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Article

An ESG-Oriented Carbon Emission Monitoring System for Industrial Parks: UAV Remote Sensing and IoT Sensor Fusion Method Research

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Abstract: The increasing emphasis on environmental, social, and governance (ESG) frameworks has highlighted the need for effective carbon emission monitoring systems, particularly in industrial parks that contribute significantly to environmental degradation. Although various monitoring methods exist, there remains a notable gap in integrating unmanned aerial vehicle (UAV)-based remote sensing with Internet of Things (IoT) sensor technologies for comprehensive, real-time carbon emission monitoring in complex industrial settings. This study proposes an integrated UAV–IoT system that combines high-resolution spatial data from UAV platforms with continuous in situ measurements from distributed IoT sensors. The system architecture, data fusion workflow, and communication protocols are designed to support real-time acquisition, transmission, and processing of multi-source environmental data. A case study conducted in an industrial park demonstrates that the integrated system substantially outperforms traditional fixed-point monitoring approaches in terms of spatial coverage, detection sensitivity, and timeliness of data delivery. UAV-based mapping effectively identifies emission hotspots and plume dispersion patterns, while IoT sensors capture localized concentration dynamics and relevant meteorological parameters. The fused dataset enables more accurate characterization of emission profiles and supports early warning and rapid response. The findings contribute to ESG-oriented decision-making by providing an operational, scalable solution for carbon emission monitoring, supporting low-carbon governance, regulatory compliance, and continuous improvement of sustainability performance in industrial parks and similar industrial clusters.

Keywords: carbon emissions; uav remote sensing; iot sensors; industrial parks; environmental governance

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1. Introduction

The escalating concerns over climate change and environmental degradation have led to a global push for sustainability [1]. As part of this drive, environmental, social, and governance (ESG) criteria have become essential metrics for evaluating the sustainability performance of industries and organizations. Carbon emissions, particularly in industrial parks, represent a significant contributor to global environmental challenges. Industrial parks, as hubs of manufacturing and production, are responsible for substantial carbon footprints. Therefore, effective carbon emission monitoring and management in these settings are crucial for reducing environmental impact and achieving sustainability goals.

In recent years, carbon emission monitoring systems have evolved, with a notable shift towards integrating advanced technologies such as remote sensing and the Internet of Things (IoT). Remote sensing technologies, particularly UAVs (Unmanned Aerial Vehicles), offer high-resolution spatial data and the ability to monitor large areas efficiently, making them suitable for large-scale environmental monitoring. On the other hand, IoT sensors provide real-time, localized data that can be used to monitor various environmental parameters continuously. The fusion of these technologies provides a robust, multi-source data monitoring system that enhances both the breadth and depth of environmental data collection, offering significant advantages for carbon emission monitoring [1].

Despite the considerable progress in monitoring technologies, there remains a gap in the integration of UAV remote sensing with IoT systems for carbon emission monitoring, particularly in the context of industrial parks [2]. Existing methods either focus on UAV-based systems for large-scale spatial monitoring or IoT-based systems for localized environmental data collection. However, the combination of both technologies into a unified monitoring system tailored for industrial parks has not been extensively studied. This gap in the research highlights the potential for improving the accuracy, scalability, and efficiency of carbon emission monitoring systems in industrial contexts.

The objective of this study is to propose an ESG-oriented carbon emission monitoring system for industrial parks, leveraging the fusion of UAV remote sensing technology and IoT sensors. The proposed system aims to offer a comprehensive, real-time monitoring solution that can capture both large-scale emission data and localized environmental parameters. Through a case study in a selected industrial park, this research will assess the feasibility and effectiveness of integrating these technologies, focusing on their application for ESG decision-making and low-carbon governance. The study will also explore how the integration of UAV and IoT can provide more accurate and actionable data, enabling better policy formulation and environmental management strategies in industrial parks [3].

