes and enable more effective visualization and interpretation. Fourth, real-time monitoring capabilities through web-based interfaces allow operators to visualize gas distributions on actual environmental maps as data is collected, enabling immediate decision-making for mission adjustment, emergency response, or detailed investigation of detected anomalies.

The significance of this research extends across multiple dimensions. From a safety perspective, improved leak detection capabilities can prevent accidents, protect public health, and reduce environmental impacts. Early detection of leaks enables proactive maintenance rather than reactive emergency response, potentially preventing small leaks from escalating into major incidents. From an economic standpoint, reducing gas losses through better leak detection directly improves operational efficiency and revenue protection for gas distribution companies. The system's ability to conduct frequent, comprehensive surveys at lower cost compared to traditional methods makes it economically attractive for routine monitoring. From an environmental perspective, reducing methane emissions through improved leak detection and repair contributes to climate change mitigation efforts and helps organizations meet increasingly stringent environmental regulations. From a technological perspective, this research advances the state-of-the-art in autonomous UAV systems, gas sensing, and spatial data processing, with potential applications beyond gas infrastructure monitoring including environmental monitoring, industrial safety, and emergency response.

The primary objectives of this research are multifaceted and interconnected. First, to conduct a comprehensive review of existing literature on gas detection and mapping systems using mobile robots and UAVs, synthesizing current knowledge and identifying the state-of-the-art in relevant technologies including gas sensing methods, mobile platform capabilities, localization and mapping algorithms, and gas distribution modeling approaches. Second, to identify limitations and gaps in current approaches through critical analysis of existing systems, particularly focusing on issues related to spatial resolution, real-world applicability, operational efficiency, and accuracy in diverse environments. Third, to design a comprehensive UAV-based system integrating SLAM and Kernel-DM algorithms that addresses identified limitations while providing practical capabilities for real-world deployment. Fourth, to develop a detailed methodology for real-time gas concentration mapping in unknown environments, including data acquisition protocols, processing algorithms, visualization techniques, and operational procedures. Fifth, to evaluate different UAV flight patterns for optimal gas distribution surveying through analysis of coverage efficiency, detection probability, and resource utilization, providing guidance for mission planning in various operational scenarios. These objectives collectively aim to advance both the theoretical understanding and practical implementation of UAV-based gas detection systems, contributing to safer and more efficient gas infrastructure management.

2. METHOD

2.1. Literature Review

Gas distribution mapping has evolved significantly with advances in mobile robotics and sensing Technologies. This section reviews key contributions in the field and identifies areas for improvement.

An autonomous mobile robot system for gas detection and mapping was developed in 2015 [5], which successfully generated gas concentration maps in explored areas. Their approach, however, produced two-dimensional trajectory graphs that lacked correlation with actual environmental coordinates, limiting practical applicability for field operations. The absence of real-world mapping context prevented operators from identifying precise leak locations.

A study on online gas contamination mapping in outdoor environments using solar-powered mobile robots [6] advanced the field by overlaying gas concentration data onto actual environmental maps and classifying positions as either dangerous or safe. While this binary classification provided useful safety information, the system did not generate continuous concentration distributions. The node-based representation failed to capture the gradient nature of gas dispersion, which is crucial for understanding leak severity and affected areas.

Research on real-world gas distribution mapping and leak localization introduced sophisticated sensing capabilities by equipping mobile robots with RMLD (Remote Multi-path Laser Diode) gas sensors capable of determining distances to specific gas sources [7]. The integration of LIDAR (Light Detection and Ranging) and GPS enabled navigation and generation of both gas source maps and distribution maps. Despite these advances, the system's outdoor detection accuracy was inferior to indoor performance, and the maps lacked real-world environmental context.

The SLAM-GDM (SLAM-Gas Distribution Mapping) implementation on Robot Operating System for gas source localization [8] made significant progress by integrating SLAM algorithms with Kernel-DM for real-time gas source localization. This approach improved navigation accuracy and distribution mapping quality. However, optimal performance required slow robot movement, limiting operational efficiency. Additionally, the maps did not accurately represent actual environmental dimensions.

