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Distributed Acoustic Sensing for Civil and Geotechnical Infrastructure Monitoring Applications

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ABSTRACT: Distributed acoustic sensing (DAS) has emerged as a powerful technology for monitoring the health and integrity of civil and geotechnical infrastructure. This technology leverages existing fiber-optic cables as dense arrays of vibration sensors, enabling continuous, real-time monitoring over long distances. This abstract summarizes recent research advancements in applying DAS to various infrastructure monitoring challenges. We first provide a brief overview of the DAS technology and its working principles. Subsequently, we present several case studies demonstrating the versatility of DAS. These include: (1) monitoring and identifying geohazards, such as landslides and rockfalls, that threaten the stability of linear infrastructure; (2) detecting disturbance events, including drilling and excavation activities, near a high-speed railway tunnel; (3) identifying wire breaks in prestressed concrete cylinder pipes for early warning of potential failures; (4) measuring flow rates and detecting illicit flows in urban underground pipelines for improved water management; and (5) integrating DAS with deep learning for traffic monitoring, providing insights into traffic dynamics and patterns, particularly during the COVID-19 pandemic. These examples highlight the potential of DAS as a cost-effective and comprehensive solution for enhancing the safety, resilience, and operational efficiency of critical infrastructure.

KEY WORDS: Distributed acoustic sensing (DAS); Infrastructure monitoring; Geotechnical hazards; Artificial intelligence; Fiber optic sensing

1 INTRODUCTION

Civil and geotechnical infrastructure faces escalating risks from geohazards, structural degradation, and operational challenges. Traditional monitoring methods often suffer from sparse spatial coverage, high deployment costs, or limited real-time capabilities. Distributed acoustic sensing (DAS) revolutionizes infrastructure health monitoring by repurposing optical fibers as ultra-dense vibration sensor arrays [1, 2]. Through precise analysis of Rayleigh backscattered (RBS) phase changes, DAS achieves meter-scale spatial resolution over tens of km ranges, enabling simultaneous strain rate measurement across thousands of sensing channels [3, 4].

Recent advances integrate DAS with artificial intelligence to address critical applications: geohazard early warning (e.g., landslides), tunnel integrity protection, prestressed pipeline diagnostics, urban water management, and intelligent traffic systems. This work demonstrates DAS's dual capability as both physical sensor network and AI-driven data platform, providing cost-effective solutions for infrastructure resilience. Case studies validate its adaptability across energy, transportation, and water sectors, highlighting its transformative potential in smart city ecosystems.

2 DAS MEASUREMENT PRINCIPLE

A DAS system consists of an interrogator unit (IU) and a sensing fiber. The IU injects a continuous pulsed laser into the fiber and detects the RBS phase changes over specified gauge lengths (Figure 1). These scattering are caused by refractive index variations in the fiber. For the same pulsed (along the fast axis), the phase delay Φ of the RBS between two points of the gauge length is:

$$\Phi = \frac{4\pi n L_g}{\lambda} \tag{1}$$

where n is the refractive index of the optical fiber, L_g is the gauge length, and λ is the wavelength of the incident laser.

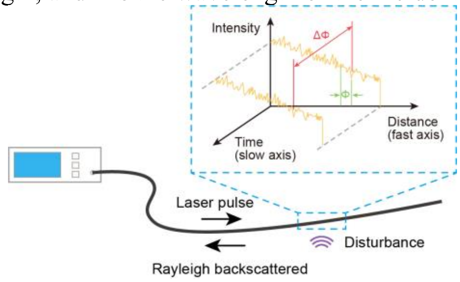

Figure 1. Schematic of DAS measurement principle.

Between adjacent pulse (along the slow axis), the change in phase delay $\Delta\Phi$ over a gauge length is linearly correlated with axial strain rate $\dot{\varepsilon}_{xx}$, following:

$$\dot{\varepsilon}_{xx}(x,t) = \frac{\lambda f_s}{4\pi n L_g \psi}\Delta\Phi \tag{2}$$

where x and t determine the spatial and temporal information of the phase delay change, f_s is the sampling rate of the DAS IU, and ψ is the Pockels coefficient.

