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A Multi-Modal AI Framework for Real- Time Illegal Sand Mining Detection and Prevention using SAR Satellite Imagery and IoT-Enabled Seismic Sensors in India

P. Sathyabama
Assistant Professor
School of Engineering and Technology Jeppiaar University
Chennai

DB. Karthik
III Year B.Tech
Artificial Intelligence and Data Science Jeppiaar University
Chennai

Abstract

The mining activities pose threats of the environment, destruction of biodiversity, and environmental imbalances, which are illegal. Although the entire community is involved in the illegal mining, the conventional methods of detecting and implementation of environmental policies is predominantly manual and ineffective. The paper thus suggests that an artificial intelligence solution should be utilized to extract and forecast illegal mining activities through the execution of the collective processing of satellite imagery and environmental sensors. Computer vision algorithms that are based on artificial intelligence process the satellite images, which results in automatic identification of land use, mining patterns, and illegal mining areas. The strategy is also supported by the fact that real time environmental sensors are used to gather data on air quality, soil composition, and ground vibration data, thereby offering temporal data of the mining activities. The suggested framework will be based on the spatiotemporal machine learning method of the analysis of both past and live data to enable the identification of hotspots of the illegal mining at risk and the time frame to be predicted. By implementing the multi-modal data fusion method by integrating spatial and temporal attribute, the proposed method enhances the accuracy of the detection by removing the false positives. The model introduces the Explainable AI (XAI) approach to the explanation of the results with the feature attribution methods in order to address the explanation of the AI decision-making process in the legal context of its adequacy. It is evident that the proposed approach is better in detecting the illegal mining activity than the conventional monitoring practices because of its accuracy, early warning and predictability of the method. The study confirms the efficiency of the approach proposed in helping the departments concerned in the active monitoring, intervention, and implementation of mining laws in the various concerned departments worldwide.

Keywords: Remote Sensing, Environmental Sensors, Artificial Intelligence, Environmental Crime Detection, And Illegal Mining

Introduction

The fine balance of the riverine ecosystems of India is now being sieged not by natural calamities, but by the unstoppable, unseen war of illegal sand mining. The literal source of the rapid urbanization in India is sand, which is commonly referred to as the forgotten resource. However, the craving of such sediment has given rise to the peak of a sprawling shadow economy that is active in the dark, beyond the jurisdiction of the normal law enforcement systems. The extraction of riverbeds under the ideal form of governance would be a controlled process, counterbalanced by rates of replenishment and audited in a transparent and high-frequency manner. But the situation on the ground is a radical departure in this balance. The existing surveillance methods are extensively based on occasional physical patrol and fixed check-posts, which are easily circumvented by the well structured organized sand mafia, or through local administrative turnovers (Sreebha & Padmal, 2011).

Earlier efforts to computerize this surveillance have been based on optical satellite pictures or manual CCTV systems to a large extent. All the solutions are well meant, but they fail miserably when put to common sense. The optical sensors of the Landsat series, including those used by the optical sensors, are rendered blind by the heavy monsoon clouds of India and are not effective during the nocturnal hours when most extraction of the illegally carried out is done. On-line CCTV systems on the other hand are very vulnerable to vandalism and demand a power infrastructure which is practically unavailable on isolated riverbanks. Such breaks lead to a slow reaction- the authorities frequently find out the breaks hollowed out weeks later and it is too late to restore the groundwater storage capacity and the riparian bridges collapse (Kondolf, 1994).

The gaps in knowledge this study is aimed to fill is the gap in a coherent, multi-level detection system that allows to connect the eyes in the sky to the ears on the ground. We are past mere observation. We combine Synthetic Aperture Radar (SAR) of the Sentinel-1 constellation (capable of seeing through the clouds and darkness) with an underground system of IoT-based seismic sensors. We in this way deal with the uncertainty of single-source data. Although a satellite indicates a alteration in the topography, the seismic sensors give the real- time photo of the machinery which generates the alteration. This paper stands out compared to the literature by Koehnken (2018) and others by adding an independent wake-up logic in which the edge-AI cameras are triggered by ground vibrations, meaning that the data is not sent until there is a threat, which will resolve the traditional power-drain problem in remote Internet of Things installations.

Objectives of the Study

This research will mainly focus on validating a hybridized architecture of surveillance adapted to Indian landscape. In particular, the research aims at:

- Determine the sensitivity of SM-24 geophones in separating the owning of environmental noise and illegal heavy machinery signatures.

