Scholar Publishing Group
International Journal of Big Data Intelligent Technology
https://doi.org/10.38007/IJBDIT.2024.050118
ISSN 2790-0932 Vol. 5, Issue 1: 172-182

Applications of Laser Radar (LiDAR) in Geospatial Intelligence and AI-Driven Emergency Management

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Keywords: Laser Radar (LiDAR), Geospatial Intelligence, Emergency Management, Artificial Intelligence (AI), Disaster Response, Geospatial Data Analysis

Abstract: Emergency management is a critical discipline aimed at ensuring the safety and resilience of communities in the face of both natural and man-made disasters. It involves four key phases: mitigation, preparedness, response, and recovery. To effectively manage emergencies, decision-makers in emergency management organizations must have timely and accurate access to large-scale geospatial data. Laser Radar, commonly known as LiDAR (Light Detection and Ranging), is an emerging technology that plays a pivotal role in modern emergency management by providing high-precision geospatial information. The integration of LiDAR with Artificial Intelligence (AI) technologies enhances the automation of data processing, enabling real-time analysis and actionable insights. This paper explores the applications of LiDAR in emergency management, emphasizing its role in geospatial intelligence, disaster response, and decision-making support. It highlights how AI algorithms can further optimize the use of LiDAR data in scenarios such as disaster response coordination, infrastructure damage assessment, and resource allocation, ultimately improving the efficiency and accuracy of emergency management operations.

1. Introduction

Emergency management is forming the structure to reduce vulnerability to hazards and cope with disasters through decision-making function. Earthquakes, fires, floods, landslides, and severe weather are examples of natural hazards. Accidents, building collapses and explosions, disease outbreaks and biological events, terrorism, utility outages, and other unanticipated events are examples of man-made hazards. Without any precise context, requirements, or conditions, phrases like "emergency," "disaster," and "crisis" are frequently used to describe a variety of situations that interfere with transportation services and necessitate action. The tools available to emergency responders and planners have considerably increased over the past several years because to technology improvements.

Common responses to disasters begin with the initial post-event rescue and relief operations, followed by recovery, reconstruction, and then transcend into mitigation actions including the development of pre-impact preparedness measures, collectively known as the emergency response cycle[1].

Emergency management keeps societies by organizing and integrating the actions required to create, sustain, and enhance the capability to mitigate against, prepare for, respond to, and recover from any type of situation created by catastrophe. The ongoing practice of managing risks by all people, organizations, and communities in an effort to prevent or lessen the effects of catastrophes brought on by the hazards is known as emergency management [2].

GIS and remote sensing in emergency management to designing conceptual framework to help organize existing research and development activities. This relies on the temporal dimension of disasters to organize the emergency management process into a cycle of four, often overlapping, phases: mitigation [3], preparedness, response, and recovery, as shown in Figure 1.