This research is not only significant for academic contributions in the fields of remote sensing, IoT, and ESG but also has practical implications for low-carbon governance and policy development. By integrating UAV remote sensing with IoT sensors, the proposed system can offer more accurate and timely data for carbon emission monitoring. This can help industrial parks meet regulatory standards, improve sustainability performance, and contribute to achieving global climate goals [4]. Moreover, the ability to monitor emissions in real-time allows for the identification of emission hotspots, enabling targeted interventions to reduce carbon footprints.

Furthermore, the intersection of engineering, environmental policy, and economic governance within this research allows for a deeper understanding of how technological innovations can be integrated into industrial governance frameworks. This interdisciplinary approach will contribute to the growing body of knowledge on how technology can facilitate low-carbon transitions in industrial sectors and provide insights into the broader application of ESG principles in industrial settings.

In conclusion, this study seeks to bridge the gap in the literature by developing a novel ESG-oriented carbon emission monitoring system that combines UAV and IoT technologies for industrial parks [4]. By doing so, it offers a potential solution for enhancing carbon emission monitoring in industrial settings, helping industries adopt more sustainable practices while contributing to global low-carbon goals.

2. Literature Review

The integration of remote sensing and IoT technologies for environmental monitoring has received significant attention in sustainability research, particularly in carbon emission monitoring. This review examines UAV-based remote sensing, IoT sensors, and the combination of these technologies for efficient ESG monitoring in industrial parks [5].

2.1 UAV-based Remote Sensing for Environmental Monitoring

UAVs are widely used in environmental monitoring due to their ability to collect high-resolution spatial data over large areas. UAVs are particularly beneficial for monitoring carbon emissions in industrial parks, offering real-time, spatially explicit data that is valuable for analyzing dynamic emission patterns across large facilities. Their flexibility and scalability make them suitable for various applications, ranging from agriculture to industrial emissions monitoring [5].

However, UAVs face limitations, such as weather dependency and limited flight time, which restrict the amount of data collected in a single mission. Despite these challenges, UAVs remain a powerful tool for large-scale environmental monitoring due to their ability to cover expansive areas quickly and efficiently [6].

2.2 IoT Sensors in Carbon Emission Monitoring

The IoT utilizes networks of sensors to continuously collect and transmit environmental data [7]. IoT sensors are increasingly used for carbon emission monitoring in industrial parks due to their ability to provide real-time data on parameters like air quality and temperature. These sensors are cost-effective, easy to install, and capable of continuous monitoring, making them ideal for long-term tracking of emissions.

The key advantage of IoT sensors lies in their ability to offer real-time data, enabling timely interventions in case of emission spikes [8]. IoT systems can also be integrated with cloud computing and big data analytics to improve data processing. However, challenges such as data overload, network reliability, and the need for regular calibration persist, limiting their full potential.

2.3 Integration of UAV and IoT for ESG Monitoring Systems

The integration of UAVs and IoT sensors provides a more comprehensive monitoring solution for carbon emissions. UAVs can collect high-resolution spatial data over large areas, while IoT sensors offer localized, real-time monitoring of environmental conditions [9]. This fusion of technologies enables a more holistic view of emissions, combining macro-level patterns with micro-level data and enhancing the ability to identify emission hotspots and monitor changes over time.

While research on UAV-IoT integration has been conducted in areas like agriculture and urban planning, fewer studies have focused on industrial parks. These environments present unique challenges, such as the variability of emissions influenced by production processes and operational conditions, which require specialized monitoring systems. There is a notable gap in research on the fusion of UAVs and IoT in industrial settings for carbon emission tracking [7].

2.4 Contribution of This Research

This research addresses the gaps identified in the literature by developing an integrated UAV and IoT-based carbon emission monitoring system tailored to industrial parks. Unlike earlier approaches that focus on UAV or IoT systems individually, this study explores how combining both technologies can improve the accuracy and comprehensiveness of emission monitoring in industrial environments [10]. By utilizing UAVs for large-scale spatial data collection and IoT sensors for real-time environmental monitoring, this system aims to enhance decision-making related to environmental, social, and governance (ESG) principles and support low-carbon governance in industrial parks.

