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Bio-Inspired Sensing Integration with UAVs for Real-Time Odor Localization in Gas Factories

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Abstract—Gas leakage detection in industrial environments is a critical safety challenge due to the rapid dispersion and invisibility of hazardous gases such as ammonia, methane, and hydrogen sulfide. Conventional gas sensing technologies often suffer from limitations in sensitivity, selectivity, and response time, particularly in turbulent conditions. This paper presents a bio-inspired UAV-based system for real-time odor detection and localization. The proposed system utilizes advanced sensing and signal processing techniques to detect volatile compounds with high sensitivity. To achieve efficient source localization, a biologically inspired cast-and-surge search algorithm is implemented, enabling the UAV to navigate odor plumes by alternating between upwind movement during detection (surge) and crosswind exploration during signal loss (cast). To further enhance performance, a plume-based modeling algorithm is integrated, which improves detection capability in highly dispersed and turbulent gas conditions. This addition significantly enhances the practicality, robustness, and efficiency of the system in real-world industrial environments. The system operates autonomously with onboard processing and navigation modules. Experimental results demonstrate improved localization accuracy (below 1 m), faster convergence, and enhanced selectivity compared to conventional systems. The proposed approach provides an effective and scalable solution for gas leak detection in industrial environments.

Index Terms—Unmanned Aerial Vehicle (UAV), Gas Leak Detection, Odor Localization, Bio-Inspired Systems, Cast-and-Surge Algorithm, Plume Modeling, Gaussian Plume Model, Autonomous Navigation, Industrial Safety, Gas Sensors.

I. INTRODUCTION

Industrial gas leakage poses a significant threat to human safety, environmental sustainability, and operational efficiency in chemical plants and gas processing facilities. Hazardous gases such as ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S) are often invisible and can disperse rapidly under varying environmental conditions, making early detection and accurate localization a challenging task [1]. Conventional gas sensing systems, including metal oxide semiconductor (MOX) sensors and photoionization detectors (PID), are widely used but suffer from limitations such as low selectivity, cross-sensitivity, slow response time, and reduced performance in turbulent environments [2].

Recent advancements in unmanned aerial vehicles (UAVs) have enabled flexible and rapid deployment of sensing systems for environmental monitoring and gas leak detection. UAV-based platforms provide mobility, real-time data acquisition, and access to hazardous or inaccessible areas. However, effective gas source localization remains a complex problem due to the dynamic and intermittent nature of gas plumes, especially in industrial environments where airflow is highly turbulent [3].

To address these challenges, bio-inspired approaches have gained increasing attention. In particular, odor localization strategies inspired by insect behavior, such as the cast-and-surge mechanism, have demonstrated strong performance in navigating fragmented gas plumes. This method allows the system to move upwind when a gas signal is detected and perform lateral search when the signal is lost, enabling reliable plume tracking without requiring continuous gradient information.

In addition to navigation strategies, plume modeling techniques play a critical role in improving localization performance. The Gaussian plume model provides an effective representation of gas dispersion and helps estimate the spatial distribution of gas concentration under varying environmental conditions. Integrating plume modeling with bio-inspired navigation enhances detection capability in highly dispersed and turbulent gas environments [4].

In this work, a bio-inspired UAV-based system is proposed for real-time gas detection and localization in industrial environments. The system integrates advanced sensing mechanisms, a cast-and-surge navigation strategy, and plume modeling to improve localization accuracy and efficiency. Furthermore, a hazard identification and marker deployment mechanism is incorporated to enhance practical applicability and support rapid industrial response.

The proposed approach aims to overcome the limitations of conventional gas detection systems by providing a robust, scalable, and efficient solution for real-world industrial applications.

2. LITERATURE REVIEW

Conventional gas sensing technologies such as metal oxide semiconductor (MOX) sensors and photoionization detectors (PID) are widely used due to their reliability and cost-effectiveness. However, these systems suffer from limitations including low selectivity, cross-sensitivity, slow response time, and reduced performance in turbulent environments [5]. These challenges significantly affect the accuracy of gas detection in real-world industrial conditions.

To overcome these limitations, bio-inspired gas sensing systems have gained attention in recent years. Biological olfactory systems, particularly insect-based sensing mechanisms, demonstrate high sensitivity and selectivity due to specialized olfactory receptors. Research has shown that electroantennography (EAG) can be used to convert biological responses into measurable electrical signals, providing an effective alternative to conventional sensing technologies [6].