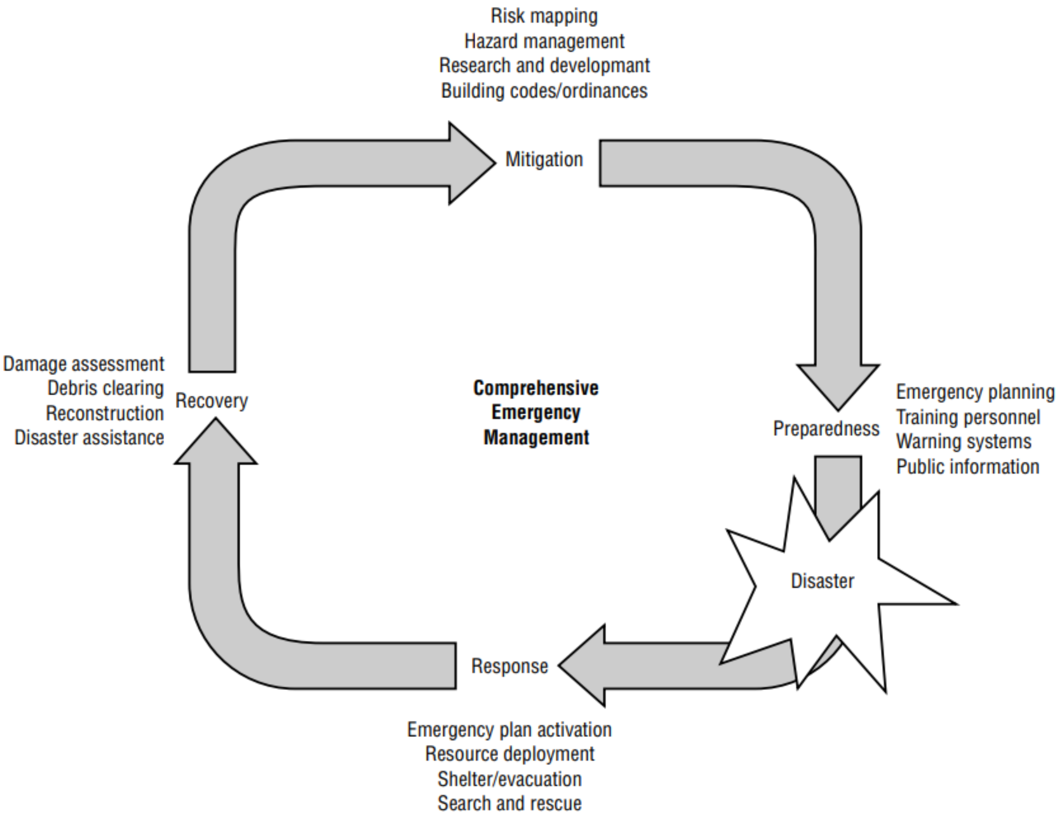

Figure 1: Comprehensive emergency management.

In order to make timely decisions, take immediate action, and complete the four-cycle processes, emergency management requires immediate access to a diverse data. Quick response and emergency services depend on timely and precise geographic information from readily available databases, which may considerably enhance decision-making, perhaps save lives, and assist residents [4].

2. Understanding Laser Radar

LiDAR stands for Light Detection And Ranging, while LADAR stands for Laser Detection And Ranging. Laser Radar, or LIDAR, is a remote sensing technology that utilizes laser light to measure distances, create high-resolution digital elevation models, and generate detailed 3D maps of the surrounding environment. The size of their objectives, however, makes a significant disparity between these two methods. LADAR is used for longer-range surface sensing, such as scanning the atmosphere or the ground. LiDAR, on the other hand, is used to detect concentrated, small-volume objects, such cars.

The use of a laser system enables day and night observation as well as range measuring in surfaces without irregularity. The laser scanner is within the category of active sensors. As seen in figure 1, a laser scanner works by emitting light energy and recording the signal of emission and return. This recorded signal is quickly converted to a digital representation and saved on a computer. Although LIDAR is an active technology that may potentially be utilized around-the-clock, it cannot be used when there is cloud cover, fog, smoke, mist, rain, or snow storms. Mostly laser systems are Nd:YAG emitting in NIR (1064nm) wavelength in a narrow spectral width (0.1-0.5nm). Some systems emit at 810 nm (ScaLARS), 900 nm (FLI-MAP), 1540 nm (TopoSys, Riegl). Laser systems generally emit in one wavelength only however bathymetric lasers emit at1064 and 532 nm, to measure both water surface and water bottom.

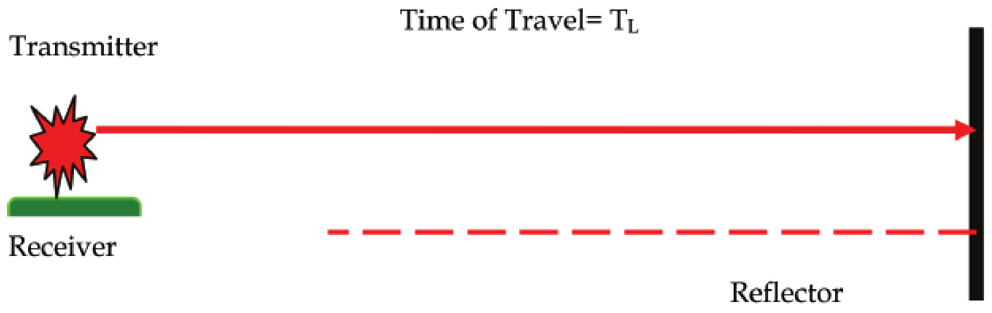

Figure 2: Principle of Laser.