A comprehensive study on combining non-selective gas sensors on mobile robots for identification and mapping of multiple chemical compounds [9] extended gas mapping capabilities beyond single-gas detection. The system employed PID (Proportional-Integral-Derivative) control for navigation and Kernel-DM+V for distribution mapping, operating successfully in both indoor and outdoor environments. The primary limitation was the focus on gas type identification rather than concentration quantification, which is essential for assessing health and safety risks.

Analysis of existing literature reveals several common limitations: lack of real-world map integration where many systems generate abstract maps without correlation to actual geographic coordinates, discrete versus continuous representation where binary or node-based representations fail to capture continuous gas concentration gradients, navigation speed constraints where some SLAM-based approaches require slow movement, indoor-outdoor performance disparity where most systems perform better indoors with reduced accuracy in outdoor environments, limited concentration quantification with focus on detection or classification rather than precise concentration measurement, and sensor limitations including high costs or limited availability of advanced gas sensors like TDLAS (Tunable Diode Laser Absorption Spectroscopy).

2.2. Theoretical Foundation

2.2.1. Simultaneous Localization and Mapping (SLAM)

SLAM represents a cornerstone capability in autonomous robotics, enabling robots to construct maps of unknown environments while simultaneously determining their position within those maps. The fundamental SLAM problem can be formulated mathematically where the motion model describes how the robot's pose evolves over time:

$$x_t = g(u_t, x_{t-1}) + \delta_t \tag{1}$$

where x_t represents the current robot pose (position and orientation), $g(u_t, x_{t-1})$ is a nonlinear function describing motion dynamics, u_t denotes the control input at time t, x_{t-1} represents the previous pose, and δ_t is Gaussian random noise with zero mean, representing uncertainty.

Data association establishes correspondences between newly observed features and previously mapped landmarks. Accurate data association is crucial for maintaining consistent maps and enabling the robot to recognize previously visited locations. Loop closure detection occurs when the robot recognizes that it has returned to a previously visited location, essential for correcting accumulated drift errors in pose estimation.

Hector SLAM offers particular advantages for UAV applications [10]. Unlike many SLAM variants that rely on wheel odometry, Hector SLAM operates using only laser scan data, making it suitable for aerial vehicles. The algorithm employs scan matching to estimate the robot's 2D pose by optimizing the alignment between current LIDAR scan endpoints and the existing map. Multi-resolution representation avoids local minima during optimization and enables real-time performance. Implemented within the ROS (Robot Operating System) framework, Hector SLAM achieves update rates up to 50 Hz, enabling real-time operation crucial for dynamic UAV applications [20].

2.2.2. Kernel Distribution Mapping (Kernel-DM)

Gas distribution modeling transforms discrete, spatially and temporally distributed sensor measurements into continuous, predictive representations of gas concentrations throughout an environment. The Kernel-DM algorithm, first introduced in 2004 [11], employs a statistical learning approach to predict gas distributions.

The method represents learned models through four complementary maps: Grid Map discretizes the environment into cells where measurements can be aggregated and predictions made; Weight Map stores the sum of kernel weights for each cell, reflecting the influence of nearby measurements; Confidence Map provides estimates of average gas concentrations at each location, serving as the primary output for visualizing gas distribution patterns; and Predictive Variance Map quantifies uncertainty in concentration estimates, helping operators assess the reliability of predictions and identify areas requiring additional measurements.

2.3. System Architecture

The proposed gas concentration mapping system integrates multiple components operating in a coordinated fashion. The system architecture comprises three main subsystems:

Sensing Subsystem: Collects environmental data including gas concentrations, LIDAR scans, and GPS coordinates

Processing Subsystem: Executes SLAM and Kernel-DM algorithms for localization, mapping, and gas distribution modeling

Visualization Subsystem: Presents real-time gas concentration maps overlaid on actual environmental maps through web-based interfaces

