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Original Article

Distributed Fiber Optic Sensor Technology for the Real-Time Monitoring and Preservation of Ancient Sites and Artifacts

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Abstract

The preservation of invaluable cultural heritage assets, including ancient artifacts and historical sites, remains a critical global concern. Existing perimeter protection methods, such as CCTV systems, infrared sensors, and conventional surveillance technologies, often exhibit significant limitations in terms of spatial coverage, sensitivity to subtle intrusions, and adaptability to varying environmental conditions. This paper presents an innovative and highly effective solution utilizing fiber optic sensor (FOS) technology, which offers numerous advantages, including lightweight construction, immunity to electromagnetic interference, ease of installation, high sensitivity, and reliable performance across a broad range of applications. Specifically, the study introduces novel designs for distributed acoustic FOS systems based on Michelson, Mach-Zehnder, and Sagnac interferometric configurations. Through comprehensive theoretical analysis, simulation modeling, and experimental validation, the research explores their practical utility in protecting cultural heritage. Two detailed case studies—focused on the Louvre Museum in France and the ancient archaeological site of Persepolis in Iran—demonstrate the implementation, functionality, and real-world efficacy of the proposed systems. The findings highlight how these FOS networks, particularly when combined with advanced artificial intelligence and machine learning algorithms, can effectively detect, classify, and localize human-induced acoustic disturbances such as walking or digging, while minimizing false alarms caused by environmental noise. This enhanced discrimination capability not only improves overall security but also significantly reduces the need for extensive human surveillance. Moreover, these systems enable precise, continuous, and real-time 24-hour monitoring over vast indoor and outdoor areas. In conclusion, the integration of FOS technology offers a scalable, intelligent, and transformative approach to addressing the complex and evolving challenges associated with the long-term preservation and protection of cultural heritage sites around the world.

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Introduction

The critical importance of preserving cultural heritage assets, including invaluable ancient objects and historical sites, is universally recognized. These irreplaceable artifacts and locations serve not only as tangible links to our collective past but also as fundamental resources for historical, artistic, and archaeological research, offering profound insights into the trajectory and accomplishments of human civilization. Consequently, ensuring their long-term protection constitutes a paramount endeavor for present and future generations. Despite this widespread recognition, the effective security and continuous monitoring of extensive heritage sites and diverse museum collections pose significant challenges. Conventional perimeter protection methods—such as closed-circuit television (CCTV) systems, infrared cameras, and traditional human or acoustic sensors—often exhibit inherent limitations. These include restricted spatial coverage, susceptibility to false alarms, heavy reliance on manpower, and insufficient sensitivity to subtle disturbances. Moreover, the vastness and often remote locations of many archaeological sites further complicate comprehensive and cost-effective surveillance, rendering these invaluable cultural assets vulnerable to threats such as theft, vandalism, and environmental degradation. The pressing need for robust, scalable, and intelligent security solutions tailored to the unique requirements of heritage protection is therefore undeniable. Recent advancements in sensing technologies have introduced innovative approaches to address these challenges. Among these, fiber optic sensor (FOS) technology has emerged as a particularly promising and versatile solution. FOS systems offer distinctive advantages, including lightweight and flexible deployment, immunity to electromagnetic interference, high sensitivity, and the capability for distributed sensing over large areas. These features position FOS as an ideal candidate for the discreet and effective protection of sensitive cultural heritage environments, where traditional monitoring systems may prove impractical or potentially damaging. The foundational concept of fiber optic acoustic sensors was first introduced by Bucaro et al. (1977) through the development of fiber optic interferometry, employing two optical fiber arms: a reference arm and a sensing arm responsive to external acoustic waves. The fiber Mach-Zehnder interferometer proposed by Bucaro subsequently gained widespread application in pressure and temperature sensing (da Silva, 2014). Significant progress ensued with innovations such as the introduction of a highly flexible composite coating by Teixeira et al. (2014) and the enhancement of acoustic sensitivity via piezoelectric polymer coatings demonstrated by Lagakos et al. (1990). Applications have further expanded into biomedical fields, exemplified by Chen et al. (2013), who utilized a 5.5-meter Mach-Zehnder interferometer to record sound waves generated by blood pressure during cardiac cycles. A major advantage of interferometer-based FOS lies in their precise positioning capabilities. Chen et al. (2015) notably enhanced localization algorithms for dual Mach-Zehnder interferometer systems, incorporating zero-crossing detection and advanced cross-correlation techniques leveraging Wiener filtering and generalized neural network (GNN) weighting functions for accurate time delay estimation. Similarly, Liang et al. (2015) developed novel algorithms for distributed fiber-based sensors utilizing Mach-Zehnder architectures. Although less prevalent in acoustic applications, Michelson interferometers have also been employed since the 1980s (Imai et al., 1981). Meanwhile, Sagnac interferometry has been adapted for vibration localization with loop and in-line configurations (Liu et al., 2016). Other notable configurations include Fabry-Pérot interferometers, introduced into fiber optic sensors in 1991 (Murphy et al., 1991), and fiber Bragg gratings (FBG), initially proposed by Hill et al. (1978) and subsequently optimized for acoustic sensitivity (Seo et al., 2009, Radak and akhgar, 2023).