For the signal processing of the laser scanner, target detection and tracking algorithms are used. The method changes the computed information into objects with properties like scale and velocity. It is simple to adjust a number of adjustable settings to various environmental factors. For instance, employing indoor or outdoor settings, low or high speed variations, and various output design options [5]. The alignment and co-registration in a defined reference system allow generating a 3D model of the object, with the possibility to associate the radiometric information useful in many applications [6].

3. Applications in Emergency Management

a) Disaster Assessment and Response

The need for quick reactions in situations of emergency has grown along with the frequency of natural catastrophes. In order to manage the situation more effectively, these catastrophe responses need geospatial information about the target locations in real-time or quickly. The primary benefit of fast mapping systems based on UAVs with laser radar for real-time aerial surveillance is the ability to quickly gather sensory data in disaster zones that are difficult to access [7]. Not only this system can access dangerous areas without interactions with human operators by employing a UAV as a platform but also can rapidly generate geospatial information of the sites through real-time transmission and processing of sensory data.

This aids emergency responders in determining the degree of damage brought on by earthquakes, floods, hurricanes, and wildfires.

It is challenging to reach impacted areas because of damage to current channels of access and a lack of precise maps that represent the situation on the ground following disasters [8]. The use of 3D mapping can benefit a digital record, a virtual scene recreation, and complete deformation measurements. It is used in the context of disaster management to depict various unseen information related to disasters (people obscured by debris, models of damages, and measurements) and to superimpose it on the image of reality [9]. The extracted models are crucial components that help engineering grasp earthquake behavior. This information is necessary for allocating resources effectively and setting priorities for rescue operations.

LIDAR data may naturally be large and a great source of information. New possibilities for utilizing LIDAR data for life-saving applications are made possible by high-speed networks. The speed at which information may be communicated among officials and emergency responders dispersed over various areas making vital judgments can be considerably accelerated in a crisis situation when a high-speed network is deployed [10].

b) Search and Rescue Operations

Laser sensors used to scan an object, output data is integrated to develop the three dimensional image. LADAR offers precise range information that is occasionally augmented to provide visuals with almost photographic quality. Due to the unambiguous representation of object location and form, LADAR is far better suited to automatic target recognition (ATR) than intensity-based imaging. By adding a grayscale filter to visible images, LADAR imaging may be mimicked for human seeing. While the final photos resemble LADAR imaging, their other qualities have been lost. A basic catastrophe setting called the Test Facility has three scenarios with varying degrees of difficulty: Yellow, Orange, and Red arenas [11].

Drones with LIDAR capabilities and ground-based systems can help locate survivors in difficult terrains such collapsed buildings, deep forests, or mountainous areas. LIDAR's high-resolution 3D maps improve situational awareness and direct rescuers to significant regions. Real-time fusing of active sensor (laser or radar) data with the synthetic database will transformation the content of the synthetic images. This aids rescuers in locating natural disaster victims in unfamiliar territory, and the detecting technology is insensitive to changes in lighting [12]. When a fire obverse or a lot of smoke are present, laser radar is used to evacuate rural inhabited areas.

In order to respond to catastrophe scenarios efficiently and to ensure good agency coordination, decision-makers in emergency management agencies must have access to a great deal of very current geospatial information. Rapid coverage of wide regions by laser radar enables short response times and reduces delays in emergency operations. comprehensive data management and collaboration tool that will significantly alter the information environment for emergency managers and contribute to the preservation of human life.

LIDAR is capable of gathering data at a distance, for instance, for damage assessment and traffic monitoring and management. During a fire or gas leak, invasive approaches are beneficial for lowering the danger to first responders and protecting the safety of both victims and rescue workers.