Commonly available commercial DAS IU offers a range of gauge length from 1 to 20 m, with channel spacing capable of reaching below 1 m and a sensing range that can extend up to 50 km. During DAS measurement, the sensing fiber is divided into dense sensing units based on the chosen gauge length. This approach enables each sensing unit to measure the axial strain rate of the fiber induced by vibration signals.

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For the case studies described in this work, we utilized an OVLINK MS-DAS2000II DAS IU. This interrogator is based on the principle of phase-sensitive optical time-domain reflectometry (Φ-OTDR), which allows for the high-sensitivity detection of dynamic strain events along the sensing fiber.

3 CASE STUDIES

3.1 Automated rockfall classification

DAS enables continuous seismic monitoring, offering valuable insights into critical infrastructure hazards like rockfalls (Figure 2). However, automated real-time classification of extensive DAS datasets remains challenging. We developed an accurate and interpretable random forest classifier that achieved over 98.4% precision, recall, and F1-score in differentiating windowed DAS signals of rockfall events and various interferences (Figure 3) [5]. Rigorous training and validation on field-collected data leveraged waveform and spectral features for robust rockfall identification. Hyperparameter optimization further improved classification, reaching 99.3% accuracy through cross-validation. Importantly, the model generalized well to unlabeled test data, demonstrating its resilience for real-world deployment. This near real-time solution transforms distributed fiber networks into comprehensive seismic monitoring systems, unlocking their potential to enhance safety and resilience of critical infrastructure worldwide.

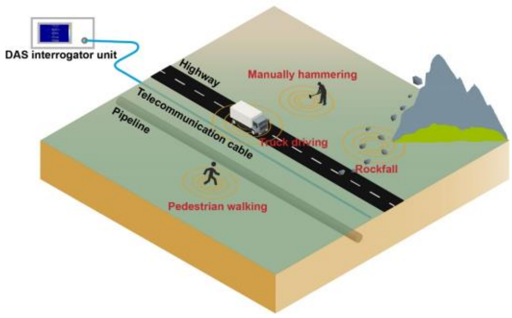


Figure 2. Conceptual overview of DAS for rockfall event monitoring along linear infrastructure.

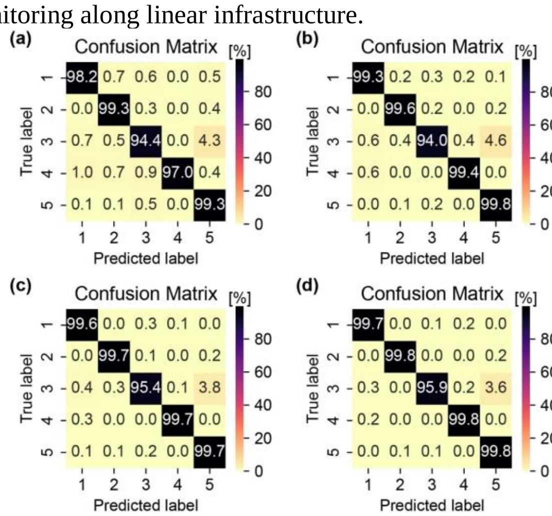


Figure 3. Confusion matrices comparing Random Forest classification performance for window lengths of (a) 2 s, (b) 4 s, (c) 6 s, and (d) 8 s. Five classes are shown: rockfall (1), pedestrian walking (2), hammering (3), truck driving (4), and background noise (5).