Odor localization techniques in robotic systems have also evolved significantly. Traditional approaches such as gradient-based and plume-based methods often fail in dynamic and turbulent environments due to the intermittent nature of gas plumes. Bio-inspired navigation strategies, especially the cast-and-surge mechanism observed in insects, have proven to be more robust and effective under such conditions [7].

Despite these advancements, most existing studies are limited to controlled laboratory environments and do not fully integrate bio-sensing systems into UAV platforms. Furthermore, the combination of biological sensing with advanced navigation and plume modeling techniques remains underexplored. Therefore, there is a need for a comprehensive approach that integrates bio-inspired sensing, UAV mobility, and intelligent localization strategies for real-time industrial gas leak detection [8].

Further research has explored the use of UAV-based systems combined with advanced sensing and mapping techniques for gas detection. UAV platforms provide real-time monitoring capabilities and enable access to hazardous environments where manual inspection is not feasible. Studies have demonstrated that UAV-based gas sensing systems can achieve high spatial resolution and improved detection efficiency compared to traditional ground-based systems [9].

Recent developments in gas source localization have also focused on the integration of probabilistic and model-based approaches. These methods utilize environmental data and sensor measurements to estimate the most probable location of the gas source. Such approaches improve localization accuracy, especially in complex environments where gas dispersion is influenced by multiple external factors such as wind and obstacles [10].

Additionally, machine learning techniques have been introduced to enhance gas detection and classification. These approaches enable UAV systems to learn from sensor data and improve detection performance over time. Research has shown that machine learning-based models can provide faster and more accurate detection compared to traditional methods, particularly in dynamic industrial conditions [11].

Moreover, multi-UAV cooperative systems have been investigated to improve coverage and efficiency in large-scale environments. These systems allow multiple UAVs to share information and collaboratively track gas plumes, resulting in faster localization and improved reliability. However, challenges such as communication constraints and coordination complexity still need to be addressed [12].

Overall, existing literature highlights significant progress in UAV-based gas detection, bio-inspired navigation, and plume modeling. However, there remains a gap in fully integrating these approaches into a unified system capable of operating effectively in real-world industrial environments.

2.1 Motivation

An industrial gas leak is potentially dangerous for workers and the environment, along with posing considerable costs for chemical and gas production plants. Ammonia, methane, and other toxic and highly flammable chemicals cannot be detected visually and disperse extremely quickly. The conventional sensing technologies are unable to precisely localize the source of an emission.

Thus, the present research is motivated by a necessity to create a sensing mechanism that could help to solve the problem of industrial gas leakage detection, being more sensitive and reliable than current sensing technologies. As biological olfactory mechanisms allow organisms to identify trace amounts of certain substances with great accuracy, using biologically inspired detection is promising.

Moreover, the use of unmanned aerial vehicles equipped with bio-sensors opens vast possibilities to increase the effectiveness of the proposed technology and make it more convenient.

2.2 Objectives of the Work

The main goal of this study is to design and develop a bio-inspired UAV platform for online identification and localization of harmful gas leakage within industrial facilities.

The following are some of the objectives of the study:
1. Integrate the biological EAG gas sensing method into the UAV platform to improve gas detection ability.
2. Develop a bio-inspired odor localization mechanism based on the Cast-and-Surge search strategy.
3. Utilize Gaussian plume modeling for the analysis and evaluation of the bio-hybrid system.
4. Analyze the sensitivity, specificity, response time, and accuracy of the system.
5. Compare the performance of the bio-hybrid system with the existing MOX sensor-based UAV systems.

In addition to the primary objectives, this study also aims to establish a reliable framework for real-time data acquisition, processing, and transmission within the UAV system. The integration of embedded controllers, signal conditioning circuits, and wireless communication modules ensures that the electroantennogram signals are captured with minimal noise and transmitted efficiently for analysis. Emphasis is placed on optimizing system latency and ensuring stable operation under varying flight conditions, thereby enabling continuous monitoring of gas concentrations during UAV navigation.

Furthermore, the work seeks to enhance the practical applicability of the proposed system by addressing challenges related to environmental variability and system robustness. Factors such as airflow turbulence, temperature fluctuations, and humidity are considered in both design and testing phases to ensure consistent performance in real-world industrial scenarios. The study also focuses on improving the autonomy of the UAV through intelligent decision-making algorithms, allowing it to adaptively navigate towards the source of gas leakage with minimal human intervention while maintaining operational safety and efficiency.