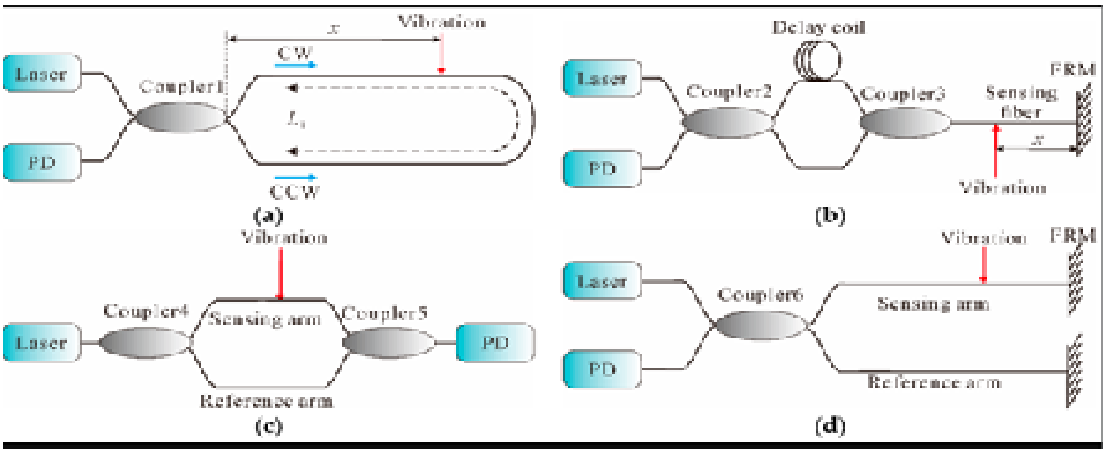

Figure1.
Distributed fiber-optic vibration sensors based on interferometric technology: (a) Sagnac sensors with a loop configuration; (b) Sagnac sensors with an in-line configuration; (c) MZI sensors; (d) MI sensors (Liu et al., 2016; Kirkendall & Dandridge, 2004; Pal, 1992; Hartog, 2017; Hocker, 1979)

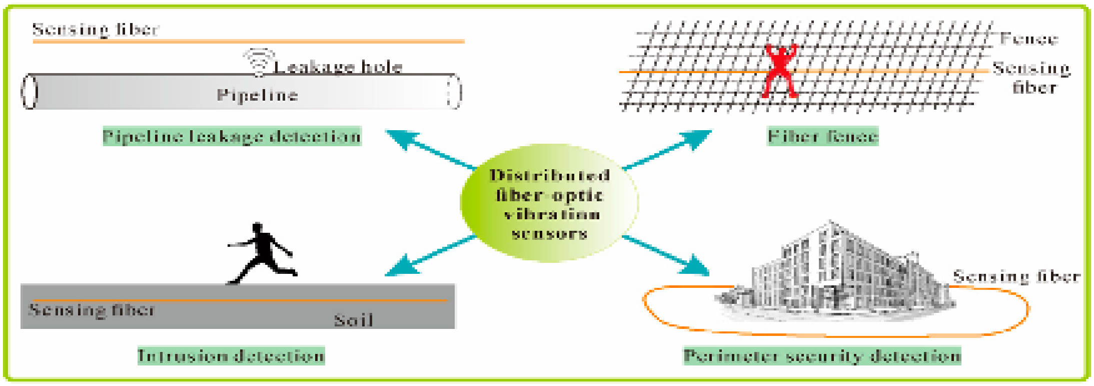

Figure2.
Several typical applications of distributed fiber-optic vibration sensors (Liu et al., 2016)

