Part IV
Environmental Sustainability and Climate Action

Chapter 27

Integration of Deep Learning with CubeSat Technologies for Environmental Monitoring

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Abstract

Satellites have revolutionised the way the planet's environment is monitored, via a unique perspective from above. Indeed, environmental monitoring is crucial for understanding and addressing the complex challenges facing the planet, thereby supporting decision-making and ensuring a sustainable future. Thus, this work aims to develop an intelligent model that includes Artificial Neural Networks (ANNs) and a Deep Learning (DL) approach, coupled with Blockchain capabilities, for secure environmental monitoring using a CubeSat. The CubeSat, a small satellite platform, is equipped with a designed communication payload, including an adaptive Multiple-Input Multiple-Output (MIMO) antenna as well as an HD camera for better connectivity and precise aerial imaging. The proposed solution is simulated, prototyped, tested, and validated across four scenarios, namely: water detection, tree counting and vegetation assessment, and oil spill detection. Ensuring the security and integrity of data transmitted between the CubeSat and the ground station is of paramount importance; this is where Blockchain technology comes into play. The obtained results show high accuracy in monitoring environmental surfaces like water, trees, and coasts, with effective and rapid deployment. Also, performance indicators of the Blockchain ensure data integrity and retrieval efficiency. Combining these technologies provides a valuable contribution to environmental monitoring. A use case scenario in Taif city, Saudi Arabia, has been considered for validation.

Keywords: *Deep Learning, Communications, CubeSat, Sustainability, Environmental Monitoring*

Introduction

Monitoring the environment is essential for tracking ecosystem health, biodiversity, and sustainable use of resources. The UN's 17 Sustainable Development Goals (SDGs) offer a global framework to address pressing challenges, with natural resource monitoring supporting progress. Satellite communications are central to modern life, enabling global connectivity, navigation, meteorology, and exploration. CubeSats, low-cost mini-satellites, expand these capabilities by supporting Earth observation, remote communication, education, agriculture, and scientific research. They represent a breakthrough in space technology, fostering innovation, efficiency, and sustainable development.

This paper proposes an intelligent CubeSat-based framework with Blockchain integration to enhance the security of environmental monitoring. Unlike prior studies, it combines Artificial Neural Networks

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(ANNs) to optimise connectivity, Deep Learning (DL) for object detection, and adaptive MIMO antennas for high data rates and reliability. Blockchain ensures secure communication between CubeSats and ground stations. The model is validated across four scenarios: water detection, tree counting, vegetation assessment, and oil spill monitoring. Although complexity is a challenge due to its hierarchical structure, modular design and mathematical modelling can improve efficiency. Overall, the framework offers a holistic advancement in secure, reliable environmental monitoring[1].

Figure **1** shows the proposed solution for environmental monitoring utilizes a two-segment system: a sky segment and a ground segment. The sky segment features a CubeSat equipped with various components, including an HD camera, sensors, and an adaptive MIMO antenna. The adaptive MIMO antenna enhances remote sensing by dynamically adjusting its radiation patterns, which optimise signal transmission and data rates. An intelligent DL algorithm, specifically YOLOv9, is integrated for object detection and analysis in high-precision aerial imaging. This CubeSat also uses the Normalised Difference Vegetation Index (NDVI) to assess vegetation health. The ground segment includes a Ground Control Station (GCS) that receives data from the CubeSat and manages its movement and energy. The GCS also collects data from ground sensors, and the communication link between the CubeSat and the GCS is secured using blockchain and optimised with ANNs.

