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AI-Based Detection of Undulation in Airport Runways

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Abstract - Airports are critical transportation infrastructures where the structural integrity of runway surfaces plays a vital role in ensuring safe aircraft landing and take-off operations. Surface undulations and uneven profiles can negatively impact aircraft stability, passenger comfort, and landing gear performance, leading to increased mechanical stress and long-term maintenance challenges. Continuous and accurate monitoring of runway conditions is therefore essential to maintain aviation safety standards and operational efficiency. This paper presents the design and implementation of a high precision runway undulation detection system utilizing advanced sensing and embedded processing techniques. The proposed system integrates a Light Detection and Ranging (LiDAR) sensor for high resolution surface profiling along with linear potentiometric sensors to provide redundant and reliable measurements. The combined sensing architecture enhances detection accuracy while minimizing false readings under varying environmental conditions. Real time data acquired from the sensors are processed using an embedded platform to quantify surface deviations and identify critical irregularity zones. The results are displayed through a structured visual interface, enabling effective runway assessment and maintenance planning. The developed system offers a practical and scalable solution for continuous runway monitoring, contributing to improved passenger safety, extended aircraft component lifespan, and efficient airport infrastructure management.

Keywords: Runway Surface Monitoring, Undulation Detection, LiDAR Sensor, Embedded Systems, Aviation Safety, Real Time Data Visualization.

1. INTRODUCTION

Airports function as critical nodes within the global air transportation network, facilitating thousands of aircraft movements daily. Among the various infrastructural components of an airport, the runway represents the most safety sensitive element, as it directly supports aircraft during high-speed take-off and landing operations. The structural integrity and surface uniformity of runway pavements play a decisive role in maintaining aircraft stability, braking efficiency, and directional control. Even minor surface undulations characterized by subtle waves, dips, or uneven gradients can significantly influence aircraft ground interaction dynamics.

Figure 1. Visual Representation of Airport Runway Surface Undulation

A runway surface exhibiting irregularities can adversely affect landing performance by inducing excessive vibration and uneven load distribution across aircraft landing gear assemblies. These dynamic disturbances not only reduce passenger comfort but also increase mechanical stress on tires, shock absorbers, struts, and braking systems. Continuous exposure to such uneven surfaces accelerates component fatigue, leading to higher inspection frequency, increased maintenance expenditure, and reduced operational reliability. Over extended periods, neglected undulations may evolve into severe pavement distress conditions, posing serious safety risks.

From a safety standpoint, surface undulations can compromise aircraft handling characteristics, particularly during wet weather conditions. Uneven pavement profiles tend to accumulate water in localized depressions, thereby increasing the probability of hydroplaning. Hydroplaning reduces tire to runway friction, resulting in diminished braking efficiency and extended stopping distances. Furthermore, abrupt elevation changes impose cyclic loads

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on landing gear structures, which may contribute to material fatigue and potential structural degradation. Considering the stringent safety regulations imposed by international aviation authorities, maintaining runway surface evenness is a mandatory requirement rather than an optional maintenance objective.

In addition to safety implications, runway surface quality has a direct impact on airport operational efficiency. Irregular pavement conditions may necessitate frequent maintenance shutdowns, thereby reducing runway availability and airport throughput capacity. Operational restrictions such as reduced landing speeds or aircraft type limitations can disrupt tightly scheduled air traffic operations. As airports represent high value infrastructure investments, premature pavement deterioration due to undetected undulations results in substantial economic losses associated with rehabilitation and reconstruction activities.

Traditional inspection approaches, including manual surveys and periodic visual assessments, are often inadequate for detecting early-stage undulations with high precision. These methods are time consuming, labor intensive, and prone to subjective errors. Therefore, there is a growing need for automated, sensor-based monitoring systems capable of delivering continuous, high resolution surface profiling. Advanced technologies such as LiDAR based scanning, sensor fusion techniques, and embedded data processing platforms provide promising solutions for accurate runway surface assessment.

In this context, the paper aims to design and implement a high precision runway undulation detection system using modern sensing and computational methodologies. The proposed system integrates a Light Detection and Ranging (LiDAR) sensor to obtain accurate distance measurements of the runway profile. To enhance measurement reliability and introduce redundancy, linear potentiometric sensors are incorporated as a complementary detection mechanism. The combination of these sensing modalities enables improved accuracy, reduced measurement uncertainty, and enhanced robustness under varying environmental conditions.