These diverse interferometric sensor configurations, illustrated in Figure 1, underscore the versatility and continuous evolution of fiber optic sensing technologies. Figure 2 further highlights typical applications, including structural health monitoring, seismic detection, and industrial vibration analysis, demonstrating the broad utility and reliability of distributed fiber-optic vibration sensors. Building upon these technological foundations, this study explores the novel application of distributed acoustic FOS systems—specifically those based on Michelson, Mach-Zehnder, and Sagnac interferometers—for enhancing the preservation and security of invaluable cultural heritage assets. Through comprehensive theoretical analysis, numerical simulations, and experimental investigations, this work evaluates the efficacy of these sensing modalities in real-world scenarios. Case studies focusing on the Louvre Museum and the ancient site of Persepolis illustrate how fiber optic interferometric sensors can provide continuous, high-resolution monitoring, effectively detecting and discriminating human-induced acoustic disturbances from environmental noise. Ultimately, this research demonstrates the transformative potential of FOS technology in revolutionizing cultural heritage protection by delivering scalable, reliable, and technologically advanced solutions that address current security challenges and support sustainable heritage management.

Methodology

This section presents the theoretical framework and operational principles underlying the proposed fiber optic sensor (FOS) system designed for the protection of cultural heritage sites. The fundamental physics of light propagation in optical fibers under external perturbations, sensor design considerations based on interferometric configurations, and experimental validation approaches are systematically elaborated.

Theoretical Foundations of Fiber Optic Sensing

The phase of light propagating through an optical fiber is fundamentally governed by two principal physical mechanisms: (a) modifications in the fiber's geometrical dimensions and (b) variations in its refractive index. When one arm of an interferometer is subjected to external perturbations—such as thermal fluctuations, applied pressure, or mechanical strain—a differential change in the optical path length arises between the sensing and reference arms. This path length variation induces measurable alterations in the interference pattern, typically manifested as fringe shifts or distortions In the context of an isotropic stress state in a fiber subjected to pressure p, the phase change Δϕ in radians can be influenced by the fiber length L and the stress components. In this scenario, the stress can be represented as a vector with three components, typically given as:Under these conditions, the internal stress state within the fiber can be mathematically represented as a three-component vector comprising the normal stress components along the radial, azimuthal, and axial directions.

$$\sigma = \begin{bmatrix} -P \\ -P \\ -P \end{bmatrix} \quad (1)$$

Since the optical fiber is subjected to an isotropic stress state, all three normal stress components become equal to the applied pressure p p, with shear components being inherently absent. This uniform stress distribution affects the optical phase change by inducing simultaneous variations in both the fiber's geometrical dimensions and its refractive index. The material's photoelastic response under such loading conditions is governed by fundamental mechanical parameters, including Young's modulus (E), Poisson's ratio (μ), strain (ε), and stress (σ). Accordingly, the resulting strain vector can be expressed as:

$$\varepsilon = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \begin{bmatrix} \frac{-P(1-2\mu)}{E} \\ \frac{-P(1-2\mu)}{E} \\ \frac{-P(1-2\mu)}{E} \end{bmatrix} \quad (2)$$

The fiber length L is defined as the diameter of the core D, and the refractive index of the core is n. The relationship between the passing beam's free space propagation constant k· and the single-mode propagation constant β is expressed by the phase equation βL=ϕ. The strain on the fiber causes a phase change:

$$\Delta\varphi = \beta\Delta L + L\Delta\beta = \beta\Delta L + \left(\frac{d\beta}{dn}\right)\Delta nL + \left(\frac{d\beta}{dD}\right)\Delta DL \quad (3)$$

The first part of the equation describes the physical effect of phase change resulting from the alteration in length due to strain. The second part addresses two specific changes that occur under strain: a) the strain modifies the refractive index of the fiber, leading to a subsequent change in the final phase, and b) the waveguide mode dispersion effect arises from variations in the fiber's diameter caused by the applied strain, which again results in a change in the system's final phase. The effective refractive index neff is determined by the interaction between the fiber core and cladding. Given that the difference in refractive index between the two is 1%, we can apply the formula β = nk0 or dβ/dn ≃ k0. if radial strain εr radial strain and axial strain εθ :

$$\Delta L = L(\varepsilon_r + \varepsilon_\theta) \quad (4)$$

The Pockels coefficients tensor, also known as the optic-strain tensor, characterizes the relationship between strain and changes in the refractive index. In standard single-mode optical fibers, both the core and cladding are typically fabricated from glass with nearly identical material properties (Hocker, 1979; Pal, 1992; Hartog, 2017; Del Villar & Matias, 2020).