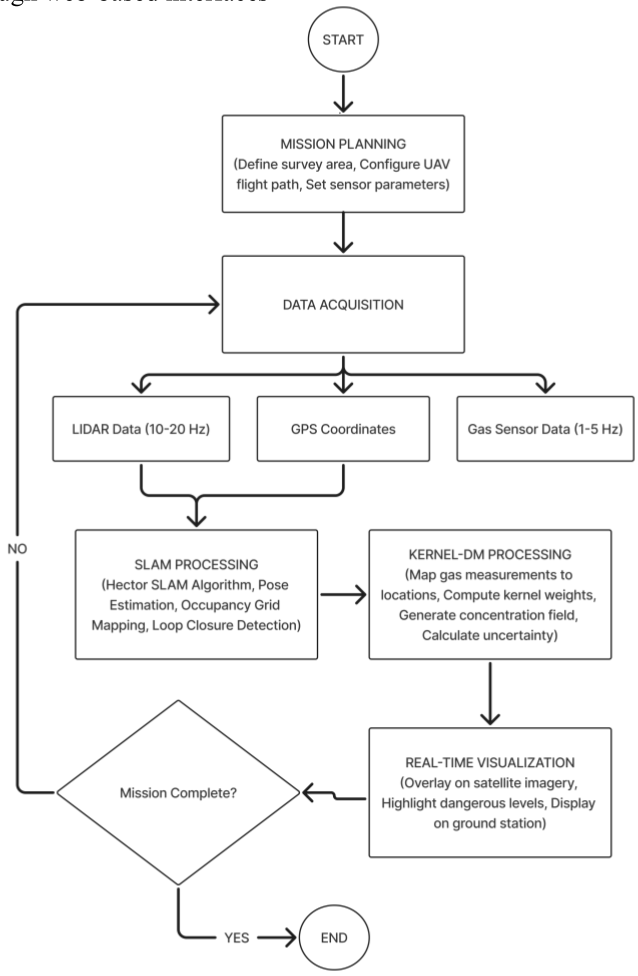

Figure 1. System Working Mechanism Diagram showing the integration of UAV, SLAM-based localization, and Kernel-DM algorithms for real-time gas concentration mapping

2.4. Hardware Design

The system employs a hexacopter configuration offering redundancy for improved safety, stable platform for sensor mounting, sufficient payload capacity, and extended flight time through efficient motor configuration. The PixHawk 4 flight controller serves as the primary autopilot, providing stabilization and attitude control, GPS-based navigation capabilities, integration with ground control software, and telemetry communication via SiK radio modules.

Key sensors include 360-degree LIDAR providing continuous 2D scanning with 10-30 meter range and high angular resolution for SLAM algorithm input. GPS module supplies initial position estimates with 2-5 meter accuracy, enabling georeferencing of maps while SLAM refines these estimates for precise localization. Gas sensors employ Metal-Oxide (MOX) technology with modifications for improved performance, detecting multiple species including Carbon Monoxide (CO) and hydrocarbons (CxHy) for natural gas component detection. The Odroid XU4 single-board computer handles ROS node execution for SLAM and Kernel-DM algorithms, sensor data acquisition and preprocessing, communication with the flight controller, and data logging for post-mission analysis

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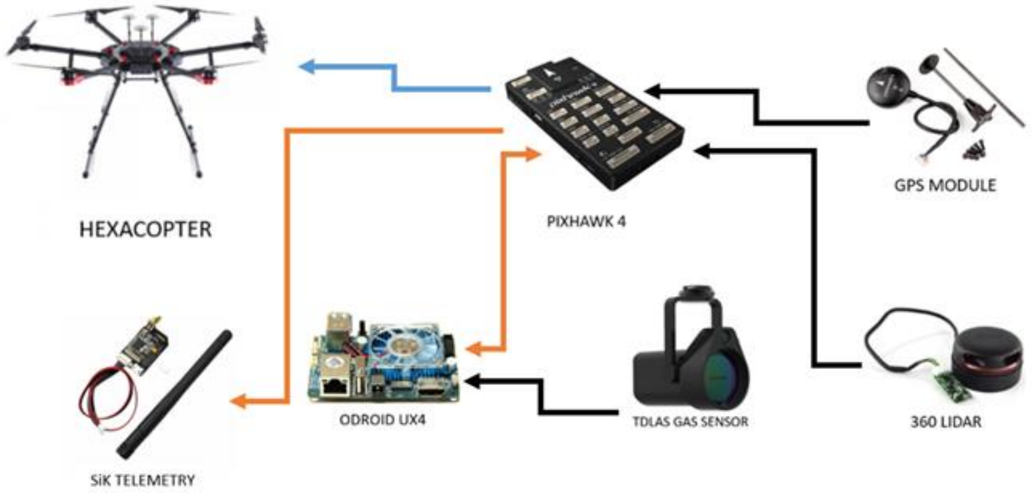