3.2 Automatic identification of diverse tunnel threats

As the backbone of modern urban underground traffic space, tunnels are increasingly threatened by natural disasters and anthropogenic activities. Current tunnel surveillance systems often rely on labor-intensive surveys or techniques that only target specific tunnel events. We present an automated tunnel monitoring system that integrates DAS technology with ensemble learning (Figure 4) [6]. We develop a fiber-optic vibroacoustic dataset of tunnel disturbance events and embed vibroscape data into a common feature space capable of describing diverse tunnel threats. On the scale of seconds, our anomaly detection pipeline and data-driven stacking ensemble learning model enable automatically identifying nine types of anomalous events with high accuracy. The efficacy of this intelligent monitoring system is demonstrated through its application in a real-world tunnel (Figure 5a), where it successfully detected a low-energy but dangerous water leakage event (Figure 5b). The highly generalizable machine learning model, combined with a universal feature set and advanced sensing technology, offers a promising solution for the autonomous monitoring of tunnels and other underground spaces.

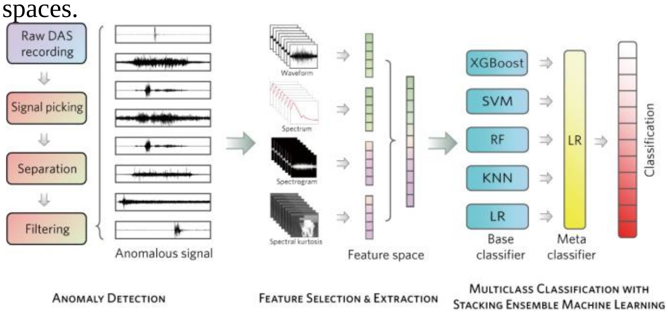
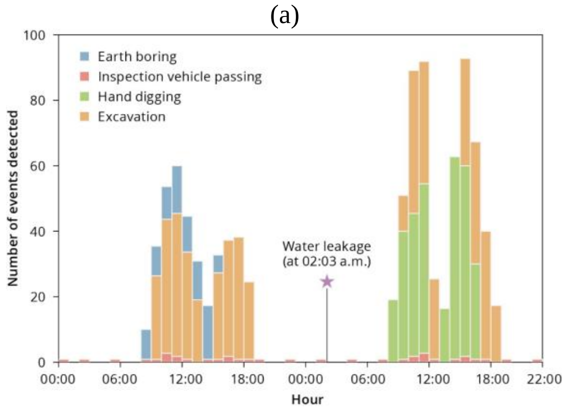


Figure 4. The framework of the DAS monitoring system for automatic tunnel threat identification.

(a)



(b)

Figure 5. (a) DAS fiber deployment scheme along the Beijing–Xiong'an Intercity Railway tunnel; (b) Disturbance events

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identified in the Beijing–Xiong'an Intercity Railway tunnel during a monitoring campaign.

3.3 Identifying wire breaks in prestressed concrete cylinder pipes

The inspection of broken wires in prestressed concrete cylinder pipes is crucial for ensuring the safety and reliability of the pipeline. Traditional point detection techniques always require labor-intensive periodic inspections and cannot deployed along the entire pipeline, significantly limiting the development of the industry. Hence, there is an urgent need for more advanced and intelligent sensors that can achieve 100% coverage and provide sufficient accuracy assurance. Figure 6 presents an overview of the PCCP wire breaking test site. We develop a DAS-based automated monitoring system to accurately classify the rupture of prestressed wires (Figure 7) [7]. First, a computer vision approach is employed to primarily screen out potential vibrational signals from DAS array images. Then, a pre-trained support vector machine model is used to classify the vibrations as either wire breakages or non-wire breakages (Figure 8). This model's performance surpassed other classification strategies, achieving 99.62% accuracy, 99.41% precision, 98.82% recall, and 99.12% F1-score in a side-to-side comparison. Our innovative workflow provides a comprehensive solution for detecting broken wires and offers guidance for the application of artificial intelligence-based DAS to complex vibration systems with limited training data.

