

Development and Preliminary Evaluation of Low-Cost Modular VOC Sensors for Potential USV-Based Oil Spill Detection

*Sadar Muhammad Ali and Duke
Schulich School of Engineering, University of Calgary, Canada

*Corresponding author: sadar.ali1@ucalgary.ca

Abstract: Oil spills that are caused by maritime transportation and offshore activities require effective monitoring solutions. Unmanned surface vehicles (USVs) offer flexible platforms for significant environmental risks, underscoring the need for rapid and cost-effective marine surveillance; however, their effectiveness depends on reliable sensing technologies. This study aims to detect the presence of surface oil spills by using a low-cost VOC sensing system with a remote monitoring capability. A modular VOC sensor system was made for USV platforms, enabling scalability and on-site integration. The performance was tested by laboratory and outdoor experiments with varying VOC concentrations and environmental conditions. Results showed consistent sensor responses to different concentrations with variability because of airflow and ambient conditions. For all scenarios, our sensor reliably distinguished oil-contaminated conditions from background environments. These results support the use of low-cost VOC sensing for scalable USV-based marine monitoring and provide a foundation for data-driven oil spill detection approaches.

Introduction

Marine oil spills are still a major environmental concern owing to their impact on ecosystems, marine life, and coastal economies (International Tanker Owners Pollution Federation [ITOPF], 2023). These oil spills are caused by offshore drilling activities, tanker accidents and failures in pipelines. Rapidly detecting them is necessary for minimal environmental damage and to allow timely response.

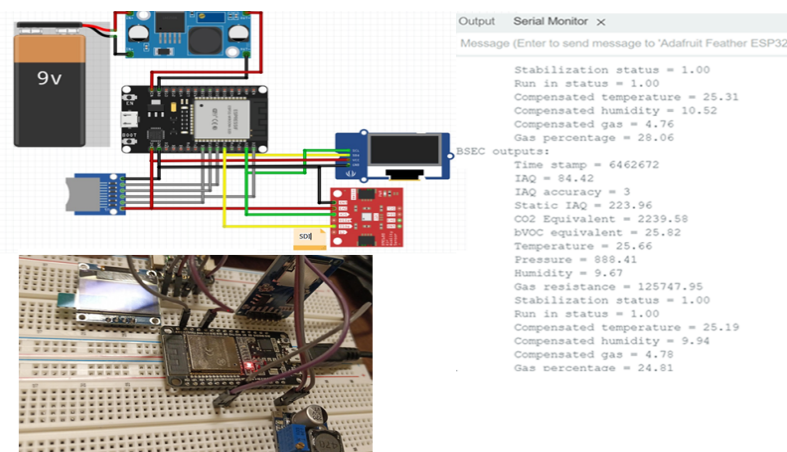
Traditional monitoring methods such as satellite imaging and aerial surveillance are often expensive and limited by environmental conditions (Leifer et al., 2012). Unmanned surface vehicles (USVs) are a promising alternative by giving continuous and localized monitoring in marine environments (Lv et al., 2025).

Low-cost volatile organic compound (VOC) sensors offer a scalable approach for detecting hydrocarbon emissions associated with oil spills. However, their reliability under changing environmental conditions must be evaluated (Hayward et al., 2024). This research is focused on making and experimentally verifying a low-cost VOC sensor system for oil spill detection and scalable deployment on USVs as a long-term objective.

System design and architecture

The developed sensing system follows a modular architecture, enabling flexibility, scalability, and ease of integration with mobile platforms such as USVs. It has a VOC sensor module, microcontroller, sensors for environmental parameters and a real-time interface to transmit and communicate data.

Figure 1: Configuration of the VOC sensor system, including



Sensor-Module and real-time data acquisition interface

This modular design allows us to replace or upgrade individual components independently, allowing maintenance and on-site adaptability. This gives us the plug-and-play functionality, making our system suitable for field deployment.