One of example of the radar is U-Ranger's onboard radar runs on the X-Band (9.3–9.4 GHz) and has adjustable range settings ranging from 50 m to 24 nautical miles. It rotates at a speed of 24 RPM. Obstacles may be consistently found by this radar at distances greater than 50–100 m. The laser scanner contains four 0.8°-spaced, vertically stacked beams that are steerable within a 110°

angle and have a horizontal resolution of 0.125 °. The obstacle detecting range is larger than 100 m, and the maximum scanning frequency is 50 Hz [13].

When conducting searches from both ships and planes, the Coast Guard frequently use radar. These radars have the ability to locate huge vessels, as well as smaller vessels equipped with radar reflectors, at night and in low visibility. It is not essential to "recognize" a specific target for the search and rescue application. The radar return only has to be identified as a probable crash site if it possesses traits that point to a man-made structure. At two levels of resolution, the idea of identifying changes in radar emissions from a region can be used to help with the hunt for downed aircraft. A considerably finer resolution also allows for change detection. Because of the loss of coherence between the images at such points and the crashed plane itself, coherent change detection (CCD) using interferometric synthetic aperture radar (SAR) data can be used to detect changes much smaller than a pixel. This raises the possibility that broken trees and foliage and/or ploughed up earth would be prominently displayed in a CCD image [14].

c) Hazard Mapping and Prediction

In both urban and rural settings, laser radar can locate possible dangers and evaluate affected area. Worldwide, high resolution results from LiDAR surveys are utilized for mapping earthquake and hurricane zones, possible landslide mapping, and flood modeling in disaster-risk prone locations. It assists in anticipating flood inundation patterns, landslide susceptibility, and other natural threats by producing precise topographic data. Planning for land use and evacuation measures can be influenced by this data. These scanners can map hazardous locations to help authorities with catastrophe risk prevention and management. laser sensors can distinguish between shallow, murky, and muddy waters, making them helpful for mapping emergency scenarios like flood zones. Some LiDAR uses include finding submerged or underwater items to eliminate obstructions from rivers and for dredging operations.

Its high precision and rapid acquisition approach make it ideal for several emergency management applications, like monitoring landslides and floods, among others. LIDAR technology offers extremely precise measurements that make it easier to model and analyze disaster-affected areas in great detail.

In disaster-prone locations, the decision-making process for land use/land cover (LULC) planning takes into account maps of landslide hazard, vulnerability. The required geographic data quality and methods used to acquire it directly affect the accuracy of these studies. Using high-resolution data from aerial laser scanning, a map of the world's landslides is created. The validation result revealed success and prediction rates of 86.22 and 84.87%, respectively. Risk maps were created using the calculated vulnerability and hazard information, and hazard maps were created using precipitation data over 15 years. A risk analysis was then performed. Losses were combined for the LULC after the LULC map was cross-matched with the return period's hazard map findings. The losses for the three return periods were then determined. Planners may benefit from using the map of the risk zones to control the total risk of landslides. With a total population of over 300 million (5% of the world's population), the total amount of land that is susceptible to landslides is roughly 3.7 million square kilometers globally. The population of these 820,000 km2—which are largely designated as high-risk areas—is close to 66 million. Researchers can identify, map, and predict slope collapses because to the availability of extremely high-resolution digital elevation models (DEMs) created by high-resolution LiDAR sensors. The final maps are directly impacted by the employment of precise and optimal conditioning parameters which is shown in figure 2. Susceptibility analysis may be used to pinpoint locations that are prone to landslides, enabling early warning and emergency action [15][16].