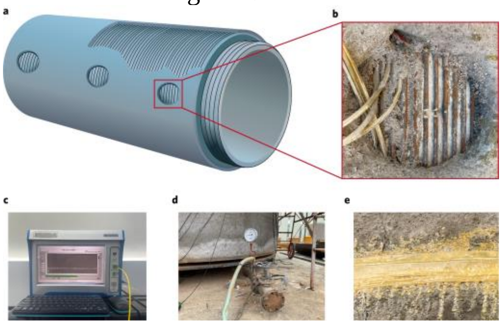

Figure 6. PCCP wire breaking test site; photos show the wires in a circular recess, DAS interrogation unit used, water pressure monitoring gauge within the PCCP, and optical fibers coupled to the outer wall of the pipe.

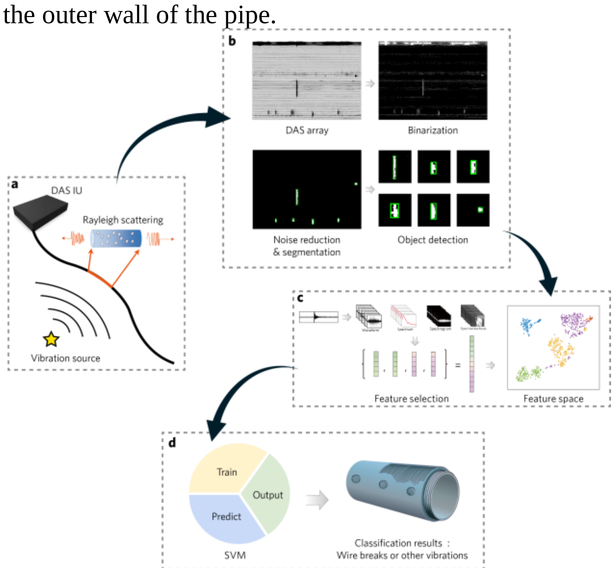

Figure 7. The framework for the autonomous monitoring of wire breaks using DAS data.

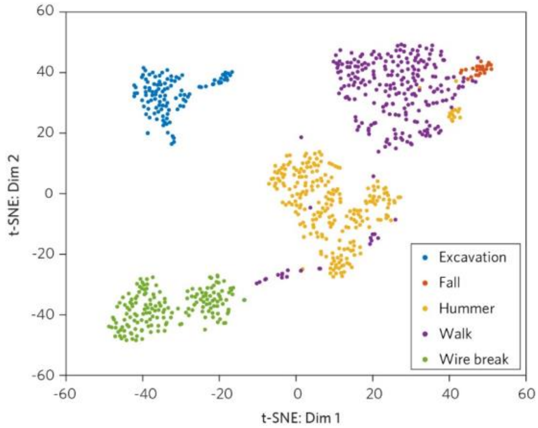

Figure 8. t-SNE is used to reduce the feature dimensionality from 15 to 2 dimensions for purpose of visualization. Five kinds of events are embedded in the same feature space, in which different types are distinguished with different colors.

3.4 Detecting illicit flows in urban underground pipelines

Wastewater discharge from outfall pipes can significantly impact river water quality and aquatic ecosystems. Effective outfall monitoring is critical for controlling pollution and protecting public health. We demonstrates a novel DAS approach for detecting wastewater discharge events from outfall pipes located along rivers [8]. Controlled field experiments were conducted in an industrial park river to systematically evaluate DAS performance (Figure 9). DAS detects vibrational signals imparted to suspended fiber-optic cables by turbulent wastewater flows, predominantly within 10–30 Hz, enabling continuous monitoring along entire river lengths. Vibrational power analysis locates outfalls with meter-level accuracy, while time–frequency techniques discern discharge timing and characteristics (Figure 10). Cable type and outfall–fiber separation influence on detection capability was assessed. Thermoplastic-jacketed cables optimized detection through enhanced vibrational coupling. Vibrational energy decreased exponentially with separation, highlighting benefits of proximal deployment for sensitivity. However, detection range scales with discharge flow rate. Frequency centroid proved a robust feature with potential for automated discharge identification. Overall, DAS enables high spatiotemporal resolution monitoring to pinpoint concealed outfalls minimally invasively. This positions DAS as a promising tool supporting improved water governance through early pollution warnings and rapid source localization via outfall vibrational signatures emanating across river networks.