Figure 2. Hardware Components Architecture depicting the system integration including flight control, onboard processing, gas sensors, LIDAR, and GPS units

The overall system design will be created using SketchUp software. The result of the system design is shown below:

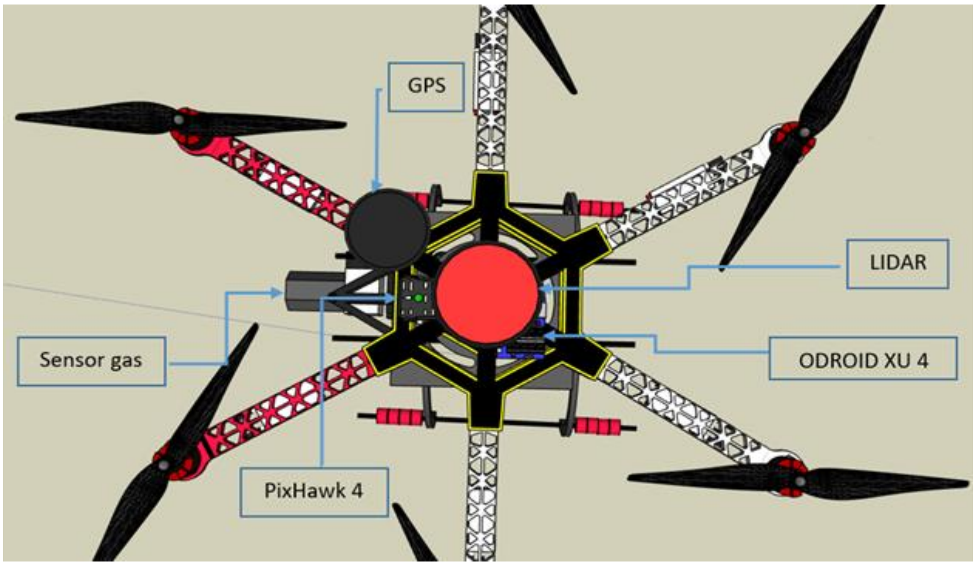

Figure 3. Hardware Design: Top View of UAV showing sensor and component placement for optimal gas detection and environmental sensing

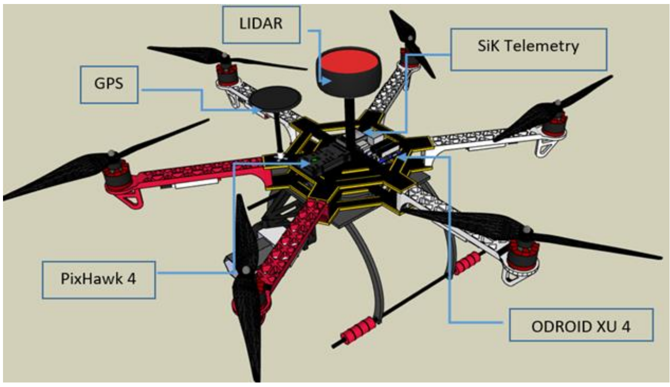

Figure 4. Hardware Design: Side View of UAV illustrating the vertical structural configuration and sensor mounting positions

2.5. Software Architecture

ROS provides a flexible framework for implementing the gas mapping system through modular node architecture, message passing between components, and standard interfaces for sensor data, navigation information, and geometry. The software operates through five main modules.

Module 1 - Sensor Interface acquires raw data from LIDAR, GPS, and gas sensors. Module 2 - SLAM Processing executes Hector SLAM algorithm and publishes pose estimates. Module 3 - Gas Distribution Modeling implements Kernel-DM algorithm. Module 4 - Mission Management controls UAV flight patterns and monitors system health. Module 5 - Visualization displays real-time maps and concentration overlays.