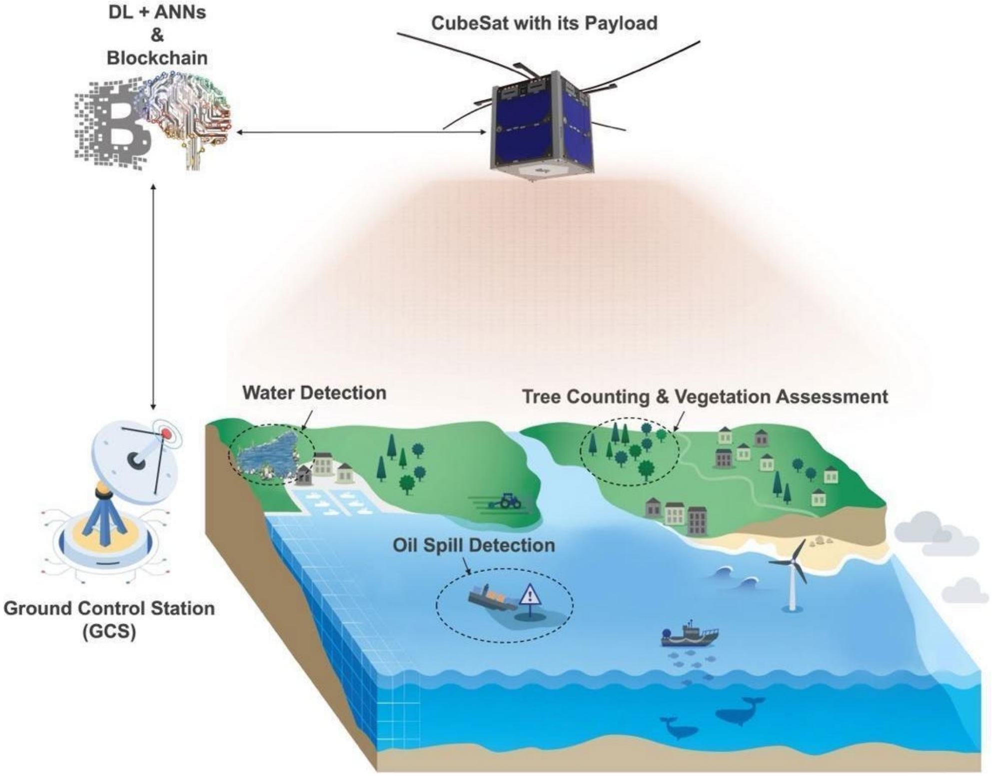

Figure 1: Conceptual outline of the proposed solution.

Figure **2** shows a flowchart of the proposed solution framework for environmental monitoring. The progress of the projection matrices for link budget, with which the ANNs (first brain) are initially

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[1] Faris A. Almalki, “Developing an Intelligent Framework with Blockchain Capabilities for Environmental Monitoring Using a CubeSat,” The Computer Journal 68, no. 8 (2025): 968–84, https://doi.org/10.1093/comjnl/bxaf017

trained, are discrete events; while the progress of the projection matrix for the water detection, tree counting and vegetation assessment, and oil spill detection, with which the DL YOLOv9 (second brain) are trained, are considered as a continuous event as they evolve after each circle orbit.

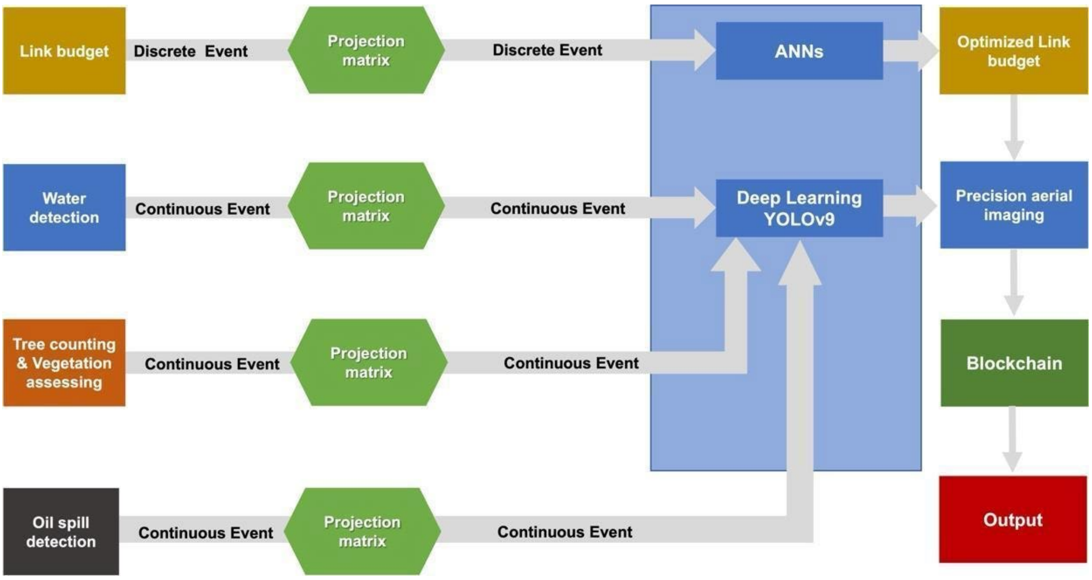


Figure 2: Detailed flowchart of the proposed framework solution.