The acquired sensor data are processed in real time using an embedded computing architecture to quantify elevation deviations and identify critical irregularity zones. The processed results are presented through a structured visual interface, allowing airport authorities to perform efficient maintenance planning and preventive corrective actions. By merging advanced sensing technologies with embedded system integration and real time visualization, the proposed solution offers an automated, reliable, and scalable approach to runway condition monitoring.

Thus, the development of an intelligent runway undulation detection system not only enhances passenger safety and aircraft operational lifespan but also supports cost effective infrastructure management and regulatory compliance. The integration of modern sensing technologies ensures faster detection, improved accuracy, and elimination of delays associated with conventional inspection techniques, thereby strengthening overall airport operational sustainability.

2. PROBLEM STATEMENT

Runway surface unevenness can affect aircraft safety during takeoff and landing. Small undulations may reduce stability and braking efficiency if not detected early. Many airports still rely on manual inspection methods, which are time-consuming and prone to human error. Advanced laser profiling systems provide accurate results but are expensive and require specialized infrastructure. Most existing approaches perform inspections only at scheduled intervals instead of continuous monitoring. As a result, surface defects that develop between inspections may remain unnoticed. Environmental factors such as vibration and weather also impact measurement accuracy. Therefore, a cost-effective and real-time intelligent monitoring system is required to detect runway undulations efficiently and improve aviation safety.

3. OBJECTIVE

The main objective of this work is to detect runway undulations using LiDAR, MEMS, and potentiometric sensors. The system aims to provide continuous real-time monitoring of runway surface conditions. It is designed to improve aircraft safety and landing comfort by identifying surface irregularities at an early stage. Another objective is to reduce maintenance costs through timely detection and preventive action. Overall, the goal is to develop a reliable and cost-effective intelligent runway monitoring solution.

4. LITERATURE SURVEY

Runway and pavement surface monitoring has become a critical research area due to its direct impact on aviation safety, operational efficiency, and infrastructure sustainability. Early inspection methods primarily relied on manual surveys, which were time consuming and prone to human error. With advancements in sensing technologies, image processing, and artificial intelligence, automated crack and defect detection systems have gained significant attention.

Recent studies focus on integrating robotic platforms, machine learning algorithms, deep learning models, and geodetic measurement techniques for accurate

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and real time assessment of surface irregularities. These approaches aim to improve detection accuracy, reduce maintenance costs, and enable predictive maintenance planning. The following section reviews ten significant research contributions related to automated runway and pavement defect detection and evenness modelling.

Lin et al. (2021) developed a robotic airport runway inspection system integrating a high-resolution camera and Ground Penetrating Radar (GPR) for detecting both surface cracks and subsurface defects. The system employed a two stage image stitching algorithm using GPS alignment and SURF with RANSAC for panoramic runway visualization. Surface cracks were identified using a hybrid intensity and shape-based method, while subsurface defects were detected from 3D GPR C scan data using Faster R CNN combined with DBSCAN clustering. The system was validated across 20 airports in China, achieving F1 scores of 70% for crack detection and 67% for subsurface defect detection. However, the method depends heavily on GPS accuracy and faces challenges in detecting thin micro cracks under poor lighting conditions.

Shi et al. (2016) proposed the CrackForest method based on Random Structured Forests (RSF) for automated road crack detection. The approach extracted multi scale features including intensity, gradient, and texture information from structured image patches. A structured learning framework was used to preserve crack continuity and reduce noise effects. The method achieved high performance on CFD and Aigle RN datasets, reaching pixel level F1 scores above 85%. The model demonstrated strong generalization ability across datasets. However, it was limited to static image processing and did not provide crack severity measurements such as width or depth.

Wahla et al. (2023) introduced an improved YOLOv5s deep learning model for accurate and real time crack detection. The enhancement included the integration of Res2 C3 modules for better multi scale feature extraction, a Global Attention Mechanism (GAM) to focus on crack regions, and Dynamic Snake Convolution to capture irregular crack shapes. The improved model achieved a mean Average Precision (mAP) of 93.9% with a detection speed of 49.97 FPS. Although the model significantly improved detection accuracy, it required GPU hardware support and was trained on a relatively limited dataset, which may affect large scale generalization.

Nguyen et al. (2018) proposed an unsupervised Minimal Path Selection (MPS) algorithm for detecting cracks in two-dimensional pavement images. The method combined photometric and geometric features to compute minimal cost crack paths using Dijkstra's algorithm. Unlike supervised approaches, the algorithm did not require prior training data or manual parameter tuning. Experimental results showed superior DICE similarity scores and robustness under varying lighting conditions. However, the computational complexity of repeated shortest path calculations limited its real time applicability.