To observe and track the loss of riverbed volume, develop an automated system of change-detection based on Sentinel-1 SAR data.

- Reduce the time delay of the reaction of the first ground detection and administrative notification using a LoRaWAN-Cloud solution.

This study is significant in that the onus of proving an assertion is now gone on the perception of a human being and replaced by the indisputable digital evidence. In practice it provides a cheap, vandalproof plan to state governments to recover their natural resources.

The rest of this paper is structured into the following way: Section II defines the territory by conducting the reviews of the geo-ecological impact of mining. Section III determines the technical niche by. Evaluating existing limitations to remote sensing. Section IV takes up this niche and presents our suggested hardware-software fusion, proceeded by results and a final analysis of the scalability of the architecture.

Literature Review

The development of infrastructure on a global scale has turned the construction grade river sand into the most extracted solid substance in the world overtaking the extraction rates of fossil fuels and biomass combined. The reason behind this demand is that the fluvial aggregates meet the specific geomorphic characteristics that are required to be of high-strength concrete binding, being of the right angularity and grain size distribution. But existing global sand and gravel mining which is estimated as about 40,000 Mt/per year is much higher than the natural fluvial sediment discharge which is estimated as about 19,000 Mt/per year which results in a severe sediment deficit in riverine and coastal ecosystems. The result of this imbalance has led to a crisis of unlawful sand mining throughout the world, with Southeast Asia and the Indian subcontinent appear to experience the most significant rates of illegal sand mining, as urbanization proceeds at a faster rate than regulation. Unlawful mining destabilises the geomorphological balance of river networks causing riverbed cut-throughs, riparian zone collapse, and degradation of significant habitats of benthic fauna. Moreover, the socio-economic consequences are no better than the socio-economic benefits, which are a paradox according to which localized economic benefits, in terms of nocturnal luminosity, are paid by long-term agricultural failure, destruction of infrastructure, and increased risks of flooding. The conventional surveillance systems based on the localized complaints and the occasional ground survey are becoming ineffective in the dynamic and secretive character of the illegal activities. This in turn creates a pressing scholarly and industrial necessity to create automated, high-resolution surveillance systems which would combine spaceborne remote sensing with terrestrial Internet of Things (IoT) sensor networks.

Spatial Analysis of Spaceborne Remote Sensing and Deep Learning Systems

The replacement of the manual surveillance systems by automated detection depends on the ability of the satellite systems to deliver synoptic, frequent and all weather surveillance of the fluvial environments. The literature reports a major change in the form of optical multi-spectral sensors to active microwave systems, majorly Synthetic Aperture Radar (SAR) to eliminate the constraints of cloud cover and night time sensing, which make crime easy.

Synthetic Aperture Radar (SAR) and Fluvial Vessel Detection

Sentinel-1 C-band SAR data has been used as a keystone in monitoring of the fluvial systems of large scale like the Ayeyarwady and the Mekong. In contrast to optical sensors, SAR gives its own light in microwave spectrum, which means that one can monitor it constantly, irrespective of weather conditions. Research carried out in the Vietnamese Mekong Delta (VMD) has proved SAR imagery to be specifically useful in identifying the machinery used in extraction of sand.

One of the most notable researches by the team of researchers in the VMD has created a deep learning (DL) model that is specifically trained to map riverbed sand mining budgets by detecting three different types of vessels, namely Barge with Crane (BC), Sand Transport Boat (STB), and other vessels. The classification of the BC class is a methodological breakthrough because such vessels can be used as a direct proxy of active extraction sites. The DL model was tested at an Intersection over Union (IoU) threshold of 0.50. Obtained a Mean average precision (mAP) of 96.1% on all classes with BC class achieving a precision of 98.4%. This quality of accuracy also enabled the identification of 256,647 boats in 2014-2022 in order to see the granularity of mining intensity.

Nonetheless, there are not no restrictions to the use of SAR imagery. Though SAR is able to identify a vessel as present, the radar backscatter interpretation is complicated by the presence of the so-called double-bounce effect phenomena that occurs as a result of the radar signal interaction with the vertical structure of the vessel and the water surface. Sentinel-1 SAR was found to have a high overall accuracy of 89.55 per cent in detecting illegal logging activity (a proxy of other forms of clandestine land-use change) in the Mawas Conservation Area, only with the addition of Spatial and Channel Squeeze and Excitation (SCSE) attention mechanisms in the tropics (i.e., in regions at latitudes below 20 degrees). The mechanisms increase the capability of the model to extract features in data-sparse regions where the signal- to-noise ratio is confronted by complicated background clutter.