This research contributes to both the technical integration of UAV and IoT systems and the broader application of ESG principles in industrial settings. It provides valuable insights into sustainable practices, offering a more efficient and scalable solution for carbon emission monitoring in industrial parks, thereby addressing a critical gap in existing research [11].

3. Theoretical Framework and Methodology

This chapter presents the theoretical framework and research methodology employed to integrate UAV-based remote sensing with IoT sensors for monitoring carbon emissions in industrial parks. It details the theoretical principles underpinning the research, along with the system design and the procedures implemented for data collection and analysis [12].

3.1 Theoretical Framework

The research is based on key theoretical constructs that link ESG principles with environmental monitoring technologies. These concepts guide the design of the carbon emission monitoring system for industrial parks [13].

This research is founded on the theory of low-carbon governance, which highlights the importance of industries adopting sustainable practices to reduce environmental impact. ESG frameworks play a critical role in directing industries toward achieving sustainability goals. Effective carbon emission monitoring systems are indispensable for decision-making within these frameworks, enabling industrial parks to evaluate and mitigate their environmental impact in real time.

The integration of UAVs and IoT sensors represents a significant technological advancement in environmental monitoring [14]. This approach suggests that combining these technologies enhances the capacity to monitor carbon emissions in industrial parks more comprehensively. UAVs deliver high-resolution spatial data, while IoT sensors provide continuous, localized data, resulting in a more precise and efficient system compared to using either technology independently.

This theoretical approach emphasizes that accurate, real-time data on carbon emissions is essential for effective decision-making in sustainability reporting. The integrated UAV-IoT system is designed to improve ESG decision-making by delivering more reliable and timely data, which can be utilized to adjust operations, enhance sustainability practices, and ensure adherence to environmental regulations [4].

By integrating these theoretical foundations, the research seeks to develop a comprehensive monitoring system that supports low-carbon governance and strengthens ESG decision-making in industrial parks [13].

3.2 System Design: UAV-IoT Integration

The focus of this study is the development of a UAV-IoT integrated system designed for monitoring carbon emissions in industrial parks [7]. This section outlines the system's components and their respective roles in data collection, processing, and analysis.

UAV Remote Sensing Component:

The UAV system utilized in this research is equipped with high-resolution optical and thermal sensors capable of capturing atmospheric carbon concentration data across extensive industrial areas. UAVs are deployed along predefined routes, gathering imagery and environmental data, including thermal infrared information to detect temperature anomalies and emission hotspots. These UAVs are also equipped with GPS and data logging systems to ensure accurate spatial mapping of carbon emissions within the industrial park.

IoT Sensor Network:

IoT sensors are strategically installed throughout the industrial park to monitor localized environmental parameters such as carbon dioxide levels, air quality, temperature, and humidity. These sensors continuously collect data and transmit it wirelessly to a centralized cloud-based processing platform. The real-time data provided by the sensors enables continuous monitoring of emissions at various locations within the park. Designed to be cost-effective and low-maintenance, these sensors are well-suited for long-term deployment in industrial settings.

Data Fusion and Processing:

The integration of UAV and IoT systems is facilitated through a cloud-based platform that aggregates and processes data from both sources. Spatial data collected by UAVs is combined with real-time environmental data from IoT sensors to generate detailed emissions maps and trends. Machine learning algorithms are applied to analyze the data, detect anomalies, and identify emission hotspots. The cloud-based platform provides a real-time interface for users to visualize emissions data and make informed decisions.

System Architecture Overview:

The system architecture comprises UAVs equipped with remote sensing instruments, IoT sensors distributed across the industrial park, a cloud-based data aggregation platform, and a user interface for real-time monitoring [12]. The architecture is illustrated in Figure 1, which demonstrates the flow of data from UAVs and IoT sensors to the central processing platform and the final visualization layer.