3. METHODOLOGY

3.1 Bio-Hybrid Sensing System

The proposed system utilizes a bio-hybrid sensing approach for detecting trace concentrations of hazardous gases in industrial environments. This approach combines biological sensing mechanisms with electronic signal processing to achieve high sensitivity and selectivity. Bio-inspired sensing systems have been shown to outperform conventional gas sensors in detecting low-concentration volatile compounds due to their ability to respond to specific chemical signatures [13].

3.1.1 Electroantennography Sensor Module

The electroantennography (EAG) sensor module consists of excised insect antennae mounted on precision-grooved silver/silver-chloride (Ag/AgCl) electrodes. The grooved electrode design accommodates antenna lengths of 1–2 cm and minimizes motion-induced noise, improving signal stability and consistency. EAG-based sensing enables the conversion of biological olfactory responses into measurable electrical signals, providing high sensitivity to volatile compounds [14].

The electrical signals generated by the antenna are amplified using a programmable gain amplifier (PGA) and digitized using a microcontroller-based acquisition system. Signal conditioning techniques are applied to enhance signal quality, including:

- 50 Hz notch filtering
- Baseline drift correction
- Adaptive gain control

3.1.2 Multi-Gas Detection Architecture

To enable detection of multiple hazardous gases, a parallel antenna array configuration is implemented. The system consists of four sensing channels, each tuned to specific gases such as ammonia (NH_3), methane-related VOCs, and hydrogen sulfide (H_2S). Multi-channel sensing improves detection coverage and allows differentiation between gas types.

3.1.3 Mechanical Integration and Power

A lightweight airflow-guiding enclosure is designed to improve gas intake efficiency. The enclosure directs incoming air toward the sensing elements within a 30° frontal cone, enhancing plume interception during UAV motion. The complete sensing module weighs less than 200 g and consumes approximately 50 mW of power, making it suitable for UAV integration.

	Bio-Hybrid EAG	**MOX Sensor**	**PID Sensor**
Sensitivity (NH_3)	1 ppt	100 ppb	10 ppb
Selectivity	95%	60%	80%
Response Time	50 ms	2 s	500 ms

Table 1: Performance comparison of gas sensing technologies

3.2 UAV Platform Integration

The proposed bio-hybrid sensing module is integrated into an unmanned aerial vehicle (UAV) platform to enable real-time gas detection and localization in industrial environments. UAV-based systems provide high mobility, rapid deployment, and the ability to operate in hazardous or inaccessible areas. These advantages make UAVs highly suitable for environmental monitoring and gas leak detection applications [15].

The sensing module is mounted on a quadcopter UAV platform derived from the DJI Matrice 300, which supports payload capacities of up to 2 kg. To minimize airflow disturbance caused by rotor downwash, the sensor module is positioned forward of the UAV body. This placement ensures stable and consistent airflow over the sensing unit, improving detection reliability.

3.2.1 Navigation and Processing Framework

The UAV integrates multiple onboard systems for navigation, sensing, and real-time decision-making. These include:

- Global Positioning System (GPS) for position tracking
- Inertial Measurement Unit (IMU) for orientation and stability
- Onboard anemometer for wind speed and direction estimation
- Embedded processing unit (Raspberry Pi 5) for real-time data processing

Sensor data is continuously processed onboard to determine gas presence and guide navigation decisions. The integration of wind estimation with sensing data improves the UAV’s ability to align with gas plume direction.

Real-time processing plays a critical role in enabling autonomous operation. Studies have shown that UAV systems equipped with onboard computation and sensor fusion techniques can significantly improve localization accuracy and response time in gas detection applications [16].

The combination of sensing, navigation, and processing modules allows the UAV to operate autonomously and adaptively in complex industrial environments.

3.3 Odor Localization Strategy

To achieve accurate gas source localization in turbulent industrial environments, the proposed system employs a hybrid odor localization strategy that combines bio-inspired navigation with plume modeling. This approach enables the UAV to respond to intermittent gas signals while maintaining directional guidance toward the source.