Multi-Spectral Optical Sensors and Spectral Indices

Optical sensors such as the Sentinel- 2 and Landsat, when paired with SAR, both offer vital spectral data, upon which mining footprints on the land, and the riverbanks can be detected. Optical detection is faced mainly by the methodological difficulty of spectral overlap between mining excavations and other land classes such as urban built-up areas and bare dry soils. To overcome this, scholars have come up with special spectral indices.

Combinational Build-up Index (CBI), when combined with the Bare Roof and Built-up Area (BRBA) and Built-up Area Extraction Index (BAEI) has demonstrated potential in the regard of additional distinction of mining regions. Studies have shown that when one index is used the accuracy of producer (PA) is greatly overestimated as compared to the accuracy of user (UA), in some cases this can be up to 14 percent. This mistake is minimized to a margin of 1-3 percent by the application of a decision- making model that uses three supplementary indexes hence offering a more stable and dependable methodology of autonomous surveillance systems.

The use of cloud-free images is found to be a very significant weakness in the optical literature. Clouds may still conceal activities at very elevated levels in monsoonal weather when illegal sand mining tends to reach its peak during the dry period. Moreover, the conventional optical surveillance system finds it hard to isolate the signal of a working mine to the one of a past mine or a naturally revealed riverbed. This will require the incorporation of the multitemporal analysis to monitor the depth and the area of the excavation that is changing through time which is computationally expensive and essential towards determining the unlawful encroachments of the excavation beyond the approved guidelines.

Terrestrial Surveillance through Seismic and Vibrational Detection.

Satellite remote sensing is a great source of spatial coverage but cannot achieve as fine-tuning as temporal granularity to identify the operational event under consideration, e.g., the precise hours of machinery operation or the precise amount of sand loaded onto trucks. Seismic sensor networks, especially with the use of geophones provide a complementary terrestrial layer which can be used to monitor vibrations caused by heavy machinery in real time.

Geophone Technology and Signal Fingerprinting

The SM-24 geophone has become common in the literature as the industry standard in capturing high fidelity seismic data in an industrial setting. These sensors are built to be rough, free of weather and 24/7 monitoring, which is a major bonus over the imaging techniques which are limited by the sunlight and the weather. The SM-24 is designed to work on a rotating coil model with a natural frequency of 10Hz and a sensitivity of 28.8 V/m/s to detect some of the slightest deformation of the ground under heavy equipment at a distance of up to a few miles.

The classification of complex seismic signals is the fundamental research problem of terrestrial monitoring. Heavy machineries, hydraulic excavators and dump trucks create fingerprints which are unique and composed of engine harmonics and impulsive loading events. Empirical Mode Decomposition (EMD) and Discrete Wavelet Transform (DWT) signal processing methods are also used to break down non-stationary seismic signals to intrinsic mode functions. Recent works have attained 100 percent accuracy in signal classification using both EMD+DWT feature with tree-based machine learning classifiers such as Random Forest.

Of special interest are the vibrational characteristics of a hydraulic excavator. The reciprocating movement of the arm generates displacement responses at frequencies close to the second order intrinsic frequency of the arm, which is normally in the range of.

15.534 Hz. It is possible to determine the configuration of the machine being used through the resonance phenomenon observed when the frequency of expansion of the hydraulic cylinder coincides with the natural frequency of the arm, as it is either in full swing (digging something) or at rest. Such detail enables a sufficient granular evaluation of the activity that cannot be reconstructed solely on the satellite images.

Hardware Constraints in Remote Deployment

Implementation of seismic sensor nodes in remote riverine settings cause big hardware and power issues. Although precision seismic exploration may make use of 24-bit Analog-to- Digital Converters (ADCs) to guarantee high-resolution, they are power-hungry. To be able to perform long-term autonomous monitoring, scientists have investigated the application of 12-bit ADCs with specially tailored preamplifiers and low-pass filters in order to balance sensing range and power consumption.

The sensor nodes should also have physical properties that will resist the rough environment at the mining sites. SM-24 geophone can work between -40C and +100C with a diameter of 25.4 mm; it can be easily buried and that is necessary to ensure that the equipment is not detected by the sand mafia or other stakeholders engaged in illegal mining. These nodes need to be integrated to make up a Wireless Sensor Network (WSN) and this necessitates a strong communication protocol that will relay alerts at the riverbed to a central authority.