Delmastro et al. (2020) focused on modelling runway surface evenness using high precision geodetic measurement techniques such as GNSS and Total Station surveys. The study generated Digital Elevation Models (DEM) to quantify deviations from ideal surface profiles and compute roughness indices. Statistical regression models were applied to predict unevenness growth trends and support preventive maintenance planning. The results demonstrated improved sustainability and cost-effective runway management. Nevertheless, the model's performance depended on measurement precision and required substantial computational resources for high resolution data processing.

Liu et al. (2023) proposed a pavement crack detection framework named PCMSDA based on a Multi Scale Dilated Spatial Attention (MSDA) mechanism. The MSDA module enhances hierarchical feature extraction by employing multiple dilation rates to capture fine grained crack textures as well as broader structural patterns. This multi scale attention strategy improves the continuity of thin and irregular cracks while suppressing background noise such as shadows and surface stains. Furthermore, the Content Aware Reassembly of Features (CARF) module replaces conventional up sampling to reconstruct spatial details more precisely. The model was trained using Binary Cross Entropy and Focal Loss to address class imbalance issues. Experimental validation on Crack500 and real pavement datasets demonstrated superior F1 score and AP compared to YOLOv9 and segmentation-based models. However, the architecture increases computational complexity and may require GPU acceleration for real time deployment in large scale road monitoring systems.

Bay et al. (2008) introduced SURF as a computationally efficient alternative to SIFT for detecting and describing local image features. The Fast Hessian detector uses integral images and box filters to approximate Gaussian second order derivatives, significantly reducing processing time. The descriptor construction relies on Haar wavelet responses within oriented subregions, forming a compact yet distinctive 64 dimensional vector. An extended SURF 128 variant further enhances distinctiveness for complex matching scenarios. Experimental evaluation on benchmark datasets confirmed that SURF achieves high repeatability and robustness under scale and rotation changes while being several times faster than SIFT. Despite its

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advantages, SURF is less robust under strong affine transformations and extreme viewpoint variations, limiting its applicability in highly dynamic scenes.

Shaoqing Ren et al. (2015) proposed Faster R CNN, a deep convolutional neural network architecture integrating a Region Proposal Network (RPN) with a Fast R CNN detector. The RPN generates object proposals directly from shared convolutional feature maps, eliminating the need for external region proposal methods such as selective search. This end-to-end learning framework significantly improves detection speed while maintaining high localization accuracy. The model demonstrated state of the art performance on benchmark datasets like PASCAL VOC and MS COCO, achieving high mean Average Precision (mAP). The shared feature extraction mechanism reduces redundancy and enhances computational efficiency. However, Faster R CNN still requires high memory and processing power, making deployment challenging on edge devices or embedded platforms.

Wang et al. (2021) developed a CNN based short term wind speed forecasting model that incorporates transfer learning from neighboring wind farms to address limited historical data availability. The convolutional layers effectively capture spatial correlations among multiple wind farms, while temporal dependencies are learned through sequential data modelling. Transfer learning enables the model to generalize wind speed patterns learned from established farms and adapt them to newly constructed sites through fine tuning. The system was evaluated using MAE and R^2 metrics and outperformed traditional statistical models such as SVR and KRR. The approach also demonstrated stability in multi-step forecasting scenarios. Nevertheless, the model's effectiveness depends on optimal hyperparameter tuning and may experience performance degradation under extreme or highly irregular weather conditions.

Zhang et al. (2023) proposed a UAV based runway obstacle detection framework aimed at enhancing aviation safety through automated aerial monitoring. The system employs deep learning detectors such as YOLOv8, Faster R CNN, and Vision Transformer architectures within a modular pipeline consisting of preprocessing, object detection, tracking, and geofencing based alert generation. The preprocessing stage includes brightness normalization and noise reduction to improve model robustness under varying illumination conditions. Comparative analysis revealed that YOLOv8 achieves a strong balance between accuracy (high mAP) and real time performance, while Transformer based models offer improved contextual understanding in cluttered scenes. The framework supports scalability and integration with airport surveillance systems. However, practical deployment requires domain specific annotated datasets and further optimization to ensure seamless integration with air traffic control infrastructure.

5. EXISTING SYSTEM

Runway surface condition plays a critical role in aircraft safety during takeoff and landing. Undulations, cracks, uneven surfaces, and structural deformations can affect aircraft stability and braking performance. Traditionally, runway inspection has been carried out through manual surveys and specialized measurement vehicles. With advancements in sensing technologies, laser profiling, image processing, and IoT based monitoring systems, automated runway surface assessment methods have been developed. The following are some existing systems related to runway undulation detection.