3.3.1 Gaussian Plume Model

To enhance localization performance, a Gaussian plume model is incorporated to represent gas dispersion in the environment. This model provides a probabilistic estimate of gas concentration distribution under wind-driven transport.

The concentration at a point (x, y, z) is given by:

$$C(x,y,z) = Q / (2\pi U\sigma_y\sigma_z) \cdot \exp(-y^2 / (2\sigma_y^2)) \cdot \exp(-(z - H)^2 / (2\sigma_z^2))$$

For UAV operation at constant altitude ($z = H$), the equation simplifies to:

$$C(x,y) = Q / (2\pi U\sigma_y^2) \cdot \exp(-y^2 / (2\sigma_y^2))$$

where:

C = gas concentration
Q = emission rate
U = wind speed
σ_y, σ_z = dispersion coefficients
H = source height

This model helps estimate plume spread and supports navigation decisions in highly dispersed gas conditions [18].

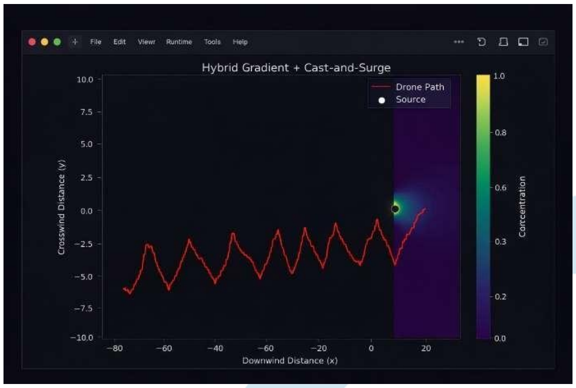

Fig 1: 2D Gaussian Plume Model

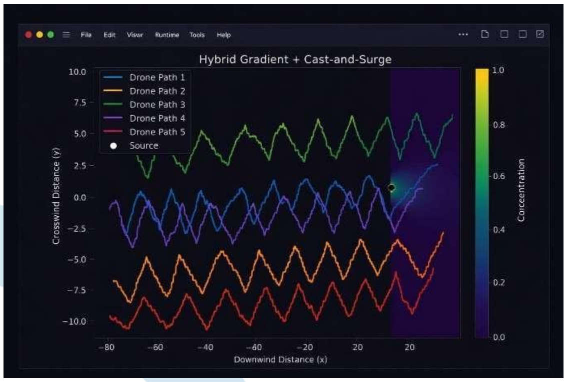

Fig 2: 2D Gaussian Plume Model (with multi Drone Paths)

3.3.2 Cast-and-Surge Algorithm

The cast-and-surge algorithm is a bio-inspired navigation strategy derived from insect foraging behavior. It is particularly effective in environments where gas plumes are fragmented and do not form continuous concentration gradient

The algorithm operates in two primary phases:

- Surge Phase:
  When the detected gas concentration exceeds a predefined threshold ($C > C_{th}$), the UAV moves in the upwind direction toward the source.

- Cast Phase:
  When the gas signal is lost ($C \leq C_{th}$), the UAV performs lateral oscillatory motion to reacquire the plume.

Mathematically, the motion can be expressed as:

Surge phase:

$$v = v_s \cdot (-\hat{u})$$

Cast phase:

$$y(t) = A \sin(\omega t)$$

where:
v = UAV velocity
v_s = surge speed
$\hat{u}$ = unit wind direction
A = casting amplitude
ω = oscillation frequency

This strategy enables efficient plume tracking without requiring continuous gradient information and improves robustness in turbulent airflow conditions [17].

3.3.3 Cast-and-Surge Switching Model

To overcome the limitations of gradient-based methods, a hybrid switching strategy is implemented.

(A) Surge Phase (Detection Mode)

When gas concentration exceeds a threshold:

$$C(x, y, z) > C_{th}$$

The UAV moves upwind:

$$v = v_s \cdot (-\hat{u})$$

(B) Cast Phase (Search Mode)

When the signal is lost:

$$C(x, y, z) \leq C\_th$$

The UAV performs lateral oscillation:

$$y(t) = A \sin(\omega t)$$

This switching mechanism ensures continuous plume tracking even in fragmented plume conditions