Results and Discussion

This section shows a brief illustration of the simulation setup and results, which is a fundamental step to get early link budget predictions of the proposed CubeSat, before starting to build the CubeSat's prototype.

Figure **3** illustrates the CubeSat communication architecture using the satellite communications simulation toolbox in MATLAB. The toolbox includes functions to simulate, analyse, and visualise the CubeSat's dynamics and communications based on parameters and network configurations. Figure **4** shows the proposed antenna shape using a 4x4 microstrip patch MIMO antenna at a frequency of 28 GHz, using CST Microwave Studio, which consists of three layers: a ground layer of copper, a substrate layer of Rogers, and a patch layer of copper. These layers would help in improving the antenna's performance, reliability, and durability.

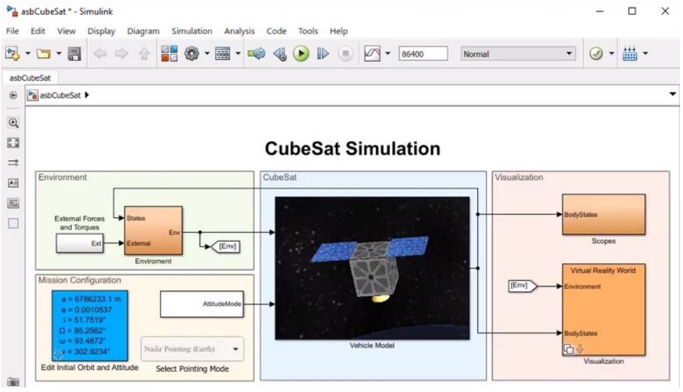

86400
Normal
$a = 6786233.1$ m
$e = 0.0010537$
$i = 51.7519°$
$\Omega = 95.2562°$
$\omega = 93.4872°$
$v = 302.9234°$
Nadir Pointing (Earth)

Figure 3: CubeSat network communication architecture.

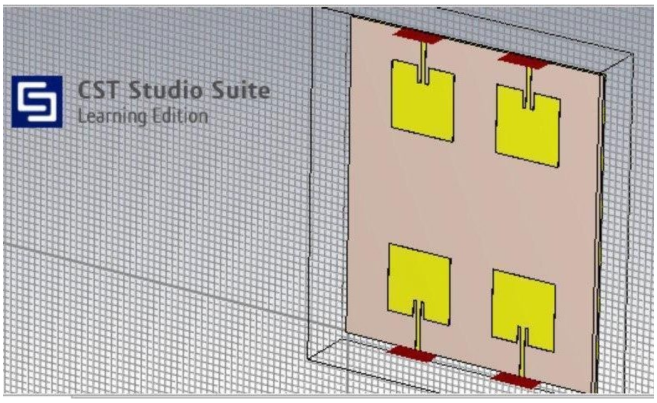
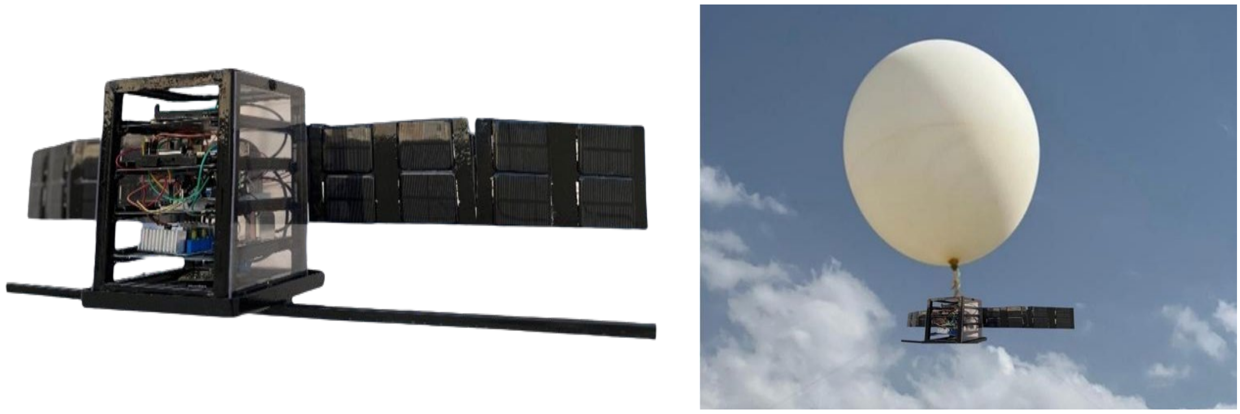


Figure 4: 4x4 microstrip patch MIMO antenna at a using CST toolbox.