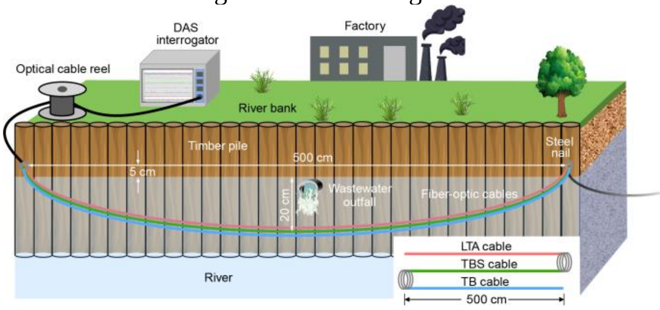

Figure 9. Layout of the DAS system used in field discharge experiments.

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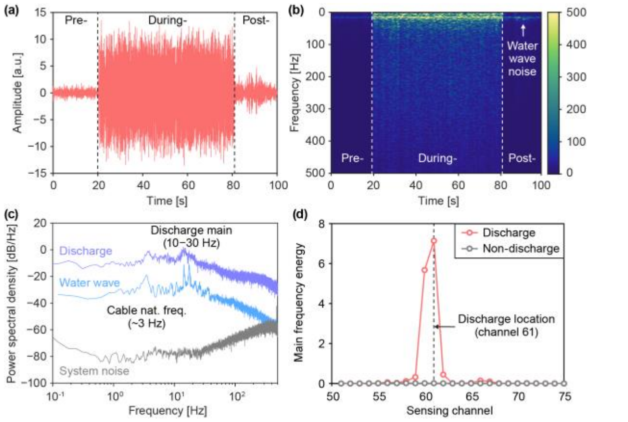

Figure 10. Wastewater discharge detection and localization. (a-b) Time series and short-term Fourier transform (STFT) plots showing pre-, during-, and post-discharge. (c) Power spectral density (PSD) comparison of the discharge signal, wave noise, and system noise. (d) Outfall location identified by calculating vibration power (10–30 Hz) along the cable.

3.5 Enhanced traffic monitoring

Traffic monitoring provides crucial data for intelligent transportation systems (ITS) but traditional sensors are expensive to deploy and maintain at scale. A field experiment was conducted using a section of telecommunications fiber-optic cable co-trenched with a natural gas pipeline in Yudu County, Ganzhou City, Jiangxi Province (Figure 11). We explore DAS using existing fiber-optic infrastructure as a cost-effective solution for traffic monitoring [9]. While DAS offers advantages, vehicle detection signals are susceptible to noise. To address this, we propose a novel approach combining DAS with deep learning object detection using YOLOv8. Pre-processed and labeled DAS data collected over two weeks on a highway during a COVID-19 lockdown were used to train the YOLOv8 network, achieving 92% classification accuracy. Applying the trained model revealed detailed hourly traffic patterns and vehicle compositions (Figures 12 and 13), demonstrating the potential of DAS for robust and cost-effective ITS. These findings highlight the effectiveness of combining DAS and deep learning for noise mitigation in traffic monitoring and provide valuable insights into traffic dynamics during the pandemic.