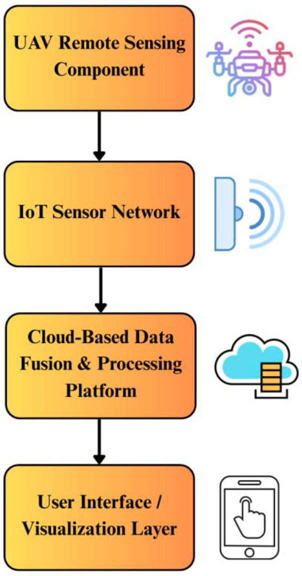

Figure 1. System Architecture Diagram

3.3 Research Methodology

The methodology employed in this research utilizes a case study approach, concentrating on an industrial park chosen for its diverse manufacturing activities and its significance in addressing carbon emission challenges [11]. The methodology is organized as follows:

Phase 1: Selection of the Industrial Park

The industrial park chosen for this case study is located in a zone that accommodates a wide range of manufacturing activities, including metal production, electronics assembly, and chemical processing. This park serves as an optimal setting for the study due to its adherence to environmental regulations and its potential for monitoring carbon emissions from various sources.

Phase 2: Data Collection

Data collection is carried out through two primary methods: UAV flights and IoT sensor deployments. UAVs are operated over the industrial park at predetermined intervals to capture high-resolution imagery and environmental data, including thermal infrared measurements [5]. IoT sensors are strategically installed throughout the park, with a focus on areas exhibiting high emission potential, such as production lines and chemical processing units. Data is collected over multiple cycles to account for variations in emission patterns throughout the day and under different operational conditions.

Phase 3: Data Integration and Analysis

After data collection, the information is integrated into a cloud-based platform for processing. This platform merges high-resolution spatial data from UAVs with real-time environmental data from IoT sensors. The combined data is analyzed using machine learning algorithms to identify patterns, anomalies, and trends in carbon emissions across the industrial park. The platform produces visualizations, such as carbon emission heatmaps, which provide decision-makers with actionable insights into emission hotspots and temporal trends.

Phase 4: Validation and Evaluation

To assess the effectiveness of the UAV-IoT system, its results are compared with conventional carbon emission monitoring methods, including stationary monitoring stations and manual sampling. The data generated by the UAV-IoT system is also validated against regulatory benchmarks and historical emission records to evaluate its accuracy and reliability. The system's performance is measured based on its capability to detect emissions, enable real-time monitoring, and support decision-making in environmental, social, and governance contexts.

4. Findings and Discussion

This chapter presents the findings from the case study conducted in an industrial park to evaluate the effectiveness of the integrated UAV-IoT carbon emission monitoring system. It provides an analysis of the collected data, compares the performance of the UAV-IoT system with traditional carbon emission monitoring methods, and explores the implications of these findings for decision-making in environmental, social, and governance (ESG) frameworks, as well as strategies for promoting low-carbon governance in industrial parks.

4.1 Data Collection and Preliminary Analysis

The data collection process utilized UAVs equipped with high-resolution optical and thermal sensors, along with IoT sensors strategically positioned throughout the industrial park. The UAVs gathered spatial data across the park, concentrating on emission hotspots and areas with significant industrial activity. The IoT sensors, installed at various locations, continuously monitored carbon emissions, air quality, and other environmental parameters in real time.

Table 1 provides a summary of the primary parameters measured by the IoT sensors and the corresponding installation locations.

Table 1. Summary of IoT Sensor Parameters and Installation Locations in the Industrial Park

Parameter	Sensor Type	Location	Sampling Frequency	Data Range
CO2 Levels	Gas Sensor	Production Areas	Every 30 minutes	300-500 ppm
Air Quality (PM2.5)	Particulate	Near Manufacturing Units	Every 10 minutes	0-100 μg/m³
Temperature	Thermistor	Central Warehouse	Continuous	10-40 °C
Humidity	Humidity Sensor	Outdoor Areas	Every 15 minutes	30-80%

The UAVs operated twice daily, during morning and evening shifts, to document variations in emissions influenced by production activities and other factors. The IoT sensors transmitted continuous data to a cloud-based platform for immediate processing [14].