Distributed fiber optic sensors (DFOS) offer a significant advantage by enabling large-area monitoring through a single sensing line. Their ability to detect mechanical or environmental perturbations is based on multiple physical principles, including interferometric methods (Chtcherbakov et al., 1999), Rayleigh backscattering, and Brillouin scattering measured using phase-sensitive Optical Time Domain Reflectometry (ϕ-OTDR) techniques (Juarez & Taylor, 2007). The general expression for the relative optical phase delay in such systems is given by:

$$\frac{d\varphi}{\varphi} = \frac{dL}{L} + \frac{dn}{n} + \frac{dk}{k} \quad (5)$$

When an acoustic wave interacts with the sensing optical fiber, it induces a dynamic perturbation in the optical path length (dL) or an associated variation in the refractive index (dn). These perturbations result in a measurable change in the output optical phase. Although variations in the propagation constant (dk) are typically attributed to fluctuations in the laser source's wavelength or frequency, in scenarios where the laser wavelength is assumed constant, the resulting phase change can be predominantly attributed to the acoustic-induced modulations in L and n. Accordingly, the optical phase variation due to acoustic wave interaction can be expressed as:

$$d\varphi = \frac{2\pi n L \xi \varepsilon}{\lambda} \quad (6)$$

p_{12} denotes the optical strain coefficient, as described in detail by Kirkendall and Dandridge(2004).

$$d\varphi = \frac{2\pi n L \xi \varepsilon}{\lambda} \quad (7)$$

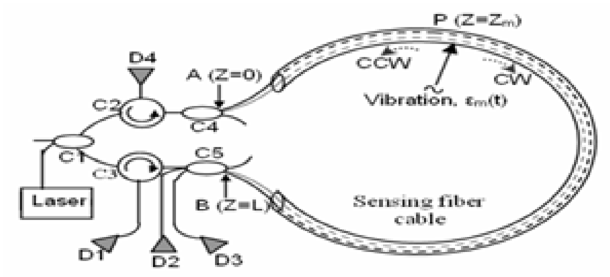

Figure3.
Fiber optic vibration sensor based on dual Mach-Zehnder interferometer (Sun, Liu, Liu, & Shum, 2007)

For vibration ranging and localization, points **A** and **B** are conventionally designated as the initial and terminal positions of the sensing fiber, respectively, as schematically illustrated in Figure 3. In this configuration, point **P** denotes the precise location at which the vibration is applied. The total cable length is denoted by L, while the active sensing segment between points **A** and **B** is represented as Z_m. When a vibration is introduced at point **P**, the interferometric system generates a phase-invariant modulation, which serves as a critical mechanism for accurate disturbance localization.

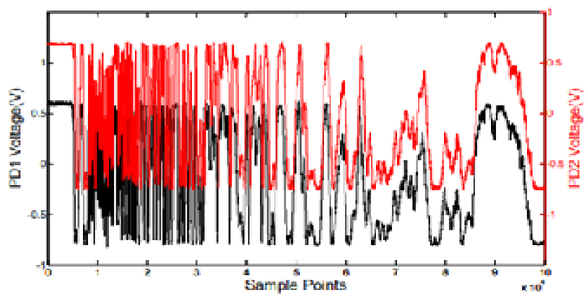

Figure4.
The interference signals when vibration occur (Tu, Xie, Jiang, & Zhang, 2012)

Figure4 and5.
illustrate the experimental results obtained from the proposed system, which utilizes a sensing fiber of 112 km in length and achieves a spatial localization accuracy of approximately 160 meters

Experimental and Simulation Framework for Fiber-Optic Vibration Sensing

This section presents the experimental setup and simulation methodologies employed for the analysis of aerial imagery of Persepolis, as well as a representative design prototype developed for the Louvre Museum.