Runway Surface Profiling System – Federal Aviation Administration

The Federal Aviation Administration (FAA) employs advanced high-speed laser based profiling systems to evaluate runway surface roughness and longitudinal evenness. These systems are typically mounted on specialized inspection vehicles equipped with laser sensors, accelerometers, and distance measurement instruments. The collected surface profile data is analyzed to determine parameters such as the International Roughness Index (IRI) and surface deviation levels.

This system provides highly accurate and standardized measurements that comply with aviation safety norms. It enables airports to schedule timely maintenance and resurfacing activities. However, the equipment cost is significantly high, and inspections are generally carried out periodically rather than continuously. Smaller airports may find it difficult to adopt such expensive infrastructure.

Pavement Condition Assessment – International Civil Aviation Organization Standards

The International Civil Aviation Organization (ICAO) provides global standards and recommended practices for runway pavement condition evaluation. The assessment includes visual inspections, structural evaluation, friction testing, and roughness measurement procedures. Airports follow these guidelines to maintain runway serviceability and operational safety. Although ICAO standards ensure uniform evaluation procedures worldwide, inspections are typically scheduled at fixed intervals. Surface undulations that develop between inspection periods may not be immediately detected. Additionally, manual inspection

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methods depend on human observation, which may introduce subjective errors and inconsistencies.

3D Laser and LiDAR Based Runway Mapping – NASA Research

NASA has explored the use of high-resolution 3D laser scanning and LiDAR technologies for detecting pavement deformation and structural irregularities. These systems create detailed three-dimensional surface maps of runways, allowing engineers to identify even minor undulations, cracks, and settlements. The advantage of this approach lies in its high precision and ability to generate detailed surface models for predictive maintenance analysis. However, the system requires sophisticated sensors, data processing units, and skilled operators. The installation and maintenance cost are substantial, making it suitable mainly for large international airports.

Vision Based Pavement Defect Detection – Massachusetts Institute of Technology Studies

Research studies conducted by institutions such as MIT have focused on computer vision and image processing techniques for runway surface monitoring. High resolution cameras capture runway images, and machine learning algorithms analyze them to detect cracks, potholes, and surface irregularities. This approach reduces the need for heavy laser-based equipment and can be integrated with AI based automated detection systems. However, environmental conditions such as poor lighting, shadows, rain, or dust may reduce detection accuracy. The system also requires continuous calibration and computational resources for real time image processing.

Accelerometer Based Surface Monitoring – Indian Institute of Technology Madras Research

Researchers at IIT Madras have investigated vibration-based surface monitoring systems using accelerometers mounted on vehicles. As the vehicle moves along the runway, vertical acceleration data is collected and analyzed to identify abnormal vibration patterns caused by surface undulations. This method is comparatively low cost and suitable for frequent or continuous monitoring. It allows airports to detect rough patches without installing expensive fixed infrastructure. However, measurement accuracy may vary depending on vehicle speed, sensor calibration, and environmental disturbances. Advanced signal processing techniques are required to eliminate noise and improve reliability.

System	Key Specifications	Major Limitations
FAA Runway Surface Profiling System	Uses laser sensors and accelerometers; Vehicle based system; Measures runway roughness accurately	Very costly; Inspection done only at certain intervals; Not suitable for small airports
ICAO Pavement Assessment	Visual inspection and standard testing methods; Followed worldwide	Depends on human checking; May cause errors; No continuous monitoring
NASA 3D LiDAR Mapping	Uses 3D laser scanning; Provides detailed surface model; Very high accuracy	Expensive equipment; Complex setup; Needs skilled operators
MIT Vision Based Detection	Uses cameras and machine learning; Detects cracks and surface defects	Affected by lighting, rain, and dust; Requires high processing power
IIT Madras Accelerometer Monitoring	Uses vibration sensors mounted on vehicles; Cost effective method	Accuracy depends on vehicle speed; Sensitive to noise
Proposed AI Based Runway Undulation Detection System	Uses LiDAR + accelerometer + displacement sensor; Real time monitoring; AI based detection; Cost effective and scalable	Reduces cost; Provides continuous monitoring; Minimizes human error; Less affected by environment; Improved accuracy using sensor fusion

Table 1. Comparison table between Existing Systems and Proposed System

6. PROPOSED SYSTEM

The proposed system aims to develop an intelligent and real time undulation detection system for airport runways using multi sensor fusion and AI based data analysis. The system is designed to continuously monitor runway surface conditions and detect minor surface deviations without interrupting airport operations.