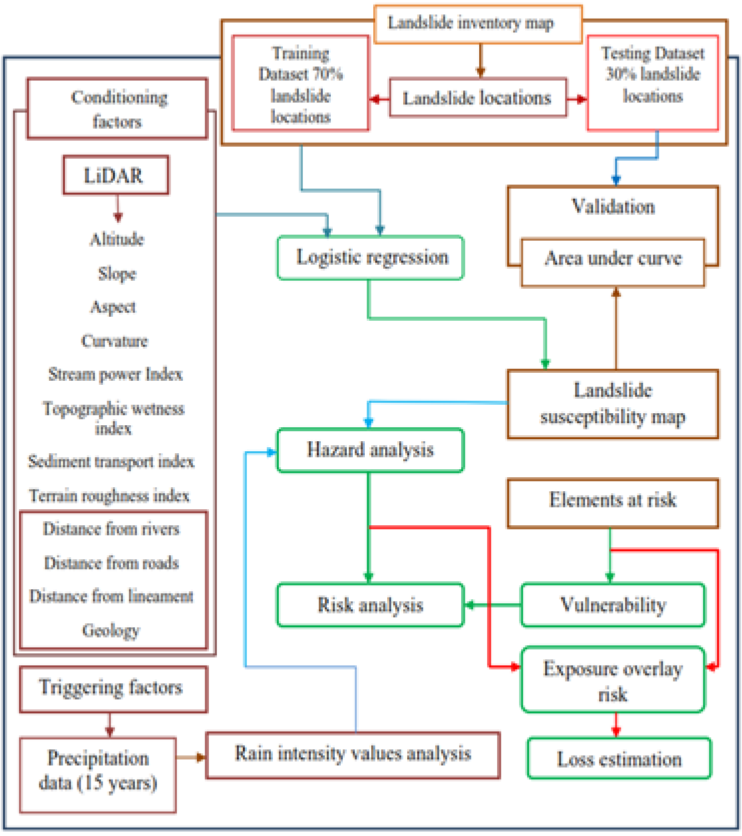

Figure 3: Example Method of Map Generation.

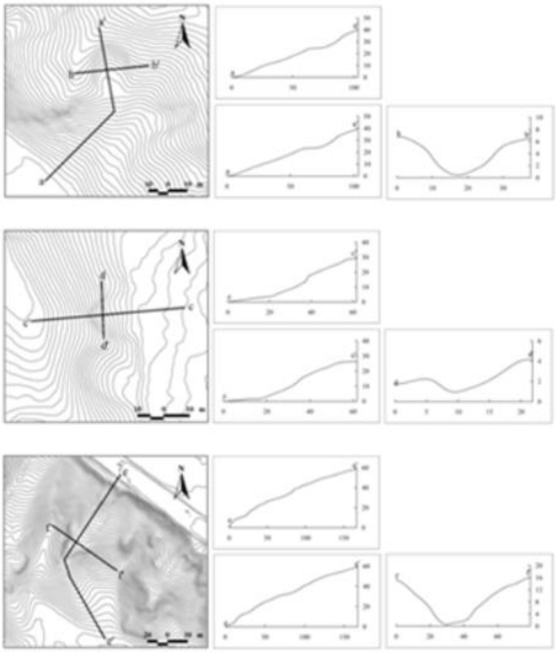

Figure 4: Maps and profiles of three different types of landslides created by laser scanning.

The mapping of flood hazards in prospective flood risk regions is required by the evaluation and management of flood risks framework. High resolution, precise geographic data, measurements of the level of the water, and flood extent are all required for the urban flood inundation modeling in order to verify the model. Research is still being done on the best ways to include high resolution geospatial data into flood models and how that will affect the results. The terrain morphology and friction coefficients that are needed as input for flood inundation models must be developed from raw data using the proper techniques. The simulation of the dynamic flood wave examined the impact of topography and friction coefficients on the flood model's output, including flood extension and water depths. Digital maps and remote sensing data both offer methods for calculating friction coefficients [17].

The ability of multi-spectral LiDAR sensors to extract physiological characteristics of vegetation, such as NDVI profiles, chlorophyll concentrations, and vegetation water content, has been established. Current remotely sensed estimates of fuel moisture generated from satellite views might be supplemented by the capacity to estimate both structural and fuel moisture using multi-spectral LiDAR. This would give a full picture of the above-ground fuel danger across the profile. Despite the fact that fuel moisture modeling has discovered significant correlations between plant structure and the moisture content of dead fine fuel beneath the forest canopy, structural information included in single-wavelength scanner data can still be useful. For fire managers seeking to use a non-subjective, more accurate estimate of fuel, the measurement of fuel from Terrestrial Laser Scanner (TLS) offers a little step forward [18]. A system for high resolution inundation analysis utilizing data from aerial laser surveys. The technology allows for the automatic development of grids while locating streets and buildings, which aids in the creation of highly accurate danger maps in metropolitan areas [19].

