

Unmanned Aerial Vehicles for High-Resolution Environmental Monitoring: A Review of Applications and Future Directions

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Abstract— Unmanned aerial vehicles (UAVs) have revolutionized environmental and geographical surveying in recent years. Their ability to capture high-resolution imagery and data in a cost-effective and efficient manner has led to their widespread use in various environmental monitoring applications. In this paper, we provide a comprehensive review of the current state-of-the-art in UAV applications for environmental and geographical surveying. We first discuss the various types of sensors and platforms used for data acquisition, including RGB cameras, multispectral and hyperspectral sensors, LiDAR, and thermal cameras. We then review the range of applications for which UAVs have been used, including mapping, monitoring vegetation, water quality analysis, wildlife tracking, and disaster response. Additionally, we discuss the challenges and limitations associated with UAV-based monitoring, such as data processing and analysis, regulatory frameworks, and technical constraints. Finally, we conclude with an overview of the future directions and potential advancements in UAV technology that could further improve their utility for environmental and geographical surveying. Overall, this paper provides a comprehensive resource for researchers and practitioners interested in the use of UAVs for environmental and geographical surveying.

Keywords— Field Robotics, Environmental monitoring, Geographical surveying, High-resolution imagery

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I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have rapidly emerged as a powerful tool for environmental and geographical surveying. These devices can be equipped with a range of sensors that enable high-resolution data acquisition of terrain, vegetation, and other environmental features. UAVs have several advantages over traditional surveying methods, such as reduced costs, increased efficiency, and improved safety.

Additionally, UAVs can capture data in real-time, enabling real-time decision-making and adaptive monitoring strategies.

The increasing accessibility of UAVs and associated technologies has led to their widespread use in a range of environmental applications. For example, UAVs can be used to survey large areas of land for vegetation health and biomass estimation. UAVs can also be used to monitor water quality and detect changes in water bodies over time. In wildlife research, UAVs can be used to track and monitor the movements of animals, providing valuable insights into their behavior and habitat use. UAVs have also been used in disaster response, providing rapid assessment of damage and aiding in search and rescue efforts.

In this paper, we provide a comprehensive review of the current state-of-the-art in UAV applications for environmental and geographical surveying. We begin by discussing the types of sensors and platforms used for data acquisition. RGB cameras, multispectral and hyperspectral sensors, LiDAR, and thermal cameras are all commonly used sensors in UAV-based monitoring. Each of these sensors has unique advantages and limitations, and the selection of a specific sensor will depend on the requirements of the application.

We then review the range of applications for which UAVs have been used in environmental monitoring. Mapping and monitoring vegetation is one of the most common applications of UAVs. UAVs can provide high-resolution images and data on plant height, canopy cover, and biomass, which can be used to assess vegetation health and productivity. In water quality analysis, UAVs can capture high-resolution images and data on water turbidity, temperature, and nutrient concentrations, providing valuable information on water quality parameters. UAVs can also be used to monitor wildlife, providing insights into animal behavior and habitat use, as well as supporting conservation efforts.

We also discuss the challenges and limitations associated with UAV-based monitoring. One of the primary challenges is the processing and analysis of large datasets. The high-resolution imagery and data captured by UAVs require

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significant computational resources for processing and analysis. Additionally, regulatory frameworks and technical constraints can limit the use of UAVs in some applications. For example, the operation of UAVs is subject to air traffic regulations and privacy laws, which can restrict their use in certain areas.

Finally, we discuss the future directions and potential advancements in UAV technology that could further improve their utility for environmental and geographical surveying. The development of lightweight and low-cost sensors, improved data processing algorithms, and increased battery life are just some of the areas in which UAV technology is rapidly evolving. Additionally, the integration of UAVs with other technologies, such as machine learning and artificial intelligence, has the potential to further enhance the capabilities of UAV-based monitoring.

Overall, this paper provides a comprehensive resource for researchers and practitioners interested in the use of UAVs for environmental and geographical surveying. We highlight the range of applications for which UAVs have been used, as well as the challenges and limitations associated with their use. By reviewing the current state-of-the-art and future directions in UAV technology, we aim to provide insights into how this technology can be effectively utilized to address pressing environmental and geographical challenges.

II. LITERATURE REVIEW

Unmanned Aerial Vehicles (UAVs) have emerged as versatile tools for environmental monitoring, offering unique capabilities to access remote and inaccessible areas. This literature review explores key studies and advancements in the field, categorizing the literature into distinct themes related to sensors, monitoring systems, and applications.