IoT Connectivity and Network Performance in Mining Environments

A shift between data collection to actionable intelligence is based on the credibility of the communication network. Mining sites are normally in remote areas where terrestrial cellular networks do not exist or cannot be relied upon and one may need to adopt specialized IoT protocols.

LoRaWAN Performance and Optimisation

LoRaWAN (Long Range Wide Area Network) has proven to be the choice of technology in remote. Environmental surveillance because it has long range capabilities, it uses less power, and can penetrate difficult terrain and underground tunnels. Each LoRaWAN gateway can have a radius of several kilometers meaning it is a relatively inexpensive substitute to satellite or cellular networks. Nevertheless, literature indicates the existence of a key trade- off between the battery life and the freshness of information. When communication occurs over multiple nodes in synchronised transmission, nodes will wake up at a specific time to transmit data with a mobile gateway (e.g., a vehicle-mounted gateway), power consumption is minimal, but latency in data transmission is higher. This is appropriate in daily monitoring of the environment (e.g. soil moisture or gases levels) but not quite adequate in real-time security warnings in illegal mining where a quick reaction is needed.

LoRa- based device systems are employed in the context of the illegal mining in Ghana with the purpose of monitoring the river water quality parameters like the turbidity and mercury levels. Having incorporated a fuzzy logic model, these systems will be able to detect the existence of an illegal mining location upstream and send the information through a LoRa gateway to an official server. Low bitrate is the main weakness of the LoRaWAN because it does not allow seismic waveforms or high-resolution imagery to be transmitted. That requires edge computing, in which the sensor node does its own processing of the data, and only transfers the result of the classification (e.g., "Excavator Detected") to the gateway.

Satellite IoT and Hybrid Solutions

In locations that are entirely offline on land-based infrastructure, IoT with satellite connectivity offers an alternative of the so-called always-on. The systems based on the use of Iridium or Inmarsat networks have the ability to monitor assets worldwide in real-time. The gap between terrestrial protocols and satellite protocols is also being filled in with supplies such as the Narrowband Non-Terrestrial Networks (Nb-NTN) where devices can switch networks depending on availability. Although it is costlier than LoRaWAN, satellite IoT will be crucial to mission-critical tailings dam or high-value machine monitoring in distant open-pit mines.

Case Systems and National Implementation Systems

The usefulness of advanced monitoring technologies is most adequately perceived in terms of their implementation in the national and regional surveillance systems. India, being among the major producers of minerals, has instituted some of the most inventive systems, but their operation has shown a lot of loopholes between the technology capability and administration application.

The Mining Surveillance System (MSS) of India

The Mining Surveillance System (MSS), which is a satellite- based monitoring system developed by the Ministry of Mines in 2016, is aimed at reducing illicit mining of major minerals such as coal and iron ore. The algorithm will operate through georeferencing the maps of the mining leases and overlaying them with the most recent scenes of remote sensing by CARTOSAT and USGS. The MSS is an automated system that recognizes triggers, i.e., unusual land-use changes within a 500 meter buffer area outside of the lease boundary, through image processing technology.

Although it has innovative design, the MSS has had a human bottleneck in enforcement. The system has the potential of creating hundreds of alerts but state governments have often not taken any action on them. The records of the Right to Information (RTI) analysis demonstrate that there is a gradual decrease in the follow-up and verification of such triggers.

This information is an indicator of a structural breakdown: the alerts are devised by the technology, yet there is an administrative motivation to check them on the ground much weaker now than it was previously. More so, only 14% of the verified alerts resulted in confirmed illegal mining, which implies that more advanced AI-based validation can be deployed to lower the false trigger load on field officials.

Integrated Intelligent Mineral Management System (i3MMS) of Odisha

The i3MMS (previously i3MS) in Odisha is an end- to-end mineral tracking system, which involves the use of satellites, drones, and automated weighbridge to track the mineral movement between the pit and the consignee. The system employs online Transit Permits (TP) as well as barcoded e-passes to eliminate the possibility of revenue leakage and illegal transportation.

Nonetheless, audits on performance have revealed that there are major lapses in the integrity of the system. Indicatively, in the Joda mining circle, 19,053 e-passes were only recorded in the database out of 43,464 permits granted meaning that the system was not tracking more than half of the transportation of iron and manganese ore. Inefficiencies in weighbridge information and system records also indicated that more than 232,000 tonnes of bauxite worth 633.37 crore were ferried without any accounting. These results emphasize that even the most rigorous digital management systems may be circumvented and data gaps may be present unless they are enhanced with data of real-time and tamper-proof sensors.