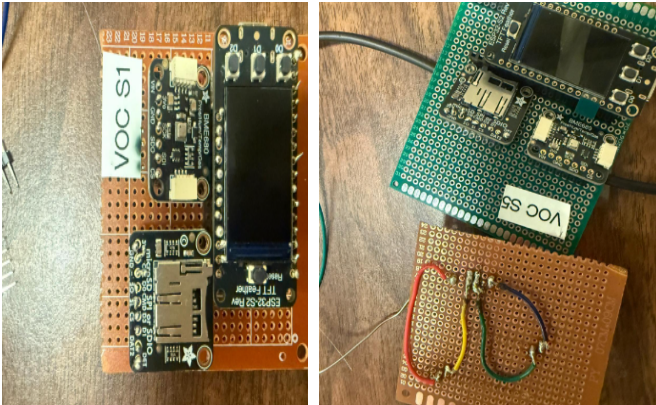
Environmental parameters, including temperature, humidity, atmospheric pressure, and wind speed, are recorded alongside sensor response to allow us to take into account environmental variability. Cloud integration enables remote data logging and monitoring, allowing real-time visualization and future data-driven analysis. Low-cost gas sensors have been widely used for environmental monitoring applications due to their affordability and scalability (Hayward et al., 2024).

Sensor fabrication and assembly

The VOC sensing modules were made by using a PCB design to support compact integration and ease of deployment. Each unit has a VOC sensing module (BME680), microSD card reader and an ESP32-based microcontroller mounted on the board.

This gives us real-time data acquisition, storage, and wireless communication. The modular approach makes the system suitable for scalable deployment.

Figure 2: Assembled VOC sensor modules



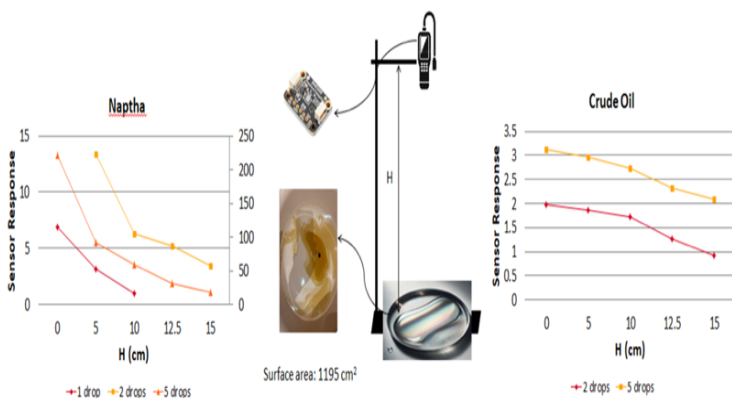
Hydrocarbon sensitivity analysis

To verify the sensitivity of the VOC sensing system to various hydrocarbon sources, controlled experiments were conducted using naphtha and crude oil. These sources have hydrocarbon compositions commonly associated with oil spills.

Sensor measurements were taken at various heights to analyze vertical dispersion behavior. Results depicted a consistent decrease in sensor response with increasing height, while higher concentrations gave stronger sensor output responses.

These preliminary experiments verified the units' ability to detect hydrocarbon presence before environmental testing was done.

Figure 3: VOC sensor response for different hydrocarbon sources



Experimental methodology

Indoor experimental setup

Indoor experiments took place under controlled conditions to evaluate sensor performance. We used a fan to produce consistent airflow while the anemometer measured wind speed. Diesel samples were introduced in controlled quantities to simulate VOC emissions.

Sensor measurements were taken at multiple heights (0 cm, 5 cm, and 10 cm) to analyze vertical dispersion behavior. Temperature and humidity were also recorded as environmental parameters.

Figure 4: Indoor experimental setup showing controlled airflow



Outdoor experimental setup

Outdoor experiments took place under real-world conditions to verify system performance. The setup was deployed in an open environment with natural airflow and environmental variability for readings from the sensor.

Readings were recorded at the same heights as indoor experiments for consistency. Even with increased variability, the setup gave realistic conditions for evaluating system robustness.

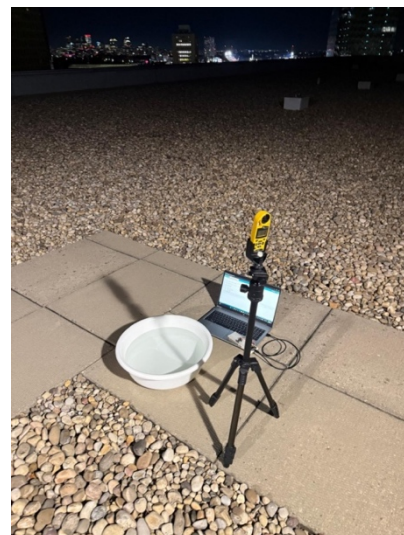


Figure 5: Outdoor experimental setup for real-world deployment conditions

Results and discussion

The experimental results demonstrate a clear relationship between VOC concentration and sensor response. Sensor output increased with higher hydrocarbon concentrations and decreased with increasing distance from the source, confirming expected dispersion behaviour.