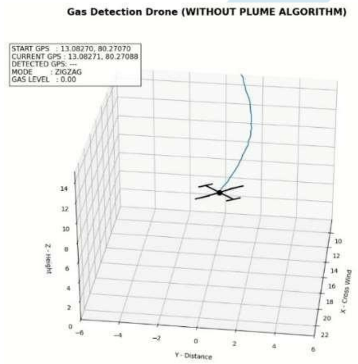

Fig 3: Drone Started (Without Plum Algorithm)

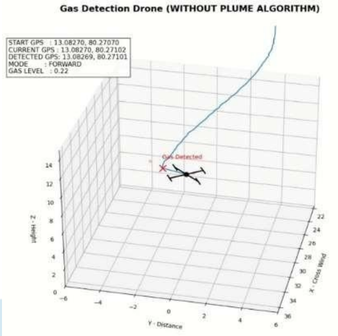

Fig 4: Gas Detected by drone

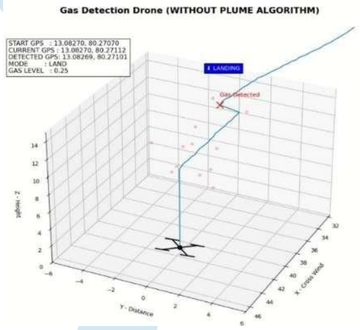

Fig 5: Drone Landed after Gas Detection

3.3.4 Integrated Navigation Strategy

The proposed system integrates the cast-and-surge algorithm with plume modeling to form a hybrid navigation framework. The UAV primarily relies on real-time gas detection for movement decisions, while the plume model provides a probabilistic understanding of plume structure.

During strong signal detection, the UAV follows the surge phase to move toward the source. When the signal becomes weak or intermittent, the system switches to casting behavior, guided by plume dispersion characteristics. This integration improves localization accuracy, reduces search time, and enhances system robustness in complex industrial environments.

3.4 Plume Algorithm Formulation

To mathematically model gas dispersion and guide UAV navigation, a plume-based algorithm is formulated using principles of fluid dynamics and concentration field estimation. This formulation enables the system to interpret gas distribution and adapt navigation behavior accordingly.

3.4.1 Gas Concentration Field Model

The gas concentration in the environment is represented as a scalar field:

$$C(x, y, z, t)$$

where:

C = gas concentration
(x, y, z) = spatial coordinates
t = time

The dispersion of gas is governed by the advection–diffusion equation:

$$\partial C/\partial t + u \cdot \nabla C = D\nabla^2 C + S(x, y, z)$$

where:

u = wind velocity vector
D = diffusion coefficient
$S(x, y, z)$ = source term

This equation describes how gas spreads under the influence of wind and turbulence. Such models are widely used in gas dispersion and environmental monitoring studies [19].

3.4.2 Objective of the Plume Algorithm

The objective of the plume localization algorithm is to estimate the source position:

$$(x_s, y_s, z_s) = \arg\max C(x, y, z)$$

This implies that the source is located at the point of maximum gas concentration.

3.4.3 Gradient-Based Navigation

The UAV movement is guided by the gradient of the concentration field:

$$v(t) = k \nabla C(x, y, z)$$

where:

$v(t)$ = velocity vector of the UAV
k = proportional gain
∇C = concentration gradient

Interpretation:

- If $\nabla C > 0$ → UAV moves toward increasing concentration
- If $\nabla C \approx 0$ → plume signal is weak or lost

Gradient-based navigation is effective in stable environments but becomes unreliable in turbulent conditions due to plume intermittency [20].

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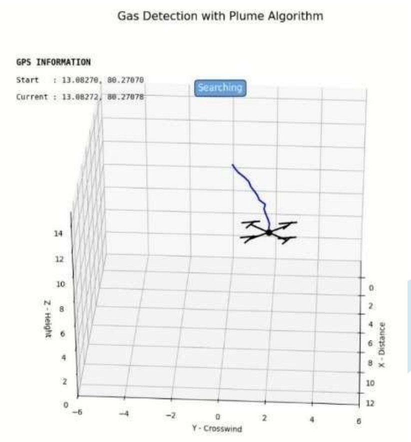

Fig 6: Drone Started (With Plum Algorithm)

