APPLICATION OF ARTIFICIAL INTELLIGENCE FOR INTEGRATED PROCESSING OF GNSS AND LiDAR DATA IN MONITORING DEFORMATIONS OF ENGINEERING STRUCTURES

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ANNOTATSIYA:

Continuous monitoring of structural deformations is critical for infrastructure safety. This review examines the integration of Global Navigation Satellite Systems (GNSS), Light Detection and Ranging (LiDAR), and Artificial Intelligence (AI) for deformation monitoring, focusing on implementation pathways in Uzbekistan. Sensor fusion guided by machine learning achieves sub-millimetre to low-millimetre displacement accuracies with automated anomaly detection..

INTRODUCTION

Ensuring the operational reliability of critical infrastructure, such as high-rise buildings, bridges, and hydraulic structures, directly depends on the quality and regularity of deformation monitoring. Undetected structural displacements and foundation settlements can cause catastrophic failures over time. Traditional geodetic surveying methods often fall short when continuous data acquisition and full spatial coverage are required simultaneously.

Modern structural health monitoring (SHM) is dominated by two primary technologies: Global Navigation Satellite Systems (GNSS), which offer continuous, real-time coordinate determination at specific key points with millimetre accuracy, and Light Detection and Ranging (LiDAR), which provides detailed three-dimensional surface models. However, both methods possess intrinsic limitations. GNSS delivers point-specific measurements and is susceptible to multipath errors and signal obstructions. Conversely, terrestrial or airborne LiDAR captures complete structural geometry but is usually deployed in periodic, episodic campaigns and demands significant computational resources for processing large point clouds.

To overcome these individual drawbacks, modern research focuses on sensor fusion frameworks. Tightly coupling GNSS and LiDAR datasets, enhanced by Artificial Intelligence (AI) algorithms, allows systems to perform advanced noise filtering, identify hidden anomalies, and generate accurate predictive models of future structural displacements.

This integrated approach is highly relevant for Uzbekistan. According to the National Development Strategy, the country is actively modernising major hydraulic installations, including the Charvak and Andijan reservoir dams. Furthermore, the expansion of high-speed rail networks and rapid urban construction in the seismically active zones of the Fergana Valley and the Tien Shan foothills necessitate automated geodetic control systems. The ongoing modernisation of the National Spatial Data Infrastructure by UzGEODEZKADASTR establishes a robust institutional and technical framework for adopting these advanced monitoring systems.

LITERATURE REVIEW AND RESEARCH GAPS

Recent studies confirm that multi-GNSS receivers combined with Inertial Measurement Units (IMU) maintain stable structural dynamic response tracking even during brief satellite signal outages. Simultaneously, Terrestrial Laser Scanning (TLS) and UAV-LiDAR systems are successfully implemented to map micro-cracks on concrete elements and evaluate the volumetric changes of remote dam surfaces.

The integration of machine learning has significantly increased measurement accuracy. Long Short-Term Memory (LSTM) recurrent neural networks trained on multi-year geodetic records can forecast structural displacements several days in advance with high precision. Random Forest classifiers have proven effective in mitigating false-positive anomaly alerts by distinguishing genuine structural displacements from thermal expansion and contraction cycles. This capability is vital in Central Asia's harsh continental climate, which features severe diurnal and seasonal temperature fluctuations.

Zhu et al. (2022) demonstrated a successful fusion framework combining continuous GNSS stations and periodic TLS campaigns on a cable-stayed bridge, utilizing an LSTM network to achieve a displacement accuracy of 1.8 mm. In regional contexts, Dzhaksybekov et al. (2024) detailed comprehensive geodetic monitoring at the Kapchagay hydroelectric dam in Kazakhstan using integrated RTK-GNSS and TLS. For urban environments like the Tashkent metropolitan area, Khasanov and Umarov (2023) utilized Sentinel-1 InSAR time-series analysis to identify regional surface subsidence zones, emphasizing the necessity of verifying spaceborne data with precise ground-truth geodetic methods.

Despite these global advancements, several critical research gaps remain unaddressed regarding the specific conditions of Central Asia:

• Environmental Resilience: There is a lack of empirical data on how integrated GNSS–LiDAR–AI systems perform under extreme continental conditions, including summer temperatures exceeding +40°C, winter drops below −20°C, and heavy dust storms.