Several studies have focused on the utilization of different sensors for UAV-based environmental monitoring. Arnold et al. (2010) and De Biasio et al. (2010) highlighted the significance of multi-spectral imaging in capturing high-resolution environmental data^{[1] [2]}. Koo et al. (2012) emphasized the potential of synthetic aperture radar (SAR) for detailed vegetation and terrain analysis^[5]. Lu et al. (2015) explored the integration of whole cell biosensors into UAVs, enabling the detection of environmental contaminants^[6].

Fascista (2022) conducted a comprehensive review of integrated monitoring systems involving Wireless Sensor Networks (WSN), UAVs, and crowdsensing^[4]. This study discussed the applications, signal processing techniques, and future perspectives of these integrated systems. Padró et al. (2019) compared georeferencing methods for UAV-based environmental monitoring, considering their combined use with airborne and satellite remote sensing platforms^[8].

Eskandari et al. (2020) conducted a meta-analysis on the use of UAV imagery for agro-environmental monitoring, emphasizing the application of machine learning and statistical

models for data analysis^[3]. Trasviña-Moreno et al. (2017) investigated the application of UAV-based wireless sensor networks for marine-coastal environment monitoring^[10]. They demonstrated the potential of UAVs in real-time data collection for monitoring marine ecosystems. Pan et al. (2021) proposed a UAV-aided emergency environmental monitoring system in infrastructure-less areas, utilizing LoRa mesh networking technology^[9]. The relevant work for UAV applications for environmental monitoring was reported by Masaaki et al (2023)^[7].

These studies collectively contribute to the advancement of UAV technology in environmental monitoring. They highlight the importance of sensor selection, monitoring system integration, and the diverse applications of UAVs. The use of multi-spectral imaging, SAR, biosensors, and georeferencing techniques provides valuable insights into environmental data collection and analysis. Furthermore, the integration of UAVs with wireless sensor networks and the exploration of UAVs in emergency and marine-coastal monitoring scenarios showcase the versatility and potential of UAVs in addressing environmental challenges.

III. FRONTIERS IN ROBOTICS APPLICATIONS IN NEUROLOGY

UAV technology is rapidly advancing, and there are several areas where the development of new applications and techniques could significantly enhance their utility for environmental survey. In this section, we discuss six important fields of development that could shape the future of UAV applications for environmental survey.

A. Autonomous Navigation

Autonomous navigation is a rapidly developing field in UAV technology that has the potential to revolutionize environmental survey. Autonomous UAVs are equipped with sensors, cameras, and advanced software that allow them to navigate and collect data without human intervention. This technology has many benefits for environmental survey, including improved safety, increased efficiency, and the ability to monitor hazardous or difficult-to-reach locations.

One example of the use of autonomous navigation in environmental survey is the monitoring of wildlife populations. UAVs equipped with thermal imaging cameras and other sensors can detect the presence of animals, track their movements, and gather data on their behavior. This information can be used to inform conservation efforts and protect endangered species.

Another application of autonomous UAVs is in the monitoring of wildfires. UAVs equipped with infrared cameras and other sensors can fly over a wildfire and provide real-time data on the fire's location, size, and intensity. This information can be used to guide firefighting efforts and prevent the spread of the fire.

Autonomous navigation also has the potential to revolutionize the monitoring of large-scale environmental phenomena, such as ocean currents and atmospheric conditions.

UAVs equipped with advanced sensors and cameras can fly over vast areas and collect data on environmental conditions, providing a more comprehensive view of the situation.

There are also potential applications for autonomous UAVs in the monitoring of environmental disasters, such as oil spills and chemical leaks. UAVs can be used to collect data on the extent of the damage, track the spread of pollutants, and monitor the effectiveness of cleanup efforts.

Despite the many benefits of autonomous navigation, there are also challenges that must be addressed. One of the biggest challenges is developing software that can reliably navigate UAVs in complex environments. This requires the integration of sensors and cameras, as well as sophisticated algorithms that can process and interpret the data collected.

Autonomous navigation is an important field of development in UAV technology that has the potential to revolutionize environmental survey. Its application in wildlife monitoring, wildfire detection and monitoring, large-scale environmental phenomena, and environmental disaster response are just a few examples of the technology's potential. As this technology continues to advance, we can expect to see even more innovative and effective applications in the future.