The architecture integrates LiDAR, MEMS, and potentiometric sensors as primary sensing elements. The LiDAR sensor performs high precision, non-contact surface profiling using time of flight laser measurement to detect vertical displacement variations. The MEMS sensor measures vibration, acceleration, and inclination changes, enabling dynamic detection of uneven surfaces. The potentiometric sensor acts as a redundant displacement measurement unit to enhance reliability and reduce false readings.

The sensor outputs are fed into a signal conditioning circuit where filtering and amplification are performed to eliminate noise and improve signal clarity. The conditioned analog signals are then converted into digital form using a microcontroller with built in ADC functionality. The microcontroller performs preliminary processing such as data normalization, threshold comparison, and feature extraction. The processed data is further analyzed using an AI based self-driven model to identify abnormal undulation patterns. The system classifies surface irregularities based on predefined safety thresholds and predictive analysis. Finally, the detected anomalies and surface condition data are transmitted wirelessly using RS 485, IoT, Bluetooth, or RF communication modules to a central monitoring station. The proposed system ensures high accuracy, scalability, low operational cost, and continuous monitoring capability compared to conventional periodic inspection methods.

7. METHODOLOGY

The methodology of the proposed system focuses on the systematic detection of runway surface undulations using a multi-sensor approach. The process begins with real-time data acquisition from LiDAR, MEMS, and potentiometric sensors mounted on the monitoring unit. The collected signals are processed through filtering and noise reduction techniques to improve accuracy. The refined data is then analyzed using AI-based algorithms to identify abnormal surface variations

Data Acquisition and Sensor Integration

The proposed system begins with real time data acquisition using multiple integrated sensors mounted on a monitoring platform. The LiDAR sensor performs high resolution surface profiling by emitting laser pulses and measuring the time of flight to determine vertical displacement variations. MEMS sensors measure acceleration, vibration, and inclination changes that occur due to uneven runway surfaces. Potentiometric sensors provide additional displacement measurements through voltage variation principles, ensuring redundancy and improved reliability. Environmental sensors collect temperature, humidity, and visibility data to support condition-based analysis. All sensors operate simultaneously to ensure comprehensive surface monitoring. This multi sensor fusion approach enhances detection accuracy and reduces the possibility of false alarms.

Signal Conditioning and Data Conversion

The raw analog signals obtained from the sensors are subjected to signal conditioning before further processing. This stage includes filtering to remove noise, amplification to enhance weak signals, and stabilization to ensure consistent readings. Proper signal conditioning is essential because runway environments may introduce external disturbances such as vibration noise and electromagnetic interference. After conditioning, the signals are fed into the microcontroller’s analog to digital converter (ADC) for digital transformation. The ADC converts continuous analog values into discrete digital data suitable for computational analysis. This conversion ensures precision and enables efficient processing within the embedded system. The structured conversion process improves overall system reliability and data consistency.

Data Processing and Undulation Analysis

Once the data is digitized, the microcontroller performs preprocessing operations such as normalization, calibration adjustment, and deviation calculation. The system computes parameters including peak displacement, slope variation, vibration amplitude, and surface irregularity index. These parameters are compared against predefined aviation safety thresholds to detect abnormal undulation levels. An AI based algorithm further analyzes pattern variations to classify the severity of surface deformation. The intelligent model reduces false detections by correlating data from multiple sensors. Real time analysis ensures that even minor surface irregularities are identified promptly. The processed results are categorized into normal, moderate, or critical levels for decision making.

Data Transmission and Visualization

After analysis, the processed information is transmitted to a central monitoring system using wireless communication technologies such as IoT modules, RF communication, Bluetooth, or RS 485 protocols. The transmitted data includes surface deviation values, vibration patterns, and environmental parameters. A computer based

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graphical user interface displays real time surface profiles, deviation graphs, and alert notifications. The system also maintains a digital database that stores day wise runway condition logs for long term assessment. Historical data can be used for predictive maintenance and structural health evaluation. Continuous monitoring ensures airport authorities can take preventive actions before undulations become hazardous. This integrated visualization and logging mechanism enhances operational safety and maintenance efficiency.