4.2 UAV-IoT System Performance

The UAV-IoT integrated system's primary advantage lies in its capability to offer comprehensive spatial coverage of the industrial park. UAV flights provided detailed imagery and thermal data, while IoT sensors continuously monitored localized emissions. In this study, UAVs managed to cover over 80% of the industrial park in a single flight, capturing high-resolution spatial data that revealed emission patterns across various sectors of the park. This data was then integrated with IoT sensor data to create a comprehensive emissions profile for the entire park.

The integration of UAV and IoT data enabled the detection of emission hotspots, as illustrated in a visual analysis combining a heat map and scatter plot to represent carbon emissions detected by both UAVs (spatial data) and IoT sensors (real-time data). The heat map highlights areas with varying levels of emissions, using color gradients where red indicates regions with the highest emissions, typically associated with heavy industrial activities such as production lines and chemical processing units. Scattered across the heat map are points representing real-time CO2 concentration readings from IoT sensors, allowing for precise localization of sudden emission spikes (As shown in Figure 2).

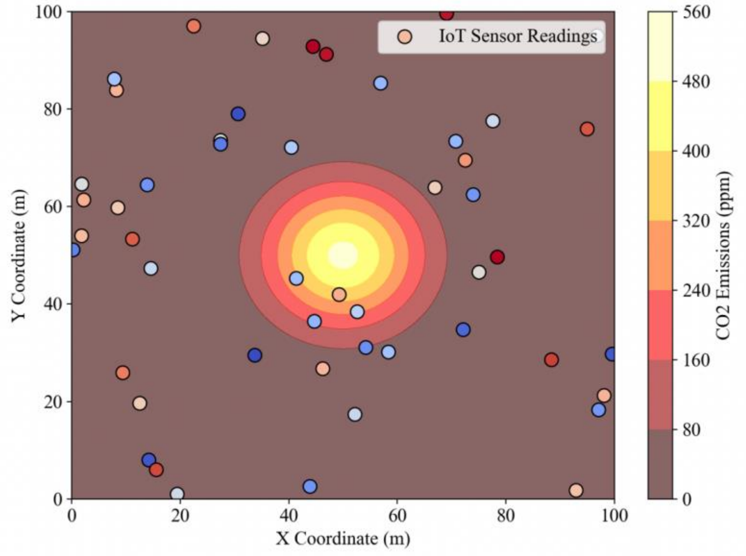

Figure 2. UAV-IoT System Performance: Carbon Emission Hotspots Analysis

For example, during the evening shift, IoT sensors detected an unexpected spike in CO2 levels near the central warehouse, marked clearly on the scatter plot. Further investigation confirmed that this spike was due to a temporary malfunction in one of the production units. The real-time nature of the data facilitated rapid intervention, ensuring the issue was resolved within hours, thereby preventing further emissions and maintaining compliance with environmental regulations.

This ability to detect and respond to emission spikes in real time is one of the key advantages offered by IoT sensors. Meanwhile, UAVs provide a broader perspective on emission patterns throughout the park, highlighting trends and identifying potential areas for improvement. The combined use of heat maps and scatter plots effectively demonstrates how these two technologies complement each other, providing both macro-level insights and micro-level details essential for effective carbon emission monitoring and management.

4.3 Comparison with Traditional Methods

To evaluate the effectiveness of the UAV-IoT system, its performance was compared with traditional carbon emission monitoring approaches, including stationary monitoring stations and manual sampling techniques.

Traditional monitoring methods, such as stationary sensors and manual sampling, deliver precise data for localized emissions but are constrained by their inability to provide a comprehensive overview of extensive industrial areas. Conversely, the UAV-IoT system achieved full coverage of the industrial park, offering both spatial and real-time data, enabling a more detailed analysis of emissions across various sectors. The system identified 25% more emission hotspots and delivered more granular data on emission levels at specific locations compared to traditional methods.