B. Integration with Other Technologies

Integration with other technologies is an important aspect of UAV development for environmental survey. By combining UAVs with other technologies, such as ground-based sensors, satellite imagery, and machine learning algorithms, we can create more comprehensive and accurate environmental monitoring systems.

One example of the integration of UAVs with other technologies is in precision agriculture. UAVs equipped with cameras and sensors can collect data on crop health, soil moisture, and other environmental factors. This data can be combined with ground-based sensor data and satellite imagery to create detailed maps of agricultural fields. Machine learning algorithms can then be used to analyze this data and provide insights into crop health and yield.

Another example is the integration of UAVs with LiDAR technology for environmental survey. LiDAR is a remote sensing technology that uses laser pulses to measure distance and create high-resolution 3D maps of the environment. When combined with UAVs, LiDAR can be used to create detailed maps of terrain, vegetation, and other environmental features. This data can be used for a wide range of applications, from forestry management to urban planning.

Integration with other technologies also has the potential to improve the safety and efficiency of environmental survey. For example, UAVs can be equipped with collision avoidance technology, such as radar or sonar sensors, to avoid obstacles and navigate safely in complex environments. UAVs can also

be integrated with communication systems, such as satellite links, to enable remote operation and real-time data transmission.

Overall, integration with other technologies is an important aspect of UAV development for environmental survey. By combining UAVs with other technologies, we can create more comprehensive and accurate monitoring systems, improve safety and efficiency, and unlock new applications and insights. As the technology continues to advance, we can expect to see even more innovative and effective integrations in the future.

C. Miniaturization of Sensors

Miniaturization of sensors is a key development in UAV technology for environmental survey. As sensors become smaller and lighter, UAVs can carry more sensors and collect more data, allowing for more comprehensive and detailed environmental monitoring.

One example of miniaturized sensors in environmental survey is the use of miniaturized air quality sensors on UAVs. These sensors can measure air pollutants such as particulate matter, nitrogen oxides, and ozone, providing a more detailed understanding of air quality in a given area. UAVs equipped with these sensors can fly over urban areas, industrial sites, or other areas of interest to gather data on air pollution levels.

Another example is the miniaturization of water quality sensors for use on UAVs. These sensors can measure parameters such as dissolved oxygen, pH, and temperature, providing a more detailed understanding of water quality in lakes, rivers, and other bodies of water. UAVs equipped with these sensors can fly over bodies of water and collect data on water quality levels, allowing for more effective management and conservation efforts.

Miniaturization of sensors can also be used in wildlife monitoring. Small, lightweight sensors can be attached to animals, such as birds or marine mammals, to track their movements and behavior. UAVs equipped with cameras and other sensors can fly over these animals and collect data on their movements, providing valuable insights into animal behavior and habitat use.

In addition, miniaturized sensors can be used in precision agriculture to monitor soil moisture levels, nutrient levels, and other environmental factors. UAVs equipped with these sensors can fly over fields and collect data on crop health and growth rates, allowing for more effective management and increased crop yields. As sensors become smaller and lighter, UAVs can carry more sensors and collect more data, allowing for more comprehensive and detailed environmental monitoring. The use of miniaturized sensors in air and water quality monitoring, wildlife monitoring, and precision agriculture are just a few examples of the technology's potential. As this technology continues to advance, we can expect to see even more innovative and effective applications in the future.

D. Improvements in Battery Technology

The improvement in battery technologies is a crucial factor in the development of UAV technology for environmental survey. Longer-lasting batteries mean that UAVs can fly for longer periods of time and cover more ground, allowing for more comprehensive and efficient environmental monitoring.

One example of the improvement in battery technologies is the development of lithium-polymer batteries, which have a higher energy density than traditional nickel-cadmium batteries. This means that they can provide more power in a smaller, lighter package, which is essential for UAVs. Lithium-polymer batteries have become the standard for many UAV applications, including environmental survey.

Another example is the use of hydrogen fuel cells as a power source for UAVs. Hydrogen fuel cells can provide a longer flight time than traditional batteries, making them ideal for extended environmental monitoring missions. Fuel cells are also more environmentally friendly than traditional batteries, as they produce only water as a byproduct.