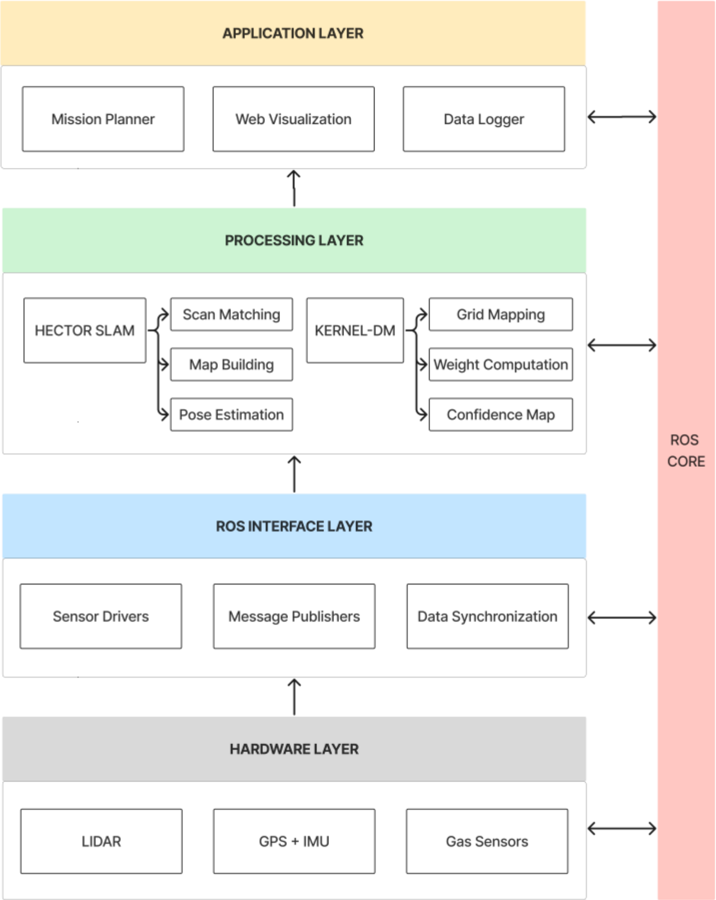

Figure 5. Software Processing Pipeline demonstrating the ROS-based workflow from sensor data acquisition through SLAM localization and Kernel-DM gas distribution mapping

2.6. Flight Pattern Strategies

Effective coverage of the surveying area requires optimized flight patterns. This research evaluates three distinct trajectory strategies.

Sweeping Pattern (Lawnmower Pattern)

The UAV follows parallel straight-line paths with systematic lateral displacement between passes. Advantages include complete systematic coverage, simple planning and execution, uniform spatial sampling density, and efficiency for large open areas. Disadvantages include frequent turning maneuvers, potential to miss concentrations between passes, and reduced effectiveness in irregularly shaped areas.

Spiral Pattern

The UAV follows a gradually expanding or contracting spiral trajectory from a central point. Advantages include continuous movement without sharp turns, suitability for circular or square areas, and enabling rapid initial assessment. Disadvantages include variable spatial sampling density, complex trajectory planning, and reduced efficiency for elongated areas.

Adaptive Pattern

The UAV trajectory adapts based on preliminary gas concentration measurements, focusing on areas with elevated readings. Advantages include concentrated effort on regions of interest, efficiency for leak localization, and optimized information gain. Disadvantages include requirements for real-time decision-making algorithms, potential to initially miss isolated leaks, and implementation complexity.

Coverage: 95-100%
Time: Medium
Description: Efficient horizontal zigzag pattern for maximum coverage

Coverage: 85-95%
Time: Low
Description: Circular pattern from outside to center, faster with good coverage

Coverage: Variable
Time: Adaptive
Description: Initial survey then focus on high concentration areas

Figure 6. Flight Pattern Comparison analyzing sweeping, adaptive, and hybrid flight strategies for efficient gas concentration mapping coverage

Hybrid Approach (Recommended)

A three-phase hybrid approach is recommended: Phase 1 employs coarse sweeping pattern covering 30% to identify regions of interest; Phase 2 uses adaptive refinement in high-concentration areas for detailed leak characterization; Phase 3 implements verification sweeps of modified areas to confirm leak extent and boundaries.