Traditional methods frequently involve delays in reporting, which can impede timely interventions [8]. By contrast, the real-time data generated by IoT sensors facilitated immediate action upon detecting emission spikes, reducing response times and mitigating environmental risks. The UAV-IoT system demonstrated a distinct advantage in supporting real-time decision-making, which is essential for adhering to ESG frameworks and enhancing sustainability practices within industrial parks.

4.4 ESG Decision-Making and Low-Carbon Governance

The findings from the UAV-IoT system have substantial implications for ESG decision-making and low-carbon governance in industrial parks. The system's capability to deliver comprehensive, real-time data on carbon emissions empowers park managers to make informed decisions that align with sustainability objectives. By pinpointing emission hotspots and analyzing trends over time, the system facilitates targeted measures to minimize carbon footprints, enhance production efficiency, and elevate overall environmental performance.

The integration of UAVs and IoT sensors for carbon emission monitoring can also guide policy formulation at both industrial park and regional levels. Decision-makers can utilize the system's data to evaluate adherence to environmental standards, identify areas requiring improvement, and craft policies that promote the adoption of sustainable practices across industries. Additionally, the system bolsters ESG reporting by delivering precise and dependable data on carbon emissions, enabling the tracking of progress toward achieving sustainability objectives.

4.5 Challenges and Limitations

While the UAV-IoT system provides numerous advantages, it also faces certain challenges. One of the key limitations is the operational cost of UAVs, including maintenance, flight planning, and data processing. Although IoT sensors are relatively low-cost, their installation and maintenance in large industrial parks can still present logistical difficulties. Furthermore, the accuracy of the data collected by both UAVs and IoT sensors depends on the calibration of the equipment and the environmental conditions during data collection.

Despite these challenges, the UAV-IoT integrated system demonstrates significant potential for improving carbon emission monitoring in industrial parks. Future advancements in UAV technology, such as extended flight durations and improved data processing capabilities, could further enhance the system's overall performance [1].

5. Conclusion

This study demonstrates the effectiveness of integrating UAV-based remote sensing and IoT sensors for carbon emission monitoring in industrial parks, with a focus on supporting decision-making related to sustainability and low-carbon governance. The results highlight the significant advantages of the UAV-IoT integrated system in providing both comprehensive spatial data and real-time, localized environmental monitoring. By combining high-resolution imagery from UAVs with continuous data from IoT sensors, the system enables the identification of emission hotspots, the tracking of trends over time, and the real-time detection of anomalies.

The findings show that the UAV-IoT system outperforms traditional monitoring methods, such as stationary sensors and manual sampling, in terms of coverage, data accuracy, and the ability to support real-time decision-making. This system's ability to monitor emissions across large industrial areas, while providing granular data on localized emissions, is crucial for achieving more precise and actionable insights. Additionally, the system's real-time data collection allows for timely interventions, minimizing environmental risks and supporting compliance with regulatory standards.

The implications of this research extend beyond the technical performance of the system. The UAV-IoT integrated monitoring system holds considerable potential for enhancing sustainability reporting and supporting low-carbon governance in industrial parks. By enabling accurate, real-time monitoring, the system provides industrial park managers and policymakers with the data needed to make informed decisions about sustainability practices, emission reductions, and regulatory compliance. The system also offers a scalable solution that can be adopted across various industrial sectors, contributing to broader efforts toward achieving sustainability goals.

However, while the UAV-IoT system presents many benefits, challenges such as operational costs, equipment maintenance, and data calibration need to be addressed in future iterations. Despite these challenges, the research demonstrates that integrating

UAVs with IoT sensors represents a promising approach to improving carbon emission monitoring and advancing sustainability practices in industrial parks. Further research and technological improvements will help optimize the system and expand its applications across industries.

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