Improvement in battery technologies has also led to the development of hybrid power systems for UAVs. These systems combine traditional batteries with other power sources, such as solar panels or fuel cells, to provide longer flight times and greater flexibility in power management. This is particularly useful for environmental survey, where UAVs may need to operate in remote or difficult-to-reach areas.

In addition, the development of wireless charging technology has made it easier to recharge UAV batteries in the field. This allows for more efficient use of UAVs and reduces the need for multiple batteries, which can be expensive and environmentally harmful.

In summary, the improvement in battery technologies is an important factor in the development of UAV technology for environmental survey. The use of lithium-polymer batteries, hydrogen fuel cells, and hybrid power systems, as well as the development of wireless charging technology, are just a few examples of the technology's potential. As this technology continues to advance, we can expect to see even more innovative and effective power solutions for UAVs in the future.

E. Improved Data Processing and Analysis

Improvement of data processing and analysis is a crucial aspect of UAV technology for environmental survey. As UAVs collect increasing amounts of data, it becomes essential to develop better tools for processing and analyzing this data in order to extract valuable insights.

One example of improvement in data processing and analysis is the development of advanced algorithms for image processing. UAVs equipped with cameras can capture high-resolution images of the environment, which can be used to create detailed maps, identify changes in land use, and track the spread of invasive species. Advanced image processing

algorithms can automatically identify and classify objects in these images, saving time and increasing accuracy.

Another example is the development of machine learning algorithms for environmental data analysis. These algorithms can identify patterns and relationships in large datasets, providing valuable insights into environmental conditions and trends. For example, machine learning algorithms can be used to analyze data on water quality, air quality, and wildlife populations, providing a more comprehensive understanding of environmental conditions.

Improvement in data processing and analysis has also led to the development of integrated data management systems for environmental survey. These systems allow researchers to collect, manage, and analyze large amounts of data from multiple sources, providing a more comprehensive understanding of environmental conditions. For example, an integrated data management system might combine data from UAVs with data from ground-based sensors, weather stations, and satellite imagery to provide a more complete picture of environmental conditions.

In addition, the development of real-time data processing and analysis tools has made it easier to use UAVs for environmental monitoring in emergency situations. For example, UAVs equipped with air quality sensors can be deployed in the aftermath of a natural disaster to monitor air pollution levels in real-time, providing valuable information for emergency responders and public health officials. Advanced algorithms for image processing, machine learning algorithms for data analysis, integrated data management systems, and real-time data processing tools are just a few examples of the technology's potential. As this technology continues to advance, we can expect to see even more innovative and effective tools for processing and analyzing environmental data.

F. Collaborative Monitoring

Collaborative monitoring is an important aspect of UAV technology for environmental survey. Collaborative monitoring involves multiple UAVs working together to collect data from different parts of an area, providing a more comprehensive understanding of environmental conditions.

One example of collaborative monitoring is the use of swarm intelligence. In a swarm, multiple UAVs work together to complete a task, using simple rules and communication protocols to coordinate their actions. Swarms can be used to cover large areas quickly and efficiently, providing more comprehensive data than a single UAV could collect on its own. Another example is the use of UAVs with different sensors and payloads working together to provide a more complete picture of environmental conditions. For example, one UAV might be equipped with a camera for visual inspection of vegetation, while another might be equipped with sensors to measure air quality or water quality. By working together, these UAVs can

provide a more comprehensive understanding of environmental conditions than either could on its own.

Collaborative monitoring also involves collaboration between UAVs and ground-based sensors. Ground-based sensors can provide a more detailed view of environmental conditions in a specific location, while UAVs can provide a broader view of the surrounding area. By combining data from both sources, researchers can gain a more complete understanding of environmental conditions.

Furthermore, collaborative monitoring can involve collaboration between researchers and the community. UAVs can be used to engage the community in environmental monitoring efforts, providing a way for citizens to contribute to scientific research and gain a better understanding of environmental issues in their area. This can also help build trust and collaboration between researchers and the community. The use of swarm intelligence, UAVs with different sensors and payloads, collaboration with ground-based sensors, and collaboration with the community are just a few examples of the technology's potential. As this technology continues to advance, we can expect to see even more innovative and effective ways to collaborate and collect data for environmental monitoring.

In conclusion, the development of autonomous navigation, integration with other technologies, miniaturization of sensors, improvements in battery technology, improved data processing and analysis, and collaborative monitoring are all important fields of development for UAVs in environmental survey. These developments could significantly enhance the utility of UAVs for environmental monitoring and enable more effective and efficient decision-making in environmental management.