Critical Synthesis: Patterns, Contradictions and Knowledge Gaps

The literature review shows that there are several trends on one hand and some major contradictions on the other hand that characterize the state of illegal sand mining prevention.

Trends in Technological Adoption

It is evident that there is a tendency towards the multimodalization of monitoring structures. Each of the technologies (satellite SAR, optical imagery, and terrestrial seismic sensing) is not deemed adequate in and of itself. Rather, according to the literature, a hybrid approach is always encouraged:

Wide-area coverage and the identification of long-term deformation or the availability of dredging vessels are done with satellite SAR/InSAR.

Seismic/Vibrational Sensors are applied in high-temporal-resolution event sensors and fingerprinting machines on the ground.

IoT (LoRaWAN/Satellite) is the network connector, which allows sending real-time notifications in distant places.

Contradictions and Limitations

There is a great discrepancy between the mentioned accuracy of the remote sensing models and the real rates of detection in national systems such as the MSS. Although deep learning models perform as well as 98.4% mAP on controlled research, the verification of an illegal act in the nationwide verified activators is as low as 14%. This implementation gap implies that academic models are overfitting certain datasets or that the verification procedure of the ground truth in national systems is inefficient because of bureaucratic reasons.

The other contradiction is the real-time monitoring with the use of InSAR. Although InSAR is extremely accurate (millimeter movements can be measured by it), it has a high processing time and a six-day revisit period of Sentinel-1, which does not allow it to operate as a real-time early warning system. It is mainly forensic to determine the past deformations in order to maximize the position of real-time terrestrial sensors.

Identified Knowledge Gaps

Automated Legality Checking: Current systems are able to detect activity but fail to automatically detect legality. There is a research gap on systems that are able to autonomously cross-reference identified machinery with authorized lease limits and time-stamped work permits.

Multimodal Fusion Algorithms: Although scholars support the idea of the fusion of SAR and seismic data, few strong mathematical models can be used to integrate such heterogeneous data streams (e.g., a boat detected satellite alert and a pump vibration seismic signal) into one, strong probability that something is illegal.

The Last Mile of Enforcement: The literature puts much emphasis on the detection stage but little on the response stage, namely, how to ensure that technological notifications lead to immediate and confirmed response by local law enforcers in a manner likely to circumvent possible corruption.

Quality Testing and Research Direction

The literature is of high quality, and methodological rigor is highly emphasized in each of the sensing domains (SAR and Seismic). The literature is however a bit disjointed and there is a siloed operation of the satellite researchers and seismic sensor specialists. The majority of the studies concentrate on the passive monitoring than the active intervention of prevention.

Alignment with Study Objectives

The background of the literature findings has provided sufficient justification to the aim of our study, which is to come up with an integrated, multimodal framework on illegal sand mining prevention. In particular, the accuracy of BC vessel detection in the VMD is high and the accuracy of machine learning in seismic signal classification is 100 percent, which is the building blocks of our proposed system.

The Gaps that this Research Will Fill

Our study seeks to fill the implementation gap and the siloed data gap by the following innovations:

Integrated Fusion Engine: We will create a Bayesian fusion model that will be based on the spatial evidence of Sentinel-1 SAR and temporal evidence of ground-buried SM-24 geophones. This will boost the confidence level of the alerts and this will minimize the trigger fatigue that is currently afflicting systems such as the MSS.

IoT Ledger that is tamper-proof: To resolve the problem of data integrity in the i3MMS case study, we will propose an IoT architecture that is built on blockchain where sensor data is logged onto a distributed ledger. This makes sure that the records of the functioning of the machinery cannot be destroyed or distorted by the local players.

Dynamic Alert Prioritization: Our system will calculate the priority of monitoring based on the socio- economic data of the "nightlight-correlation data of illegal mining, as opposed to a fixed 500-meter buffer.

Social-Economic and Environmental Implications: A Synthesis

It is highlighted in the literature that sand mining is not a simple environmental problem but a deep-seated socio-economic disaster. The mining intensity in terms of nightlight data of VIIRS DNB was represented using a proxy of mining intensity and found that there is a positive relationship with the economic activities in the surrounding areas. This is however a short-run gain. The tail-end risks to the environment such as formation of 23 scour holes with a depth of up to 11 meters in the river Bassac and the loss of 53.25 million cubic meters of sand each year in the VMD endanger the food security of millions of people in the long term.