The practical implementation of both designs is also demonstrated. A central component of these designs is the schematic configuration of a fiber-based Mach-Zehnder interferometer, employed for the detection of acoustic disturbances. This configuration is elaborated upon in the subsequent subsections.

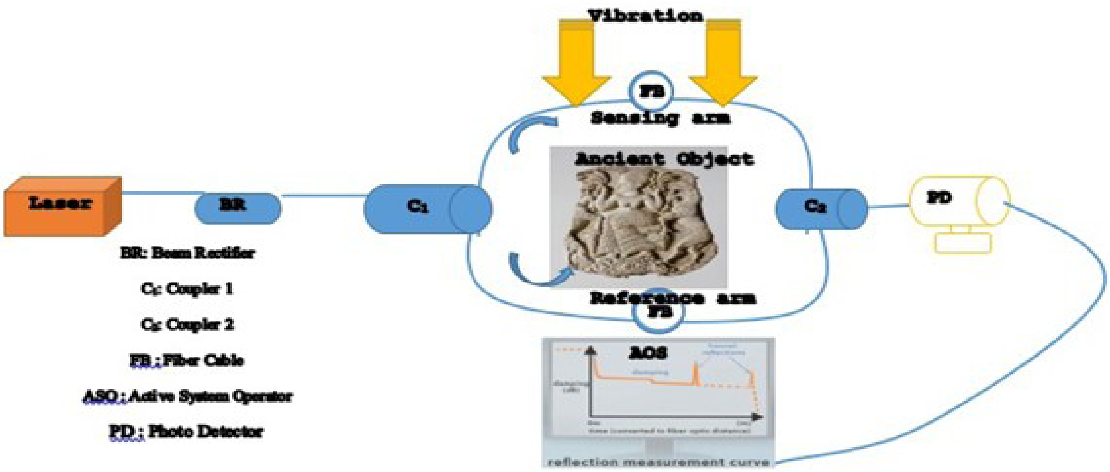

Figure6.
Simple schematic of a fiber optic protection system protecting an ancient specimen using Mach-Zehnder interferometry

Figure 6 presents a schematic layout of the fiber-optic sensor system based on the Mach-Zehnder interferometry principle. In this configuration, continuous laser light is first passed through a rectifier and then split into two separate paths by Coupler 1. The resulting beams travel in clockwise and counterclockwise directions, forming the sensing arm and the reference arm, respectively. The sensing arm is deliberately arranged around the ancient object, enabling real-time detection and protection against potential disturbances. When external vibrations occur, the photodetector instantly captures the induced phase change and transmits a corresponding alert to the system operator at the speed of light. The fiber-optic cable exposed to acoustic waves is integrated into the sensing arm, introducing a measurable optical path difference between the two arms of the interferometer. This phase variation forms the basis for accurate detection of environmental disturbances approaching the cultural artifact. Subsequently, the optical outputs from the two detectors are fed into an oscilloscope card, where the signals are recorded for post-processing and analysis. The system operator then interprets these signals to identify and classify the nature of the disturbances. The following section introduces the implementation of a fiber-optic sensing system based on the Sagnac interferometry technique as an alternative approach for the protection of the selected archaeological object.