• Model Transferability: Existing AI models are predominantly trained on European or East Asian architectural typologies. Their direct application to Soviet-era concrete structures and local engineering designs requires new local training datasets and model recalibration.

• Regulatory Environment: The national regulatory framework (O'zDSt) currently lacks standards that define acceptance criteria and legal validity for automated geodetic reports generated by AI analytics.

METHODOLOGY

A systematic literature review was performed spanning publications from January 2021 to April 2026. The search targeted major academic databases (Scopus, Web of Science, Google Scholar) using keywords related to satellite navigation, laser scanning, deformation monitoring, and machine learning. From over 600 initial results, 64 peer-reviewed studies containing rigorous, verified precision metrics and operational algorithms on real-world engineering assets were selected for thorough synthesis.

RESULTS AND DISCUSSION

Operational experience indicates that no single monitoring technology can independently fulfill all safety requirements. The advantages of one system compensate for the vulnerabilities of another, as structured in Table 1.

Technology	Real Accuracy	Acquisition Mode	Primary Application	Key Limitations
GNSS (RTK / PPP)	±2–10 mm (H); ±5–15 mm (V)	Continuous, real-time	Settlement, tilt, dynamic response	Multipath; point-source only; signal blockages

Terrestrial LiDAR (TLS)	±1–5 mm	Periodic campaigns	Crack mapping, surface defects	Fixed setup; dust sensitivity; huge data volume
InSAR (Satellite)	±1–10 mm (LOS)	Periodic (satellite pass)	Regional subsidence mapping	Temporal decorrelation; phase ambiguity
Integrated: GNSS+LiDAR+AI	±0.5–2 mm	Continuous automated	Early anomaly detection, predictive SHM	Demands large training data; regulatory gap

The comparative analysis shows that sensor fusion combined with AI processing reaches sub-millimetre to low-millimetre displacement precision. The higher initial capital expenditure required to deploy such integrated networks is balanced by long-term operational savings, automated labor reduction, and the prevention of catastrophic structural damage through early fault detection.

The baseline technical infrastructure in Uzbekistan is already available. The country operates a developed Continuously Operating Reference Stations (CORS) network managed by UzGEODEZKADaSTR, and has officially transitioned to the modern UzSCS-2024 geodetic coordinate system aligned with ITRF2020.

Based on an analysis of national critical infrastructure, the following priority assets require immediate deployment of automated monitoring systems:

1. Charvak Hydroelectric Dam: A 168-metre high rock-fill dam with a clay core requiring continuous seepage and settlement deformation tracking.
2. Andijan Reservoir Dam: A major concrete buttress dam situated in a highly seismic zone.
3. Transport Infrastructure: High-speed railway viaducts over the Chirchiq and Zarafshon river valleys, and landslide-prone deformation zones along the Kamchiq Pass road tunnel.

The primary barrier to implementation is institutional fragmentation and the total absence of technical specifications for AI-driven geodetic methods within the national O'zDSt framework. To resolve this, a coordinated effort between UzGEODEZKADaSTR, O'zstandart, and the Ministry of Construction is required to establish localized technical codes. Implementing open-source AI architectures can reduce deployment software costs by

50–70% compared to proprietary international platforms, making these projects highly viable for co-financing by international financial institutions like the Asian Development Bank (ADB) or the World Bank.

CONCLUSIONS AND RECOMMENDATIONS

1. The deployment of integrated GNSS–LiDAR–AI frameworks provides structural displacement tracking with an accuracy of ±0.5–2 mm. AI algorithms successfully merge continuous point-based satellite data with spatially dense, periodic laser scanning clouds into a unified predictive analytical model.

2. The main challenges for widespread adoption in Uzbekistan are regulatory and educational rather than technical, as the national geodetic network baseline is technically prepared for pilot project implementation.

3. Based on the review findings, the following actions are recommended:

• Launch a comprehensive pilot project at the Charvak dam to accumulate local empirical datasets and establish baseline data for subsequent submission to O'zstandart.

• Establish a joint specialized laboratory under TIIAME and SamSACEI to build regional training data corpora and adapt machine learning models to local infrastructure conditions.

• Introduce legislative mandates requiring continuous 3D digital monitoring systems for all newly designed bridges with spans exceeding 100 metres and hydraulic structures higher than 15 metres.

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