An experiment was conducted on September 18, 2024, at Taif University, Saudi Arabia, using a CubeSat prototype. The prototype, as shown in Figure **5**, was lifted to an altitude of 50 meters with a helium-filled tethered balloon. The CubeSat was equipped with an adaptive MIMO antenna, a camera, a GSM module for communication, and an AI framework that included ANNs and YOLOv9 models. The purpose of the experiment was to validate a sustainable environmental monitoring solution. The prototype was tested for four main tasks: water detection, tree counting, vegetation assessment, and oil spill detection.



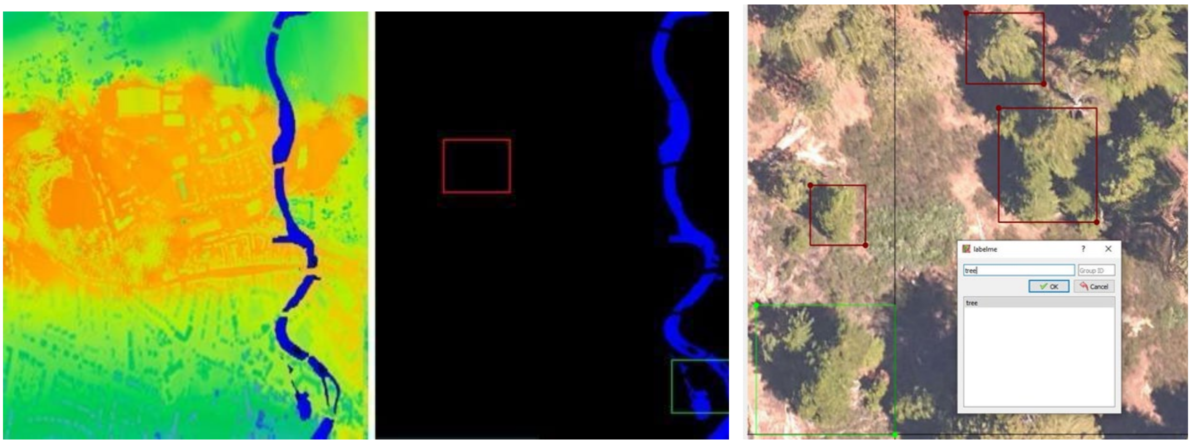
a. CubeSat prototype with its payload.

b. CubeSat prototype with its payload.

Figure 5: The porotype implementation using a tethered balloon.

Graphs in Figure **6** show the implementation results when deploying the proposed solution for environmental monitoring. Figure **6**a shows the water detection task, which is indicated by a green box, while the red one indicates that it is not a water body. The detection includes watersheds, water bodies, and their sizes, rather than their volumes. Figure **6**b shows the tree counting task, where red boxes mean that the trees have been counted, while green box shows the latest recognition and counting. This can help in vast areas. Figure **6**c shows the vegetation assessment task using NDVI, where squares with percentages show the NDVI results. The high percentage indicates that the plants are very healthy. Figure **6**d shows the oil spill detection task, which shows the accuracy of detecting the oil substances against water.

The obtained results emphasise that the prototype demonstrates high accuracy in monitoring environmental surfaces such as water, forests, and farms in a cost-effective, rapid-deployment manner. These tasks would cover land and sea aspects, which give holistic environmental monitoring. To precisely detect and monitor items in various environments, such as trees and water, bounding boxes must be applied within the proposed algorithm to improve performance and accuracy. These bounding boxes are a fundamental tool for defining and localising objects within a given space. They are essentially rectangular regions that enclose objects of interest, providing valuable information about their positions, sizes, and orientations.