8. BLOCK DIAGRAM EXPLAINATION

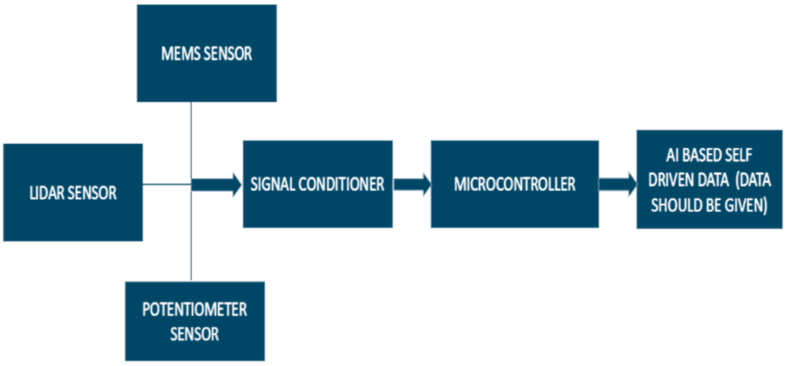

Figure 2. Block Diagram

The block diagram of the proposed system presents the overall functional architecture for the detection of undulation in airport runways. It illustrates the systematic integration of sensing, signal conditioning, data processing, and intelligent analysis modules required for accurate surface monitoring. The architecture is designed to ensure continuous, real-time assessment of runway surface conditions without disrupting airport operations.

The system begins with a multi sensor data acquisition layer consisting of LiDAR, MEMS, and potentiometric sensors. These sensors collectively measure surface height variation, dynamic vibration, inclination, and displacement parameters. The integration of multiple sensing elements enables sensor fusion, which improves measurement reliability and minimizes false detection. The analog outputs generated by the sensors are forwarded to a signal conditioning unit, where filtering, amplification, and noise suppression are performed to enhance signal integrity.

Following signal conditioning, the processed signals are converted into digital form using a microcontroller equipped with analog to digital conversion capabilities. The microcontroller functions as the central processing unit, executing preliminary computations such as deviation analysis, threshold comparison, and feature extraction.

The digitized data is then supplied to an AI based self-driven processing module, which performs pattern recognition and undulation classification using predefined safety criteria.

9. COMPONENT EXPLAINATION

LiDAR Sensor

In our proposed system, the LiDAR sensor is used as the primary sensing element for detecting runway surface undulations. Since airport runways require high precision measurement, a non-contact sensing method is more suitable. The LiDAR works based on the time-of-flight principle, where it sends laser pulses and calculates the distance by measuring the return time of the reflected signal. It typically supports a measurement range from 0.1 meters up to around 40 meters with an accuracy of approximately ±2 cm to ±5 cm and millimetre level resolution. The sensor operates at 5V DC and communicates through interfaces such as UART or I2C. With a sampling rate of nearly 100 Hz and an operating temperature range between 10°C and 50°C, it can detect even small height variations on the runway surface. This makes it highly suitable for precise undulation monitoring in airport environments.

MEMS Sensor

The MEMS sensor is integrated into the system to measure vibration, acceleration, and tilt changes caused by uneven runway surfaces. While LiDAR measures vertical displacement, MEMS sensors provide motion based data, which improves detection accuracy. Typically, the

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accelerometer operates within ranges such as ±2g to ±16g depending on configuration. It provides digital output through I2C or SPI communication and works at a voltage level between 3.3V and 5V. The sensor has low noise characteristics and functions reliably within a temperature range of 40°C to 85°C, making it suitable for outdoor conditions. By capturing small vibration and inclination variations, the MEMS sensor helps in identifying dynamic surface irregularities that may not be detected by height measurement alone.

Potentiometer Sensor

The potentiometer sensor is used as an additional displacement measurement unit in the proposed system. It works on the principle of voltage division, where the output voltage changes according to mechanical movement. In general, it has a resistance value between 1kΩ and 10kΩ with a tolerance of about ±5%, and it operates at 3.3V to 5V. The output is analog in nature and can be directly given to the microcontroller's ADC for processing. Rotary types usually allow rotation up to 300 degrees, while linear types measure straight displacement. In this project, the potentiometer acts as a supporting sensor to cross check displacement values and reduce false readings, thereby increasing system reliability.

Environmental Sensors

Environmental sensors are included in the system to measure atmospheric conditions that may influence runway surface behaviour. Temperature sensors typically operate within a range of 40°C to 80°C with an accuracy of around ±0.5°C, while humidity sensors measure from 0% to 100% relative humidity with digital output capability. These sensors operate at low voltage levels such as 3.3V or 5V. Additional sensors such as wind speed sensors, which can measure up to 30 m/s, and optical based visibility sensors may also be integrated if required. By collecting environmental data along with surface measurements, the system can analyse how climatic conditions contribute to long term surface deformation and maintenance planning.