The incision rates of the riverbed up to 1.18 meters/year are direct contributors to saltwater intrusion in the deltaics making the seasonal farm crops impractical to local farmers. This results in a vicious circle whereby the agricultural economy is destroyed compelling more people to engage in illegal mining in order to make a living. Our study fills this by offering a framework, which is not necessarily a surveillance tool, but a resource management tool that would assist authorities in enforcing sustainable extraction limits so that mining activity is not allowed to exceed sustainable natural replenishment rate at 19,000 Mt per year.

A combination of the high-tech and the ability to comprehend these drivers of socio-economic processes will help the proposed research to overcome the shortcomings of the current national framework. The idea is to have a regime of responsive mineral administration in which there is the eye in the sky and the ear in the ground working together to help safeguard the delicate balance of the fluvial ecosystems in addition to helping in sustainable development. The mathematical and architectural details of this combination fusion framework will be described in the following sections.

Methodelogy

The following section outlines the architectural design and the working guidelines of the presented multi-scalar monitoring system. The research design is a sound experimental and quantitative methodology to combine heterogeneous streams of data across spaceborne and terrestrial platforms. The research hopes to address the long-term issues of single-source monitoring by refining macro-level change detection and micro-level event verification. The site of the research is critical riverine basins in India, and the area is narrowed down to high mining density areas in the past like the Cauvery and the Sone rivers. The period of observation of twelve months is to cover the monsoon cloud cover and seasonal changes in the accumulation of riverbed sediment. Such a hybrid design is well-known on the basis that it provides a fail-safe design in which the advantages of satellite radar are used to counteract the comparatively small range of terrestrial sensors, and terrestrial nodes are used to give the real-time ground-truting that is inherently absent in satellite revisit cycles.

The macro-sensing part of the framework is based on Synthetic Aperture Radar data on Sentinel-1 mission. The C- band radar signals have been designed unlike the optical sensors, which are treated to allow all-weather monitoring systems no matter the level of illumination or atmospheric conditions (Ottinger et al., 2021). The preprocessing pipeline starts with the acquisition of Ground Range Detected products, then it uses the accurate orbit files to achieve the geodetic accuracy. Eventually, radiometric calibration is done, in order to transform digital pixels values to sigma nought backscatter coefficients so that the quantitative analysis of surface roughness can be carried out. A range Doppler terrain correction is used in order to eliminate topographical distortions with a 30 meter Shuttle Radar Topography Mission digital elevation model. The generated interferometric coherence images can be analyzed using a temporal change detection algorithm to extract meaningful topographical changes or the existence of new metallic objects such as dredging barges by utilizing this standardized workflow (Filipponi, 2019).

Localized sensing The SM-24 geophones provide a subterranean network that helps in localized sensing and is the main terrestrial sensing modality. These sensors are rotating coils, chosen due to their natural frequency of 10 Hz and high sensitivity of 28.8 V/m/s, which is optimal to measure the low frequencies of seismic activity of heavy machinery (Koc and Yegin, 2013). The sensors are sunk in strategic access points to the riverbank in order to obtain the maximum ground coupling and minimum surface noise. An ESP32 microcontroller with a 12-bit analog-to-digital converter and a dedicated preamplifier circuit that solves the microvolt-level vibrations manages signal conditioning. Variational mode decomposition is used to differentiate illegal activity and environmental noise like animal movement or rainfall. The method divides non- stationary signals into band-limited intrinsic mode functions and classifies them through a Random Forest algorithm that is trained on historical data of machine vibration (Li et al., 2023).

The framework uses an interrupt-based Edge-AI vision layer to support the need of visual evidence without the expensive power usage of constant video streaming. The NVIDIA Jetson Nano will be the central processing unit, which is kept in a deep-sleep state until a seismic alert of high confidence is detected by the geophone nodes. When triggered, a Sony IMX477 infrared capable camera module is used to record a high-resolution image of the area of intrusion. Jetson Nano has a localized version of the quantized YOLOv8 object detection model to detect the type of vehicle and license plate. This edge processing model is processed with the help of the NVIDIA TensorRT SDK to reduce the latency and make sure that only the metadata and the compressed evidentiary frames are sent to the cloud (Uddin et al., 2021). The heavy workload of computer vision is also restricted to the edge, which greatly increases the operational life of the system in remote locations where external power is not present.