a. Water detection task

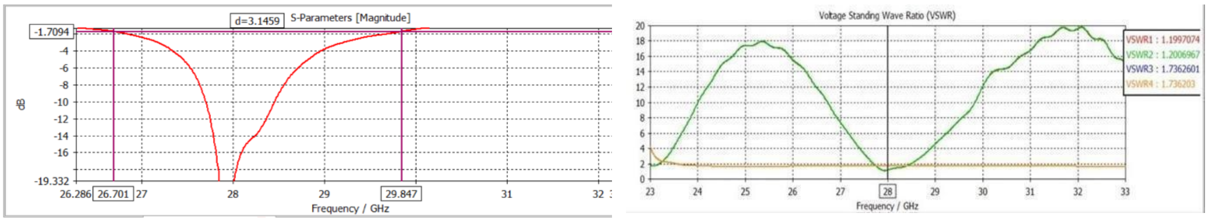
b. Tree counting task

c. Vegetation assessing task using NDVI

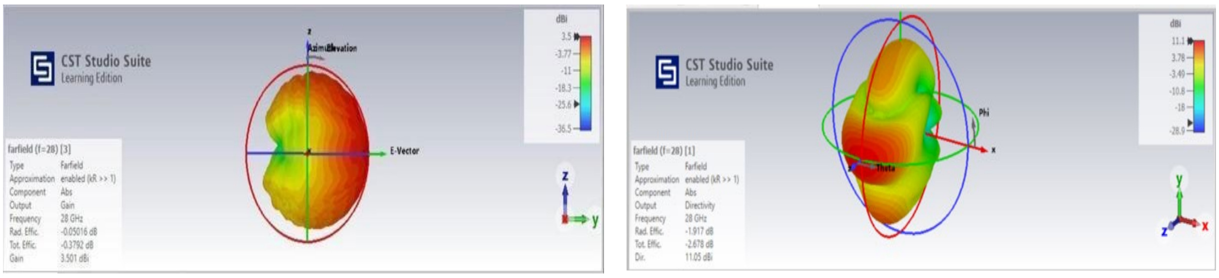
d. Oil spill detection task

Figure 6: Implementation results of the proposed solution for environmental monitoring.

Graphs in Figure 7 show the performance of the 4x4 microstrip patch MIMO antenna. The graphs include indicators that evaluate the performance of the designed smart MIMO antenna includes S11, Voltage Standing Wave Ratio (VSWR), antenna gain, and antenna directivity. Overall results show that the S11 parameter, which evaluates impedance matching and efficient power transfer. A low S11 value, typically below -20 dBm, is desired for better performance and wider bandwidth. A VSWR of less than 2 is considered acceptable, as it reflects the efficiency of power transmission. Antenna gain and directivity are also measured, showing a focused radiation pattern that reduces power consumption and increases effective range with decent outcomes.



a. S11 parameter *b. Antenna VSWR*



c. Antenna gain *d. Antenna directivity*

Figure 7: Performance of the 4x4 microstrip patch MIMO antenna.

Plots in Figure **8** show the link budget parameters. Using an optimisation technique, likely employing ANNs, the communication link's performance was significantly improved. The Received Signal Strength (RSS) increased from -74.05 dBm to -60.01 dBm, leading to more effective data reception. Path loss was reduced from 143.49 dB to 100 dB, enhancing communication quality across all distances. The Signal-to-Noise plus Interference Ratio (SNIR) improved from 8.23 dB to 5.02 dB, increasing signal strength relative to noise. Lastly, throughput rose from 30.06 Mb/S to 32 Mb/S, indicating faster data transfer. Overall, across all link budget parameters at an altitude of 400km, the optimised indicators are better than the non-optimised ones, which reflects improvement in the wireless network connectivity, coverage, and throughput.