3. RESULTS AND DISCUSSION

3.1. Expected System Capabilities

The proposed UAV-based gas concentration mapping system is expected to deliver several key capabilities. Enhanced localization accuracy through integration of SLAM algorithms with GPS provides precise localization even in GPS-degraded environments. Continuous gas distribution maps generated by Kernel-DM transform discrete sensor measurements into smooth, continuous concentration fields. The system's architecture enables real-time data processing and visualization. Gas concentration data is precisely tied to actual geographic coordinates through accurate georeferencing. The probabilistic framework provides confidence estimates alongside concentration predictions through uncertainty quantification.

3.2. Operational Advantages

UAV mobility enables surveying of large areas including difficult-to-access locations, providing extensive coverage. Quick deployment for incident investigation or routine monitoring offers rapid response capabilities. Lower operational costs compared to traditional inspection methods demonstrate cost effectiveness. Remote operation keeps personnel away from hazardous zones, enhancing safety. High spatial resolution measurements support informed decision-making through superior data quality.

3.3. Performance Evaluation Framework

The system will be evaluated through comprehensive testing protocols. Coverage metrics assess percentage of area surveyed and spatial distribution uniformity. Efficiency metrics measure survey completion time and energy consumption. Accuracy metrics evaluate error in estimated concentration fields, uncertainty reduction, and leak localization precision. The evaluation framework systematically compares different flight patterns across these dimensions to identify optimal strategies for various operational scenarios.

Table 1. Flight Pattern Performance Comparison

Pattern Type	Coverage	Efficiency	Best Application
Sweeping	High (95-100%)	Medium	Rectangular areas, initial surveys
Spiral	Medium (85-95%)	High	Circular areas, centered sources
Adaptive	Variable (70-100%)	Very High	Leak localization, follow-up

3.4. Implementation Challenges and Solutions

Several implementation challenges have been identified with proposed solutions. GPS signal degradation in urban or forested environments is addressed through Hector SLAM's ability to maintain accurate localization using only LIDAR data. Limited UAV flight time of 20-25 minutes is mitigated through efficient mission planning and potential multi-UAV deployment. Sensor cross-sensitivity where MOX sensors respond to multiple gases is handled through multi-sensor arrays and signal processing algorithms. Wind effects on gas plume dispersion are considered in the Kernel-DM modeling with potential integration of meteorological data. Real-time processing requirements are met through optimized algorithms and efficient ROS implementation on embedded hardware.

3.5. Future Research Directions

Future work will focus on several key areas. Integration of meteorological data including wind speed and direction can improve gas dispersion modeling. Development of autonomous leak source localization algorithms will enable the system to automatically identify and track leak sources. Extension to multi-UAV collaborative mapping can dramatically increase coverage area and reduce survey time. Machine learning approaches for adaptive flight path optimization can improve efficiency. Integration with existing GIS (Geographic Information System) infrastructure will enhance practical utility for industrial applications

4. CONCLUSIONS AND SUGGESTIONS

This literature review and proposed methodology present a comprehensive approach to gas concentration mapping using UAV technology integrated with advanced robotics algorithms. The analysis of existing research reveals significant gaps in current methodologies, including lack of real-world map integration, discrete rather than continuous gas distribution representation, and limitations in outdoor detection accuracy.

The proposed system addresses these limitations through several key innovations. Robust localization is achieved through Hector SLAM providing accurate position estimation without relying solely on GPS. Continuous distribution modeling transforms discrete sensor readings into smooth, continuous concentration fields through Kernel-DM algorithms. Real-time capabilities are enabled by ROS-based software architecture supporting high-frequency updates up to 50 Hz. Practical implementation is ensured through hardware design considerations for deployment in real-world environments. Optimized flight patterns through systematic evaluation of trajectory strategies identify the most effective approaches.

The integration of these components creates a powerful tool for enhancing safety in gas infrastructure management. The system offers advantages in coverage area, operational efficiency, cost-effectiveness, and data quality compared to traditional manual inspection methods. The hybrid flight pattern approach combining sweeping, adaptive, and verification phases provides an optimal balance between comprehensive coverage and focused investigation of detected anomalies.

Future work will focus on system implementation, field testing, and validation against operational requirements. Additional research directions include integration of meteorological data for improved gas dispersion modeling, development of autonomous leak source localization algorithms for automatic detection and tracking, extension to multi-UAV collaborative mapping for increased coverage and efficiency, and integration with existing GIS infrastructure for enhanced practical utility in industrial applications.

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