In key performance metrics, our sensors showed consistent sensitivity with an estimated limit of detection (LOD). Our repeatability tests gave us stable responses, and inter-sensor variation indicated reliable reproducibility.

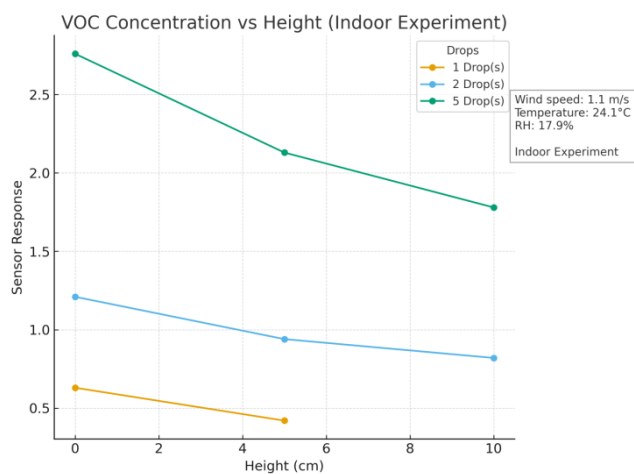
Indoor results

Indoor experiments showed smooth and consistent trends, with higher sensor responses observed closer to the VOC source. Sensor response decreased with increasing height due to vertical dispersion and dilution of the VOC concentration in the air.

This behaviour is governed by diffusion and airflow-induced mixing. At 0 cm, the sensor is closest to the emission source, leading to higher concentrations, and as we increase the height, our sensor response decreases due to dispersion.

Controlled airflow gave us relatively stable conditions, minimizing fluctuations and allowing clear observation of dispersion-driven trends.

Figure 6: VOC sensor response as a function of height under indoor conditions

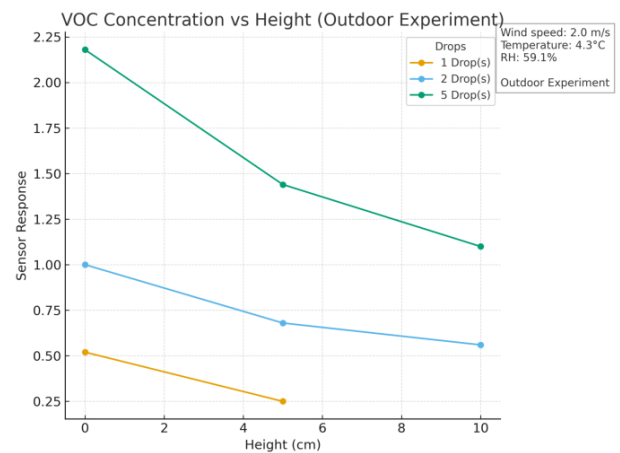


Outdoor results

Outdoor experiments showed similar decreasing trends in sensor response with increasing height, although minor fluctuations were observed due to environmental variability such as wind speed, temperature, and humidity.

In comparison to indoor conditions, our outdoor responses were slightly lower due to enhanced dispersion caused by natural airflow. Variations in wind speed led to fluctuations as stronger airflow increased the dilution. Still, our overall trend remained consistent, showing the robustness of the sensing unit.

Figure 7: VOC sensor response as a function of height under outdoor conditions



Comparative analysis

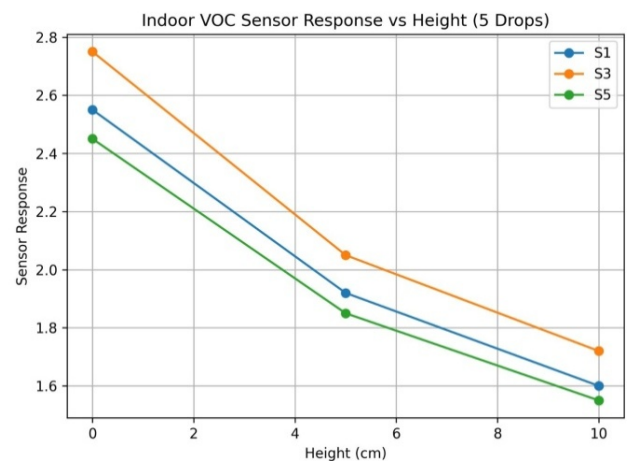
Across both indoor and outdoor conditions, the sensor system effectively differentiated oil-contaminated environments from background conditions. This demonstrates the capability of the system for both controlled and real-world monitoring scenarios.