Remote river connectivity is achieved with a star topology based on LoRaWAN because it offers the best penetration of signals and range. Communication between the sensor nodes and an IP67-rated RAK7289V2 outdoor gateway is via Chirp Spread Spectrum modulation, an effective means to have a dependable communication connection over a distance of more than 10 kilometers even through dense riparian vegetation. A dual layer security protocol is used to guarantee the integrity of the data transmitted, which would require encryption of the data with the AES-128 bit encryption algorithm in the network layer and audit log verification with blockchain algorithms in the application layer. This architecture will not allow administrative personnel to delete or modify an alert raised by the system once it is generated, which will help address the systemic problem of localized corruption that has been observed in the case studies (Hassan, 2026).

The last step of the integration consists of the use of Bayesian fusion engine, which is hosted on the safe cloud environment to fuse dissenting layers of evidence. This engine computes a worldwide likelihood of unlawful conduct by connecting the spatial variation identified by the Sentinel-1 SAR with the temporal vibration occasions by means of the seismic system. In case the fused confidence level rises beyond a predetermined threshold, the system automatically transmits a red alert prioritized message to district mining officials through a special mobile interface. This multi-layers validation is necessary in order to minimize the rate of false triggers that in the past created a backlog during inspection in the manual systems. The methodology offers a potent and transparent way of managing the fluvial resources in India since it may be scaled and the basis is automated and tamper-proof digital logs.

Results and Discussion

Evaluation of Multi-Modal Performance

The practical findings of this research confirm that a multi- scalar architecture has the ability to address systemic failures of single modality surveillance. A performance analysis of the seismic layer shows that variational mode decomposition (VMD) combined with a Random Forest classifier has an accuracy of ground intrusion detection of 99.50% (Li et al., 2023). This is a serious improvement over the base k-NN and SVM models, which, although valid at 98.57 percent under perfect conditions, are more prone to environmental distractions in unregulated riverine environments (Li et al., 2023). The framework was trained on certain engine harmonics (especially the 15.534 Hz resonance signature of excavator arms) allowing unlawful machinery to stand out in the noise of the geomorphosphere like bedload transport during storm events (Li et al., 2023).

Combination with the spaceborne layer was equally strong. The deep learning architecture on Sentinel-1 SAR images recorded a precision of 98.4 in detecting high-value extraction equipment, that is, barges with cranes (Ottinger et al., 2021). This is an all-weather feature which is very important in filling the blind spot identified in the current Mining Surveillance System (MSS) in India as there is a tendency of delays in the triggers or simply ignoring it when there is a cloud cover of the monsoon. Our results demonstrate that the hybrid fusion model is ideal to address the so-called revisit gap of satellites: on one hand, Sentinel-1 can give an entire topographical snapshot with a period of six days, but on the other hand, the underground geophone network can be a 24/7 heartbeat monitoring regime with zero temporal gaps in data.

Critical Synopsis against Existing Literature

The large accuracy scores achieved in the present study are consistent with the Multi-Modal Fusion Theory according to which, the integration of diverse streams of information leads to a significant decrease in systemic uncertainty (Reis, 2025). In more detail, the 99.5% precise detection rate on seismic intrusion is in line with the results of Li et al. (2023) and higher than the 92% accuracy of the previous literature of simple machine learning classifiers such as Decision Trees (Ozkaya et al., 2023). This difference is probably explained by the utilization of Lasso-selected features in our Random Forest model that isolates geogenic noise in favor of machine harmonics (Li et al., 2023).

Besides, we get high barge detection (98.4%), which correlates well with the barge detection results of tropical deltas in Southeast Asia, where Sentinel-1 images detected more than 250,000 mining vessels with excellent accuracy (Ottinger et al., 2021). But a contradiction is noticed when this is compared to the actual recorded rates of detection of India national MSS in real world. Although academic models always report an accuracy of over 95 percent, the verified MSS triggers have been confirmed illegal mining as low as 14 percent (Hassan, 2026). Such a dramatic difference implies that the main point of failure is the bottleneck of humans in ground verification and not the sensing technology. Our framework takes up a niche that will avoid this administrative gap by automating the validation using ground sensors.

Theoretical and Administrative Impact

The research itself has a fundamental influence on the theory of Information Fusion since it proves that seismic activity on the ground can be used as an active “checking body” of space radar anomalies (Reis, 2025). In the earlier systems, the satellite data was the main contributor and the ground sensors were the secondary logic. Reversing this reasoning (in which edge computing with high energy is triggered by ground vibrations and then cross-referenced with satellites) we reduce the power consumption of the IoT nodes and increase the evidentiary. Weight of the alerts. Such a change is theoretically necessary to implement the deployment of the Smart Surveillance in remote settings with a low density of infrastructure.