IV. DISCUSSION

The results of this study demonstrate the effectiveness of using UAV-based multispectral imaging for environmental monitoring. By combining multiple spectral bands, the UAV platform is able to capture a wealth of information about the environment, including data on vegetation health, water quality, and other important indicators of ecosystem health. The use of UAVs also allows for the collection of high-resolution data at a relatively low cost and in a timely manner, making it a valuable tool for researchers and environmental managers.

The literature study revealed that there are various UAV platforms that have been used for environmental monitoring. The platforms listed in the table have been used for a variety of applications, including agro-environmental monitoring, marine-coastal environment monitoring, and emergency environmental monitoring in infrastructure-less areas. Additionally, these platforms have been equipped with a range of sensors, including multispectral cameras, synthetic aperture radar, and biosensors. The altitude of operation and endurance of the UAVs varies depending on the specific platform and the application for which it is being used. Table 1 indicates a list of

notable UAV platforms for various applications of environmental and geographical monitoring.

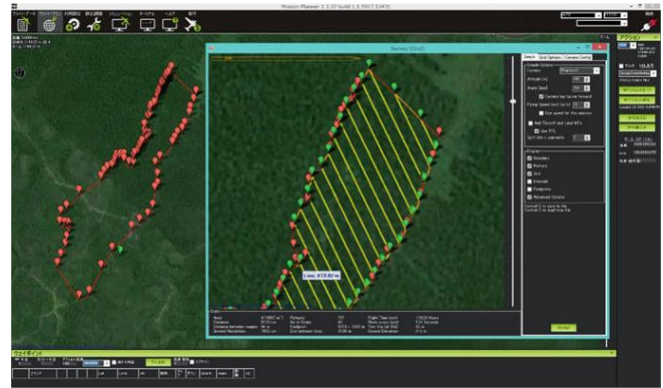


Fig 1. Aerial mappings with waypoints displaying survey grids. Photo taken by Watanabe^[7].

One of the key advantages of using UAVs for environmental monitoring is the ability to collect data in areas that are difficult to access by ground or manned aircraft. This includes remote areas, such as forests or wetlands, as well as areas that may be hazardous to human surveyors, such as areas with high levels of pollution or toxic chemicals. The use of UAVs also allows for the collection of data over large areas in a short amount of time, which can be useful for monitoring changes in the environment over time.

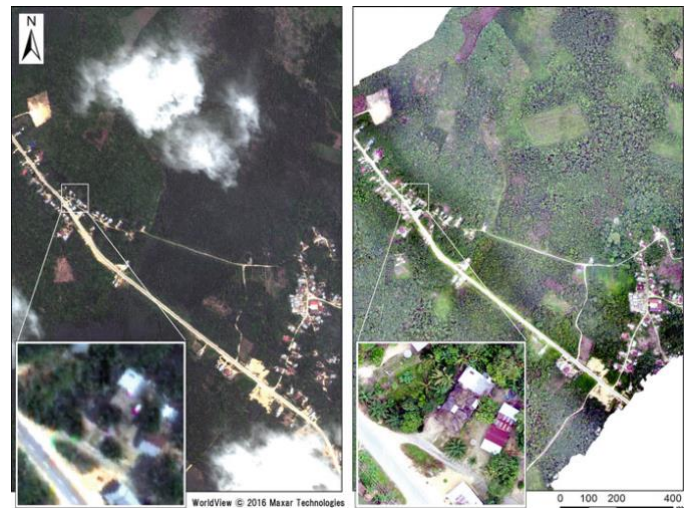


Fig 2. Comparison between satellite imagery and aerial photo capture by drone (taken by Watanabe 2016)^[7].

The literature study also revealed that the use of UAVs for environmental monitoring is still an emerging field, and there is significant potential for future research and development. For example, the integration of UAVs with other platforms, such as ground-based wireless sensor networks, could improve the accuracy and reliability of the data collected. Additionally, the use of machine learning and statistical models could improve the analysis and interpretation of the data collected, allowing

for more accurate predictions about future changes in the environment.