d) Infrastructure Damage Assessment

Roads, bridges, and other essential infrastructure may all have their structural integrity promptly evaluated using laser scanning. As a Non-Destructive Testing (NDT) technique, a 3D Light Detection and Ranging (LiDAR) scanner may be used to detect surface flaws (such as cracks) in concrete bridges [20]. Engineers may utilize this information to prioritize maintenance and make sure that emergency vehicle routes are secure. From a laser scanner, a detailed view of hair-line fractures can be obtained. The material of the infill and the most likely scenario that resulted in the damage were revealed by simulation of the effects of the existing fracture pattern. This information may be incorporated into a number of approaches for calculating costs and failure rates .

In an attempt to promote the use of sensor and data fusion to improve target detection, classification, identification, and tracking as well as situation and threat assessment in real-time using cost-effective, resilient, and maintainable systems. Comprehensive situational awareness may be created by combining LIDAR data with additional geospatial data, such as satellite photography and GPS data.

After an earthquake, damage assessment plays an important role in leading rescue team to help people and decrease the number of mortality. Damage map is a map that demonstrates collapsed buildings with their degree of damage. With this map, finding destructive buildings can be quickly possible. The framework of the proposed approach has four main steps. To find the location of all buildings on LiDAR data, in the first step, LiDAR data and vector map are registered by using a few number of ground control points. Then, building layer, selected from vector map, are mapped on the LiDAR data and all pixels which belong to the buildings are extracted. After that, through a powerful classifier all the extracted pixels are classified into three classes of “debris”, “intact building” and “unclassified”. Since textural information make better difference between “debris” and “intact building” classes, different textural features are applied during the classification. After that, damage degree for each candidate building is estimated based on the relation between the numbers of pixels labelled as “debris” class to the whole building area. Calculating the damage degree for each candidate building, finally, building damage map is generated. considering textural information of LiDAR data such as homogeneity in a building area can be helpful in distinguishing damaged buildings from undamaged buildings.

Damage Evaluation following categorization, DD (damage degree) is calculated for each candidate building based on the relationship between the number of pixels labelled as “debris” class to the whole building area .

DD = number of pixels to debris to class /number of pixels inside the building area.

Finally, damaged and undamaged buildings may be identified, and a damage map can be created, by calculating the damage degree for each candidate structure and taking a threshold level into account for DD. A kappa coefficient of 71.61% and an overall accuracy of 91.59% demonstrated the effectiveness of SVM classification in differentiating between demolished and undamaged structures. The test area's structures were accurately classified as damaged or undamaged [21].

Rooftop inclination angle was used to identify damaged building candidates, and damage was subsequently evaluated using planarity and point height criteria. SAR imaging techniques generally use backscattering intensity and phase data to pinpoint damage. Data offers precise height information that makes it easier to find building damage. The structural health of a building may be determined by looking at geometric parameters like planarity and inclination angle in combination with surface characteristics like curvature and size. Automated damage assessment might drastically shorten the time required to create damage maps, resulting in quicker and more effective search and rescue operations and resource allocation [22].

Among the factors being utilized to create rules for building extraction and vegetation removal are normalized height, height variation, intensity, and multiple return data. Only in areas where the findings of the building recognition algorithm overlapped the real locations of buildings was the accuracy of the damage detection method evaluated. Despite having a poor Kappa accuracy of k = 0.275, the total damage detection accuracy was 73.40%. Another continuing project uses parallel computing and effective data structures to develop better algorithms in Java. Rapid processing of massive volumes of data is essential in the setting of disaster response. According to preliminary findings, a 100 MB LAS file can often be handled in 10 seconds. MATLAB, the initial algorithm development and testing environment, was unable to get this outcome [23].