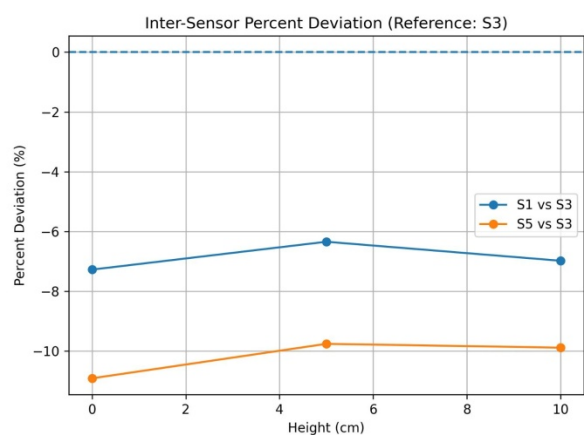
The performance of multiple sensor units (S1, S3, and S5) was compared to evaluate consistency and inter-sensor variability. As shown, all sensors had a similar decreasing trend in response to increasing height, giving consistent behaviour.

Percent deviation analysis relative to reference sensor S3 showed that S1 exhibited approximately 6–7% lower response, while S5 showed approximately 9–10% deviation. These variations are attributed to manufacturing differences and inherent sensor sensitivity.

In short, despite minor deviations, the consistency in response trends confirms suitability for scalable deployment and aligns with VOC sensing behaviour reported in literature (Stewart et al., 2023).

Figure 8: Comparison of sensor response and inter-sensor percent deviation for sensors S1, S3, and S5





Data integration and future work

Our ongoing work explores the integration of sensor response with environmental parameters such as temperature, humidity, wind speed, and measurement height. The combined dataset will lead to the development of data-driven models for oil spill detection.

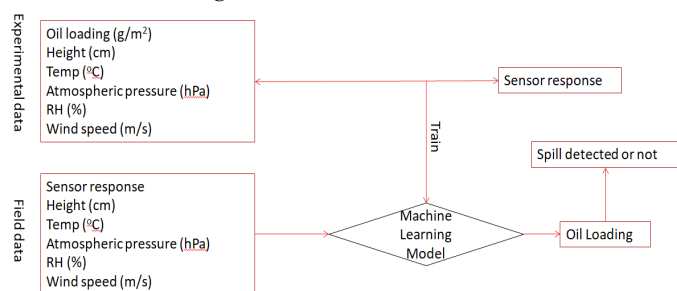
Data-driven approaches that use low-cost sensors have a strong potential for improving environmental monitoring and source attribution (Pinakana et al., 2025). This framework supports the transition from detection to predictive monitoring.

From a marine deployment perspective, these results show the feasibility of integrating low-cost VOC sensors on USV platforms for real-time oil spill detection. The consistent trends observed in both environments support their applicability in dynamic marine conditions.

However, we have several challenges for full-scale deployment. Marine environments have additional complexities like saltwater exposure, wave-induced motion, variable wind conditions and power constraints on mobile platforms. In addition to this, real oil films may have different evaporation and dispersion characteristics in comparison to controlled test samples.

Our future work will focus on improving sensor packaging, extended field testing and refining calibration models. These efforts aim to enable reliable, scalable, and autonomous oil spill monitoring using USV-based sensing systems.

Figure 9: Framework for integrating sensor and environmental data into a machine learning model



Conclusion

This study depicts the design and evaluation of a low-cost VOC sensor system that will be deployed for marine oil spill detection. Our experimental results verified consistent and reliable sensor response for both indoor and outdoor conditions.

The sensor system was able to successfully detect oil-contaminated environments from background conditions, completing the primary objective of detecting oil spills. By having a modular design and cloud integration, we enabled scalability and real-time monitoring.

These findings highlight the potential of low-cost VOC sensing systems for USV-based marine monitoring and provide a foundation for future data-driven and autonomous oil spill detection systems.

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Acknowledgments

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