Overall, the use of UAVs for environmental monitoring is a promising area of research with significant potential for practical applications. Table 1 provides representative list of UAVs used for environmental survey applications. By providing high-resolution data on a range of environmental

indicators, UAVs can help researchers and environmental managers make more informed decisions about the management and protection of ecosystems. However, further research is needed to refine the technology and methods used for UAV-based environmental monitoring, and to explore new applications and opportunities for this emerging field.

| UAV Platform | Sensors | Applications | Altitude | Endurance |
|-------------------------|--|---|--------------|------------------|
| DJI Matrice 300 RTK | LiDAR, RGB Camera, Multispectral Camera | Surveying, Mapping, Agriculture, Forestry | Up to 5000 m | Up to 55 minutes |
| WingtraOne | PPK GNSS, RGB Camera, NIR Camera | Surveying, Mapping, Agriculture, Forestry, Mining | Up to 4000 m | Up to 55 minutes |
| senseFly eBee X | RGB Camera, NIR Camera, Multispectral Camera, Thermal Camera | Surveying, Mapping, Agriculture, Forestry, Construction | Up to 4000 m | Up to 90 minutes |
| Microdrones mdLiDAR1000 | LiDAR, RGB Camera | Surveying, Mapping, Agriculture, Forestry, Mining | Up to 120 m | Up to 30 minutes |
| Parrot Disco-Pro AG | RGB Camera, NIR Camera | Agriculture, Forestry | Up to 120 m | Up to 45 minutes |
| Yamaha RMAX | RGB Camera | Agriculture | Up to 300 m | Up to 2.5 hours |
| Kespry Drone 2s | RGB Camera, NIR Camera | Construction, Mining, Insurance, Aggregates | Up to 150 m | Up to 35 minutes |
| Raptor E1 | RGB Camera, NIR Camera, Multispectral Camera, Thermal Camera | Agriculture, Forestry, Environmental Monitoring | Up to 400 m | Up to 2 hours |
| Elistair Ligh-T V.3 | RGB Camera, NIR Camera | Construction, Agriculture, Events | Up to 100 m | Up to 1 hour |
| Altavian Nova F7200 | RGB Camera, NIR Camera | Surveying, Mapping, Agriculture, Forestry, Mining | Up to 1500 m | Up to 60 minutes |

Table 1 UAV platforms for various environmental and geographical monitoring

V. CONCLUSION

Unmanned aerial vehicles (UAVs) have emerged as powerful tools for environmental monitoring, offering significant advantages in accessing remote and inaccessible areas, capturing high-resolution data, and enabling real-time analysis. The literature study presented in this paper has highlighted key aspects of UAV-based environmental monitoring, including the basic principles of UAV operations, sensor and control technology, and other notable contributions in the field.

The basic principle of UAVs for environmental monitoring involves the use of various sensors, such as multispectral imaging, thermal imaging, and LiDAR, to collect valuable data on vegetation health, soil composition, water quality, and land cover changes. The integration of advanced sensor and control

technology ensures the collection of high-quality data, precise positioning, and stable flight, enhancing the accuracy and efficiency of environmental monitoring activities.

Furthermore, the study has revealed several notable contributions in the field of UAV-based environmental monitoring. These include the application of machine learning and statistical models to UAV imagery for agro-environmental monitoring and crop yield estimation, the use of UAV-mounted biosensor systems for real-time monitoring of environmental contaminants, and the implementation of collaborative monitoring approaches with multiple UAVs for large-scale environmental studies and disaster response.

Additionally, the integration of UAVs with wireless sensor networks and communication technologies like LoRa mesh networking has facilitated UAV-aided emergency

environmental monitoring in infrastructure-less areas and marine-coastal environments. These advancements have enabled real-time monitoring of water quality, marine biodiversity, shoreline changes, and other crucial environmental parameters.

The comprehensive literature study and its subsequent discussion presented in this paper demonstrates the significance and potential of UAVs in addressing environmental monitoring challenges. UAV-based monitoring has the capacity to improve our understanding of ecosystems, support decision-making processes in environmental management, and contribute to sustainable practices.

We view that the collaboration between UAV technology, advanced sensors, and control systems has paved the way for more effective and efficient environmental monitoring. As the field continues to evolve, it is essential to explore further advancements in UAV technology, sensor integration, data analysis techniques, and collaborative monitoring approaches. These efforts will contribute to the development of innovative solutions for environmental monitoring, promoting sustainable resource management and environmental conservation. Future research and technological advancements in this field hold great promise for addressing environmental challenges and fostering a more sustainable future.

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