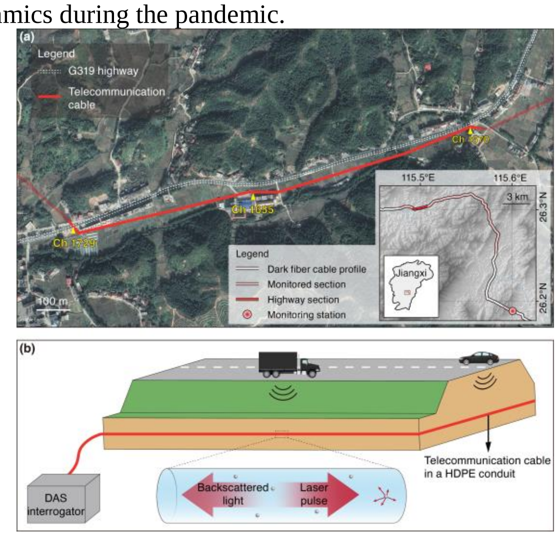

Figure 11. (a) Field experiment site for traffic monitoring and (b) Operating principle of DAS for measuring vehicle signals.

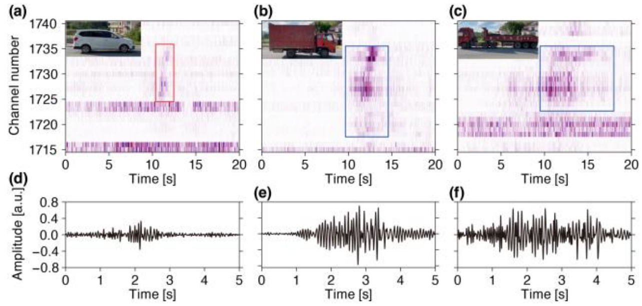

Figure 12. DAS signals from passenger (a, d) and commercial (b, c, e, f) vehicles. (a-c) Waterfall diagrams. (d-f) Time series.

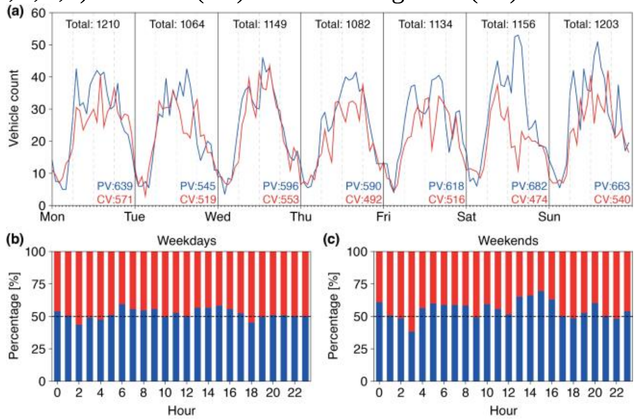

Figure 13. Comparison of passenger (blue) and commercial (red) vehicle traffic patterns determined via DAS. (a) Daily traffic volume trends. (b-c) Vehicle proportions on weekdays and weekends.

4 CONCLUSIONS

This overview demonstrates the transformative potential of DAS as a unified monitoring solution for heterogeneous infrastructure systems. Across geohazard monitoring, structural integrity assessment, and urban network management applications, DAS consistently proves its capacity to convert standard optical fibers into high-resolution vibration sensor arrays. By synergizing Rayleigh backscattering physics with machine learning architectures, the technology overcomes traditional trade-offs between spatial granularity, coverage range, and operational scalability.

The case studies reveal two paradigm-shifting attributes: First, DAS inherently operates as a cyber-physical transducer, simultaneously capturing mechanical wavefields and feeding AI-driven digital twins. Second, its compatibility with existing fiber networks enables rapid deployment at marginal cost, particularly advantageous for linear assets like pipelines and tunnels. While signal interpretation remains context-dependent, emerging standardization frameworks for DAS data annotation are reducing domain adaptation barriers.

As cities prioritize infrastructure resilience, DAS emerges as a strategic tool for converged monitoring of above-ground and subsurface environments. Future implementations could expand its use in decarbonization initiatives, such as CO_2 storage integrity verification and smart grid dynamics tracking. By bridging physical infrastructure with computational analytics, this technology redefines the boundaries of structural health monitoring in the era of ubiquitous connectivity.

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