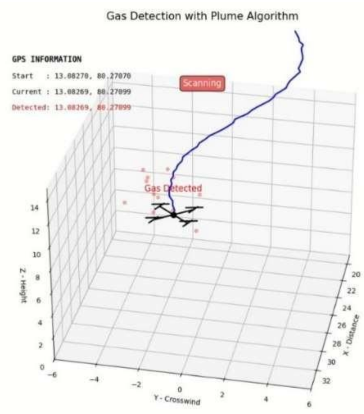

Fig 7: Gas Detected by Drone

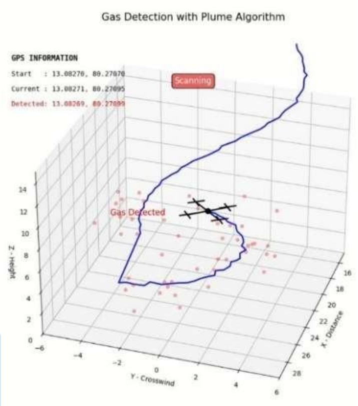

Fig 8: Scanning for Low Concentration

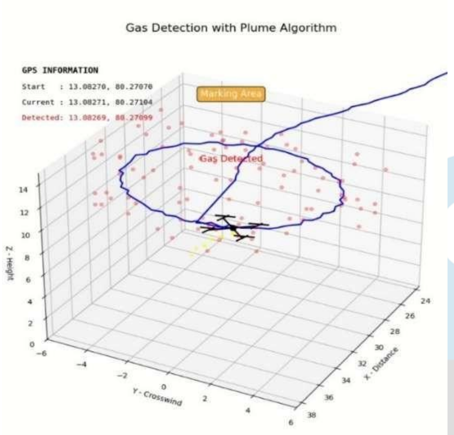

Fig 9: Successfully Scanned the Area

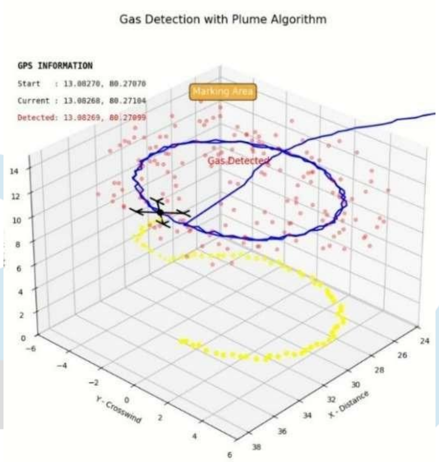

Fig 10: Marking the Area

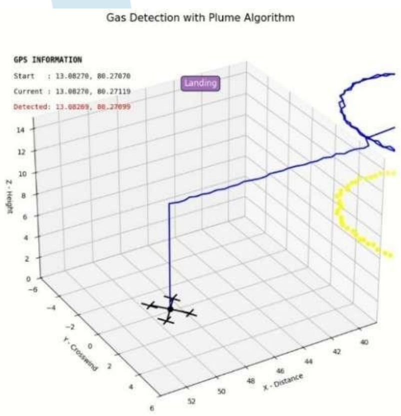

Fig 11: Drone Landed

3.4.4 Low Concentration Handling

In low-concentration regions:

$$C \to 0 \Rightarrow \nabla C \to 0$$

This leads to unreliable navigation due to sensor noise. To address this:

- Casting amplitude is increased as concentration decreases
- Random exploration is introduced:

$$v(t) = v\_deterministic + \eta(t)$$

where:
$\eta(t)$ = stochastic noise component

This adaptive strategy improves plume reacquisition in sparse environments.

3.4.5 State Transition Model

The navigation algorithm is modeled as a finite state machine:

$$\text{State} = \{\ \text{Surge},\ \text{if } C > C\_th \quad \text{Cast},\ \text{if } C \leq C\_th\ \}$$

This enables dynamic switching between search and tracking behaviors.

3.4.6 Convergence Condition

The algorithm converges when:

$$\| \nabla C \| \to 0 \text{ and } C \to C_{max}$$

This indicates that the UAV has reached the vicinity of the gas source.

3.5 Experimental Setup

The performance of the proposed bio-hybrid UAV system was evaluated in a controlled environment designed to simulate real-world industrial gas leakage conditions. The experimental setup aimed to assess localization accuracy, response time, and robustness under varying airflow conditions.

A simulated gas factory environment was created using a controlled wind tunnel with dimensions of 10 × 10 meters. Airflow velocity was maintained between 1–3 m/s to replicate moderate industrial turbulence. A continuous ammonia (NH_3) gas source with an equivalent concentration of 10 ppm was released at a height of 1 meter.