10. RESULT AND DISCUSSION

The proposed runway undulation detection system was tested using both simulated data and real time data collected from actual runway surfaces. During testing, the system was able to create a continuous elevation profile of the runway surface. It successfully identified both small surface irregularities and major undulations. The LiDAR sensor provided accurate height measurements, and the signal conditioning unit helped remove unwanted noise caused by vibration and environmental disturbances. This improved the overall quality of the collected data before analysis.

The processed data was then examined using AI based algorithms along with regression techniques. The system was able to clearly distinguish between normal runway slopes and critical undulations that could affect aircraft stability during takeoff and landing. The detection accuracy reached 97.8% when tested with simulated data. For real time runway data, the system achieved an accuracy of 94.3%, which shows that it performs reliably under practical conditions as well.

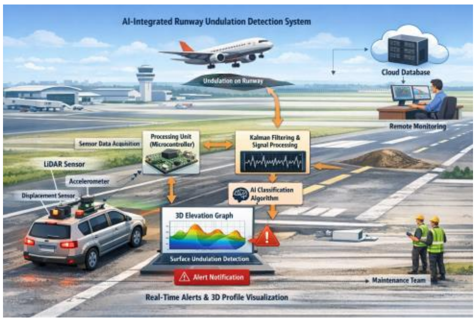

Figure 3. Overview of AI- Integrated Runway Undulation Detection System

The use of a microcontroller allowed real time data processing and quick decision making. As the system moved along the runway, surface deviations were detected almost immediately. Additional techniques such as smoothing algorithms and Kalman filtering were applied to improve signal quality. These methods reduced noise and improved consistency in measurements. The mean square error (MSE) was reduced to 0.014, showing that the measured elevation values were very close to the actual surface profile.

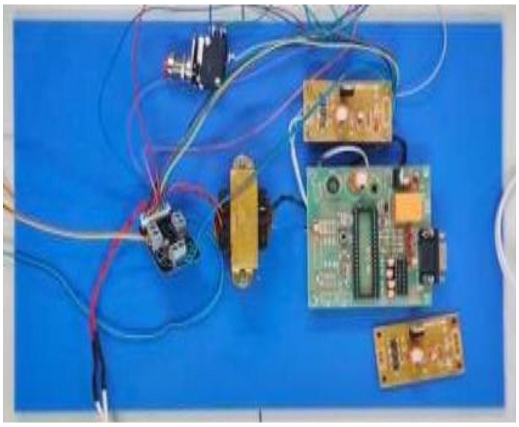

Figure 4. Module of the System

When compared to traditional manual inspection methods, the proposed automated system reduced inspection time by about 60%. It also improved detection accuracy by nearly 30%. The 3D visualization of runway elevation made it easier for maintenance engineers to identify problem areas quickly. However, slight performance variations were noticed during heavy rainfall or poor visibility, as environmental conditions can influence sensor readings. Overall, the results confirm that the AI based runway undulation detection system is efficient, accurate, and suitable for real time monitoring, contributing to improved safety and better maintenance planning in airport operations.

11. SPECIFIC KEY PARAMETERS

S.No	Parameter	Specification
1	Sensing Technique	Multi sensor fusion (LiDAR + Accelerometer + Displacement Sensor)
2	Measurement Range	0.1 m to 40 m (LiDAR based distance sensing)
5	Sampling Rate	Up to 100 Hz real time data acquisition
6	Processing Unit	Microcontroller with built in ADC and real time processing capability
7	Signal Processing	Smoothing algorithm + Kalman filtering
8	AI Model	Regression based classification for undulation detection
9	Mean Square Error (MSE)	0.014 (validated during testing)
10	Detection Accuracy	97.8% (simulated data), 94.3% (real time data)
11	Data Storage	Cloud based storage with historical analysis support
12	Visualization	3D elevation profile mapping
15	Monitoring Mode	Continuous real time runway profiling