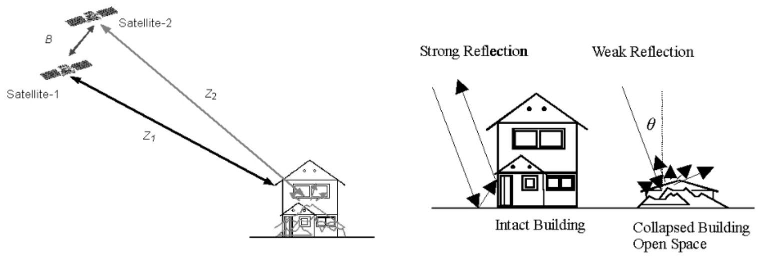

Figure 5: Fundamentals of repeat pass radar interferometry.

The potential and appeal of these technologies' applications in the area of "structural safety and reliability" is considerable. SAR sensors can cover significantly greater regions, making them useful for macro-scale urban modeling and the detection of large-scale natural catastrophe damage[24]. Basis principle of the radar detection of the building is shown in fig.5.

Most laser scanning systems also capture intensity data in addition to accurate 3D coordinates, which has been useful for object extraction and point cloud segmentation. Target recognition, point cloud registration, land cover categorization, and cultural heritage protection are a few instances of the applications of lidar intensity that are currently being explored. Since lidar intensity is correlated with surface reflectance and, unlike color data, is unaffected by damage size, roof color, and lighting conditions, it has several advantages over color data. Therefore, various materials (each with a distinct reflectance) may be distinguished in scans using lidar intensity data. However, there are certain more variables that might affect lidar intensity readings in addition to surface reflectance that must be taken into account.

It is theoretically possible to use the radar range equation to show parameters affecting lidar intensity data. The connection between the sent and received signal powers is shown by this equation. We recommend the following tactics for using lidar intensity data to detect building wind damage based on the findings of this study. 1) To minimize the scanning angle of incidence as much as feasible, the position and height of scanners during data collecting should be carefully calculated. 2) In addition to the intensity data, extra spectrum information such as color data should be employed when the angle of incidence is greater than 70 degrees. 3) To reduce the impact of the angle of incidence, scanning should be done up close [25]. TLS is highly useful for promptly identifying damage and for calculating the volume of spalled concrete [26].

e) Environmental Monitoring

Laser Radar can help monitor environmental changes, such as the movement of glaciers, instable sand dunes, and coastal erosion. For anticipating and lessening the effects of disasters connected to climate change, this data is useful. LiDAR is preferred over other technologies in such activities because to the limited access to mining sites and the requirement for precise data for operations like cut-and-fill, grading, slope analysis, and volumetric computation. However, depending on how large the region is, both airborne and terrestrial LiDAR technologies may be useful in mining and geological activities. Differential Absorption LiDAR (DIAL), a recent innovation in LiDAR operations, may be used to precisely measure greenhouse gas emissions from anthropogenic and natural sources and sinks. The DIAL system operates in the near infrared spectral range and may be used to find air molecules with wavelengths that are comparable to or greater than those. The device may be used for oil and gas exploration and mining since it can track the volumes of gases above the hydrocarbon zone. The DIAL method would also be useful for detecting greenhouse gases including carbon dioxide, methane, and nitrous oxide, making it efficient for precisely quantifying carbon stocks in accordance with national and international regulations.

For ground operations in a mining setting to scan, model, and evaluate geological characteristics, robust terrestrial LiDAR technology is available. These LiDAR devices can work in open pit and underground mines while producing high-accuracy results.

It is possible to draw a line at the edge of an unstable area. The amount of the ground's differential movement aids in determining the pace and size of displacement, both of which are important for preventing accidents. Consequently, its monitoring is essential for the mine's workers' and materials' safety [27].

Additionally, the ability of lasers to cut through vegetation has expanded their use in lithology mapping, enabling them to produce maps with an adequate level of detail and high resolution[28].

4. Conclusions

Laser radar is rapidly developing into a potent tool in disaster management. Its capacity to quickly gather accurate and thorough information on disaster-affected areas improves the ability of emergency responders and planners to make decisions and take action. Laser radar technology has the ability to help secure populations in times of crisis by aiding in disaster assessment, search and rescue operations, hazard mapping, and infrastructure evaluation. As technology develops, incorporating Laser Radar into emergency management procedures may improve the effectiveness of preparedness, response, and recovery operations in the event of a disaster.

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