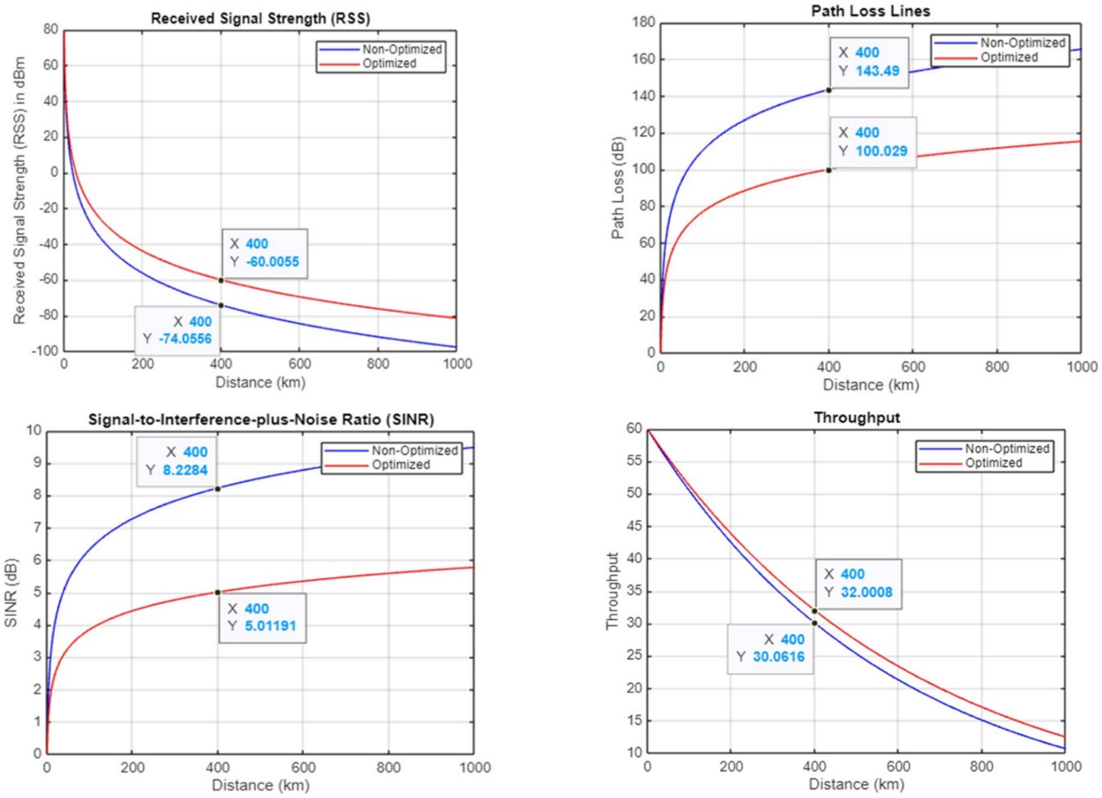


Figure 8: Link budget parameters in non- optimized and optimised scenarios.

Figure **9** shows that the ANN model achieved optimal performance at 192 epochs with a low Mean Squared Error (MSE), indicating good fitting. Training stopped at 193 epochs, showing no significant overfitting.

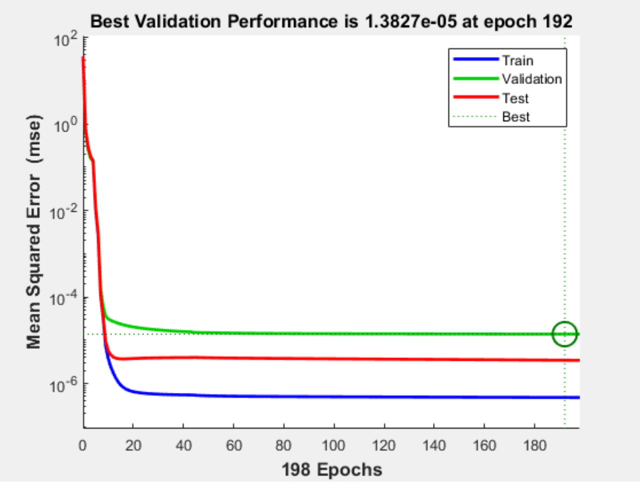


Figure 9: MSE performance of the ANN model.

Figure **10** shows the precision-recall curve of the YOLOv9 model. It serves as an evaluation of the performance of the object detection capability of the YOLOv9 model. The curve indicates a good predictive model with high accuracy, reaching 92%, since the precision stays high as the recall increases.