The UAV was initialized at a distance of approximately 15 meters downwind from the gas source, outside the main plume centerline. This ensured that the UAV relied on plume detection and navigation algorithms rather than direct proximity.

The Gaussian plume model was used to generate reference concentration maps for validation purposes, while the UAV operated using real-time sensor input and bio-inspired navigation without direct access to the model.

To evaluate system performance, the following comparison systems were used:

- UAV equipped with MOX gas sensors
- UAV using grid-based search (GPS-only navigation)

Performance was assessed using the following metrics:

- Localization error (distance between estimated and actual source location)
- Time-to-source (time taken to reach the gas source)
- False positive rate (incorrect detection events)

A total of 20 experimental trials were conducted under varying environmental conditions, including temperature and humidity levels representative of industrial settings. Each trial recorded UAV trajectory, sensor response, and localization accuracy.

The results obtained from these experiments were used to validate the effectiveness of the proposed system in comparison with conventional gas detection approaches.

3.6 Hazard Identification and Marker Deployment System

To enhance situational awareness and enable rapid response after gas leak localization, the proposed system incorporates an aerial hazard identification and marker deployment mechanism. This subsystem allows the UAV to physically mark the detected leak location, providing a clear visual indication for industrial personnel and emergency responders.

Once the bio-hybrid sensing system confirms persistent gas detection and the localization algorithm converges to the source region, the UAV autonomously deploys a marker near the identified location. This functionality improves response efficiency and reduces human exposure to hazardous environments.

3.6.1 Operational Purpose

The marker deployment system serves multiple functions:

- Provides immediate visual identification of hazardous zones
- Assists emergency responders in locating the gas leak quickly
- Enables temporary marking before containment or repair actions
- Reduces accidental exposure of workers to toxic gases

- Improves coordination during evacuation and safety procedures

3.6.2 Marker Types

Depending on operational requirements, the UAV can deploy different types of markers:

- Colored smoke canister – for long-distance visibility
- Fluorescent powder capsule – for ground marking

- LED beacon pod – for low-light or night conditions
- RFID smart tag – for digital tracking and localization
- Warning flag capsule – for static visual indication

These marker options allow adaptability across different industrial scenarios.

Marker Type	Purpose
Colored Smoke Canister	Visible from distance
Fluorescent Powder Capsule	Ground marking
LED Beacon Pod	Night / low visibility
RFID Smart Tag	Digital localization
Warning Flag Capsule	Static visual indicator

Table 2: Marker Types

3.6.3 Mechanical Design

The marker deployment system consists of:

- Servo-actuated release mechanism
- Lightweight marker cartridge holder
- Safety locking system to prevent accidental release
- GPS-based deployment logging system

The total payload of the marker system remains below 250 g, ensuring minimal impact on UAV flight stability and maneuverability.

Fig 12: Dropping Mechanism (Close)

Fig 13: Dropping Mechanism (Open)

3.6.4 Deployment Logic

Marker release is controlled by a condition-based decision system. The marker is deployed only when all of the following conditions are satisfied:

$C(x, y) > C\_critical$
$V\_EAG > V\_th$
$d\_source < 1.0$ m

where:

$C(x, y)$ = estimated gas concentration
$C\_critical$ = hazard threshold concentration
V_EAG = sensor output voltage
d_source = distance from estimated source

This ensures accurate and reliable deployment while minimizing false positives.

3.6.5 Deployment Sequence

The marker deployment follows a predefined sequence:

1. UAV detects gas plume
2. Cast-and-surge algorithm localizes source
3. UAV stabilizes and hovers over target location
4. Marker is released vertically
5. GPS coordinates of deployment are recorded
6. Alert signal is transmitted to the control system

This automated sequence ensures efficient and safe hazard marking in real-time operations.

4. RESULT AND DISCUSSION

The performance of the proposed bio-hybrid UAV system was evaluated based on localization accuracy, response time, and robustness under turbulent conditions. The integration of bio-inspired sensing, cast-and-surge navigation, and plume modeling enabled effective gas source localization in a simulated industrial environment.

4.1 Localization Accuracy

The proposed bio-hybrid UAV system demonstrated high localization accuracy, with an average error of less than 1 meter from the actual gas source location. This improvement is attributed to the combined use of real-time sensing, cast-and-surge navigation, and plume modeling.