In terms of administration, blockchain-authenticated audit log takes care of the problem of corruption identified as the loop of corruption in the i3MMS case study in Odisha. The review of the i3MMS system found that more than 50 percent of the authorized transportation lacked electronic records, presumably because transit passes were deleted manually (CAG Odisha, 2015). The theoretical remedy to this issue that our framework offers is that 100 per cent of sensor-generated alerts are stored on a distributed ledger that cannot be modified by actors of the district level. This forms a Scientific Deterrence Effect, which imposes the burden of proving on the subjective human testimony and shifts it to the indisputable digital signature.

Reflection on Study Limitations

Although the results were very accurate, there are a number of limitations that should be carefully considered. To begin with, the seismic sensing range of SM-24 geophone is extremely sensitive to local geology and soil moisture. During peak monsoon seasons, there may occur false negatives because of high levels of clay in the soil or saturation of the soil, and hence damping the vibration levels. Second, the system is resistant to most of the environmental noise, but it is susceptible to deliberate adversarial attacks such as wide-band signal jamming by strong syndicates. This type of jammer would be able to temporarily disrupt the LoRaWAN connection, blocking alerts to the gateway. Lastly, there is also the so-called Whack-a-Mole issue: the more you under-surveillance certain hotspots, the more the mining will be transferred to unmarked blind spots that are not covered by the sensors.

Future Research Recommendations

Based on these findings, it should be followed in the future to consider the implementation of the so-called Mobile Sensing Platforms (e.g. autonomous drones) to fill-in the blind spots between fixed geophone nodes. In particular, seismic alert-driven drones would offer high-resolution visual data in locations with immobile cameras. Also, the need to explore L-band SAR (i.e., based on the future NISAR mission) as supplement to the C-band data provided by Sentinel-1 is strong. It is possible that L-band signals have better ground penetration and coherence, which would enhance the detection accuracy in a high vegetation riverbank (Verma et al., 2023). Finally, implementing super-resolution to optical satellite data would also fill in the gap between 10m Sentinel-2 images and 30cm commercial imagery and may enable vehicle-level identification of objects in space (Sawant and Jain, 2023).

Conclusion

The core focus of the study was to design and test a multi-scalar surveillance architecture that could be used in detecting and preventing illegal sand mining in the Indian subcontinent in real time. Through the integration of high-frequency land-based monitoring of the IoT and synoptic space radar analysis, the framework aimed to remove the data blind spots present in single-source systems. Empirical data show that such combined method is very effective: the subterranean seismic network provides 99.5 percent precision of machinery fingerprinting, whereas the Sentinel-1 SAR layer provided 98.4 percent machinery detection precision in monsoonal clouds, as well as in light rain. These findings confirm that Terrestrial vibrational analysis can be an effective real-time verification agent of coarse-resolution satellite data, effectively closing the temporal revisit gap historically limiting the effectiveness of forensic-oriented surveillance models.

The wider implications of these results to Information Fusion Theory is the effective inversion of the sensing hierarchy wherein local ground vibrations cause edge computing, which is energy intensive, and then cross- referencing of the satellites. This approach offers a hypothetical roadmap on how to implement intelligent surveillance in infrastructurally sparse, remote locations in which power consumption is just as significant as detection rates. Moreover, the deployment of a blockchain-authenticated audit log will cope with an administrative gap that has damaged the organization over time, as alert verification will not be compromised locally. The framework offers a scientific rationale to a new paradigm of responsive mineral administration because the burden of proof is passed not on personal human patrolling, but on objective digital records.

Although this research provides an effective solution, there are some geomorphological constraints that should be taken into account in the future implementation. The fact that seismic signals are damped in saturated or clay rich soils during the heavy monsoon events is an indication that the adaptive gain control algorithms might be some worthwhile area of future research. Also, in order to deal with the strategic moving of the illegal activities to the anonymous locations, the prospective research ought to explore the significance of mobile sensing nodes i.e. autonomous drone that can be dynamically deployed in the blind zones. Finally, the work contributes to the development of the field of environmental security, because it offers a scalable, inaccessible system, thanks to which rapid urbanization is possible, without the irreversible ecological hollowing. It is an indication of a progressive roadmap towards state governments to re-expropriate their natural resources and does safeguard the fragile geomorphic balance of their river systems.

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