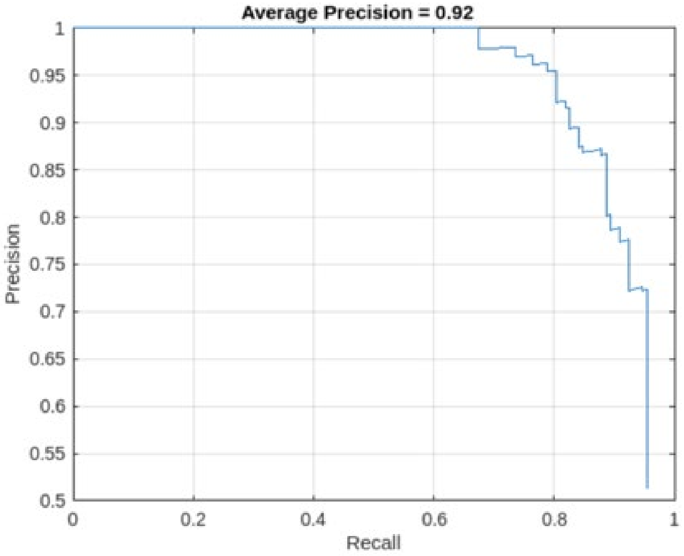
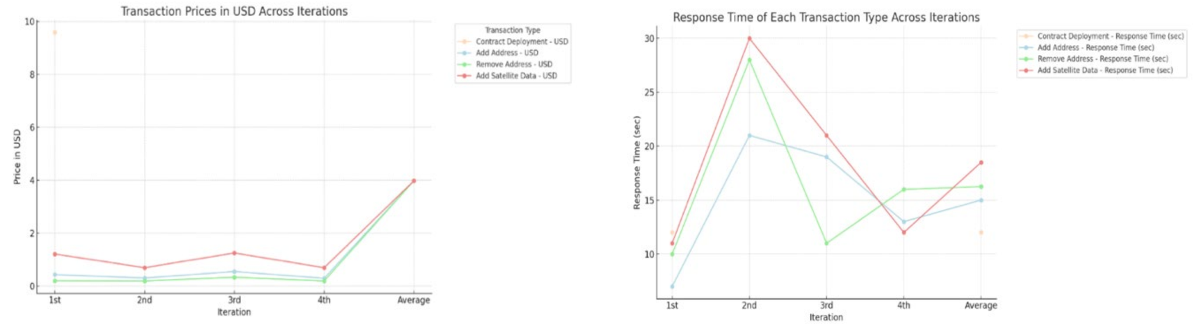
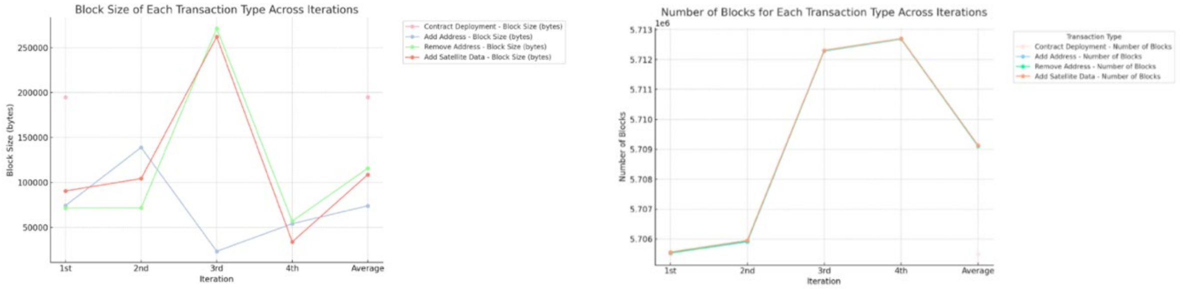


Figure 10: Precision-recall curve of the YOLOv9 model.

Blockchain performance can be analysed using key metrics like transaction prices, response times, block sizes, and the number of blocks. Figure **11** shows a framework in which transaction prices are influenced by market factors, such as Ethereum price volatility. Response times lengthen as network activity increases, reflecting throughput limitations. Block sizes expand with more transactions, posing scalability challenges and impacting processing latency. The number of blocks tracks network activity, indicating potential increases in orphan blocks under high throughput. Overall, the analysis reveals periods of stress on the network, highlighting areas for enhancement. CubeSat data is stored on IPFS, with its hash stored on a blockchain for integrity.



(a) Transaction prices (b) Response times



(c) Block sizes (d) Number of blocks

Figure 11: Performance indicators of Blockchain.

Conclusions

This work introduces an intelligent model integrated with a Blockchain framework for secure environmental monitoring using a CubeSat. The system utilises a CubeSat equipped with a camera and an adaptive MIMO antenna, complemented by ground-based IoT sensors. The solution was simulated and validated across four scenarios: water detection, tree counting, vegetation assessment, and oil spill detection. Blockchain technology ensures the security and integrity of data transmitted from the CubeSat to the ground station. The results demonstrate high accuracy in monitoring environmental surfaces with effective and rapid deployment. Future work includes potential CubeSat launches with space agencies and the development of a user-friendly data dashboard for analysis.

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References

Almalki, Faris A. 2025. "Developing an Intelligent Framework with Blockchain Capabilities for Environmental Monitoring Using a CubeSat." The Computer Journal 68 (8): 968–84. https://doi.org/10.1093/comjnl/bxaf017.