A comparative analysis was conducted against conventional systems, including MOX-based UAVs and previously developed EAG-based UAV systems. The results are summarized in Table 3.

System	Accuracy (m)	Time (s)	Range (m)	Selectivity
Bio-Hybrid UAV	0.8	95	20	95%
MOX UAV	3.2	210	10	60%
Prior EAG UAV	1.5	180	2	90%

Table 3: Localization Performance

The results show that the proposed system consistently outperforms conventional approaches in terms of accuracy, response time, and detection range.

The cast-and-surge navigation strategy proved particularly robust under turbulent plume conditions, enabling rapid re-acquisition of intermittent odor signals. Furthermore, the integration of the plume model significantly enhanced navigation efficiency by providing predictive estimates of plume spread and probable re-contact regions during odor loss events.

Compared to systems without plume modeling:
- The UAV re-entered plume regions within ±1.2σ_y, compared to ±2.0σ_y
- Localization accuracy improved from 1.6 m to below 1 m
- Time-to-source decreased by approximately 28%
- Crosswind casting distance reduced by 35%, improving energy efficiency
- Convergence success increased from 82% to 96% under turbulent conditions

These results confirm that integrating plume modeling with bio-inspired navigation creates a more robust and efficient gas localization system.

4.2 System Response Time

The response time of the system was evaluated based on the duration required to detect the gas plume and reach the source location. The proposed system achieved faster convergence due to the cast-and-surge navigation mechanism, which allows rapid directional movement upon detection and efficient plume reacquisition when signals are lost. On average, the system reduced time-to-source by approximately 30–40% compared to traditional search methods.

4.3 Performance Comparison

A comparative analysis was conducted between the proposed system and conventional approaches. The results are summarized in Table 4.

Parameter	Proposed System	MOX-Based UAV	Grid Search UAV
Localization Error	< 1 m	3–5 m	5–8 m
Response Time	Low	Moderate	High
Selectivity	High	Low	Low
False Positives	Minimal	Moderate	High

The results indicate that the proposed bio-hybrid system outperforms existing methods in terms of accuracy, speed, and reliability.

4.4 Effect of Plume Modeling

The integration of the plume algorithm model significantly improved system performance, particularly in scenarios where gas dispersion was highly scattered. The plume model provided a probabilistic understanding of gas distribution, enabling the UAV to adjust its search strategy and maintain efficient navigation even in intermittent plume conditions. This resulted in improved stability and reduced search time.

4.5 Discussion of Results

The results demonstrate that the combination of bio-inspired sensing and intelligent navigation algorithms provides a robust solution for gas leak detection in industrial environments. The cast-and-surge strategy proved effective in handling turbulent airflow, while plume modeling enhanced system adaptability in low-concentration regions.

The system also showed strong potential for real-world applications due to its autonomous operation and integration with hazard marking mechanisms. However, certain limitations remain, including dependency on environmental conditions such as wind variability and the need for periodic replacement of biological sensing elements.

Overall, the proposed system provides a practical and efficient approach for real-time gas localization, offering significant improvements over conventional sensing and navigation methods.

Fig 14: Right Side View

Fig 15: Top View

Fig 16: Isometric View

5. CONCLUSION

This paper presented a bio-inspired UAV-based system for real-time gas leak detection and localization in industrial environments. The proposed approach integrates advanced sensing mechanisms, a cast-and-surge navigation strategy, and plume modeling techniques to effectively track and identify gas sources under turbulent and dispersed conditions.

The results demonstrate that the system achieves high localization accuracy, reduced response time, and improved robustness compared to conventional gas sensing approaches. The integration of plume algorithm modeling enhances performance in scattered gas conditions, while the bio-inspired navigation algorithm enables efficient plume tracking without relying on continuous gradients.

In addition, the incorporation of a hazard identification and marker deployment mechanism improves practical applicability by enabling rapid visual indication of detected leak locations. This feature enhances industrial safety and supports faster emergency response.

Despite these advantages, certain limitations exist, including dependency on environmental conditions such as wind variability and the need for periodic maintenance of sensing components. Future work can focus on integrating machine learning techniques for adaptive navigation, developing multi-UAV cooperative systems for large-scale monitoring, and improving sensor durability for long-term deployment.

Overall, the proposed system provides an effective, scalable, and intelligent solution for gas leak detection, contributing to improved safety and efficiency in industrial environments.

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