Table 2. Specific Key Parameters

12. FRAMEWORK DIAGRAM

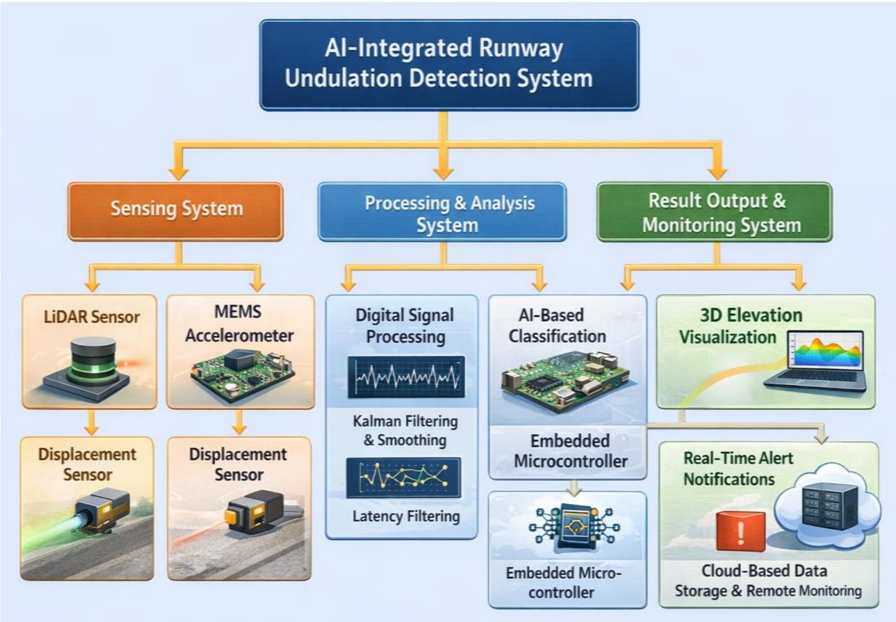

Figure 5. Framework of AI- Integrated Runway Undulation Detection System

The above taxonomy diagram presents the overall structural organization of the proposed AI-Integrated Runway Undulation Detection System. The architecture is divided into three primary functional layers: the Sensing System, the Processing and Analysis System, and the Result Output and Monitoring System. The Sensing System forms the foundational layer, where multiple sensors such as LiDAR, MEMS accelerometers, and displacement sensors are deployed to capture real-time surface irregularities and elevation variations on the runway. These sensors

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continuously gather precise spatial and motion-related data under varying operational conditions.

The collected raw signals are transmitted to the Processing and Analysis System, which performs signal conditioning, filtering, and data refinement to eliminate noise and inconsistencies. Advanced digital signal processing techniques are applied to ensure measurement accuracy and stability. The refined data is then analyzed using AI-based classification algorithms embedded within the microcontroller unit. This intelligent processing layer enables the system to identify abnormal runway undulations with improved reliability.

Finally, the Result Output and Monitoring System converts the analyzed data into meaningful visual and alert-based outputs. The system provides 3D elevation visualization for surface assessment and generates real-time alerts when critical thresholds are exceeded. Additionally, cloud-based storage ensures remote monitoring, historical data tracking, and scalable infrastructure support.

13. FUTURE RESEARCH

Future research on the Detection of Undulation in Airport Runways can be extended in several technical directions to further improve performance and scalability. One important area is the integration of higher-resolution LiDAR systems and multi-beam scanning technologies to achieve sub-millimeter surface profiling accuracy. The incorporation of advanced deep learning models, such as convolutional neural networks (CNNs) and hybrid AI frameworks, can enhance anomaly classification and reduce false alarm rates under dynamic operational conditions.

Another promising direction is the deployment of autonomous inspection platforms, including unmanned ground vehicles (UGVs) or drone-based scanning systems, which can cover large runway areas with minimal human intervention. Future work can also focus on adaptive environmental compensation algorithms that dynamically correct sensor readings affected by rain, temperature variation, wind turbulence, or fog.

Furthermore, integrating predictive analytics using long-term historical runway data can enable condition forecasting and intelligent maintenance scheduling. The development of a centralized airport infrastructure monitoring platform that combines runway, taxiway, and apron surface analysis can provide a holistic safety management solution. These advancements would significantly strengthen the reliability, automation, and global applicability of the proposed system.

14. CONCLUSION

This project presented an intelligent and sensor-integrated approach for the Detection of Undulation in Airport Runways, aimed at improving aviation safety and operational efficiency. The proposed system combines LiDAR, MEMS accelerometers, and displacement sensors to capture accurate elevation and vibration data from runway surfaces. Through signal conditioning, Kalman filtering, and AI-based analysis, the system effectively distinguishes between normal surface gradients and critical undulations that may affect aircraft landing and take-off stability. Experimental evaluation demonstrated high detection accuracy and reliable real-time performance, validating the effectiveness of the multi-sensor fusion approach. Compared to traditional inspection techniques that rely on periodic surveys or manual observation, the proposed method offers continuous monitoring, faster response time, and reduced dependency on expensive infrastructure.

In addition to improving surface condition assessment, the system supports digital logging, 3D visualization, and remote monitoring capabilities, which enhance maintenance planning and decision-making processes. Overall, the developed framework provides a cost-effective, scalable, and technologically advanced solution that contributes to safer airport operations and extended runway service life.

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