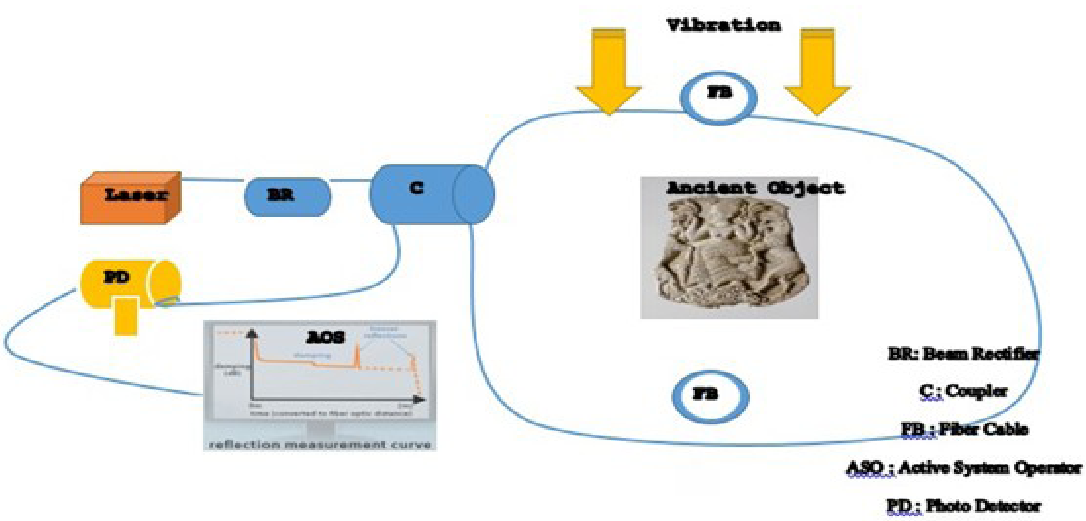

Figure7.
Simple schematic of a fiber optic protection system protecting an ancient specimen using agnac interferometry

As illustrated in Figure 7, a protection system analogous in principle to the Mach-Zehnder interferometer is introduced. In the final design example, the Michelson interferometry technique is employed for the preservation and monitoring of ancient artifacts.

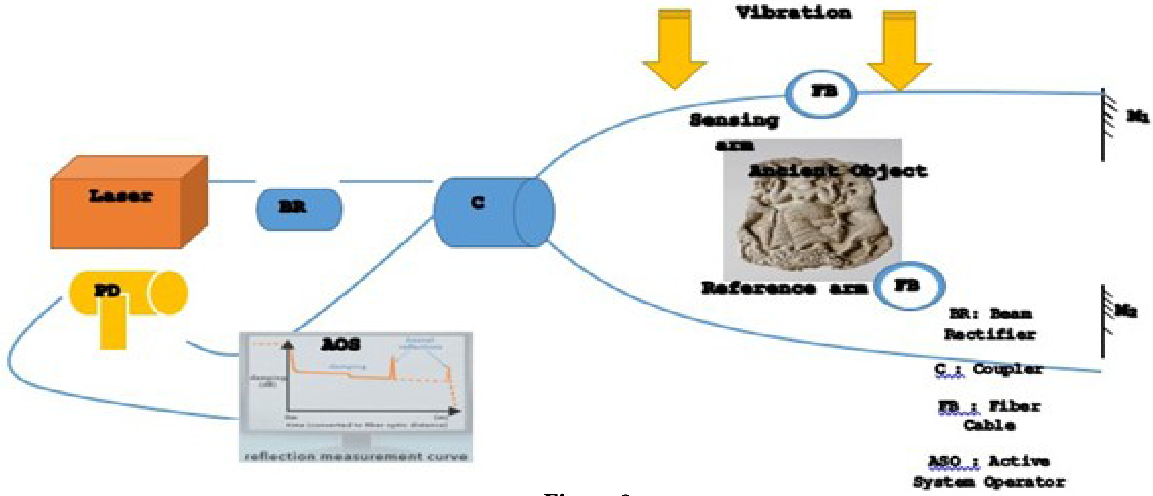

Figure8.
Simple schematic of a fiber optic protection system protecting an ancient specimen using agnac interferometry

Figures 6, 7, and 8 illustrate three distinct conceptual frameworks for the deployment of fiber optic sensors based on the Mach-Zehnder, Sagnac, and Michelson interferometric principles, respectively. Each schematic demonstrates how its corresponding interferometric configuration can be strategically applied to safeguard ancient artifacts and to reliably detect the presence of potential intrusions.

Discussion

This article presents and evaluates an innovative distributed Fiber Optic Sensor (FOS) system designed for the autonomous and intelligent protection of cultural heritage sites and museum environments. By significantly minimizing reliance on conventional security personnel, the system facilitates continuous, 24/7 surveillance across large areas. Utilizing a single laser source, it effectively detects acoustic signals generated by human activities (e.g., walking, running, or digging) and accurately distinguishes them from ambient environmental noise. The integration of advanced machine learning algorithms and artificial intelligence enables precise identification of human intrusions while robustly filtering out irrelevant natural sounds such as bird calls, wind, or overhead aircraft. Upon intrusion detection, the system allows real-time threat assessment and response through seamlessly integrated surveillance cameras and unmanned aerial vehicles (UAVs). This architecture not only enhances situational awareness and reduces operational costs but also offers a smart, precise, and highly reliable approach to safeguarding irreplaceable cultural assets.

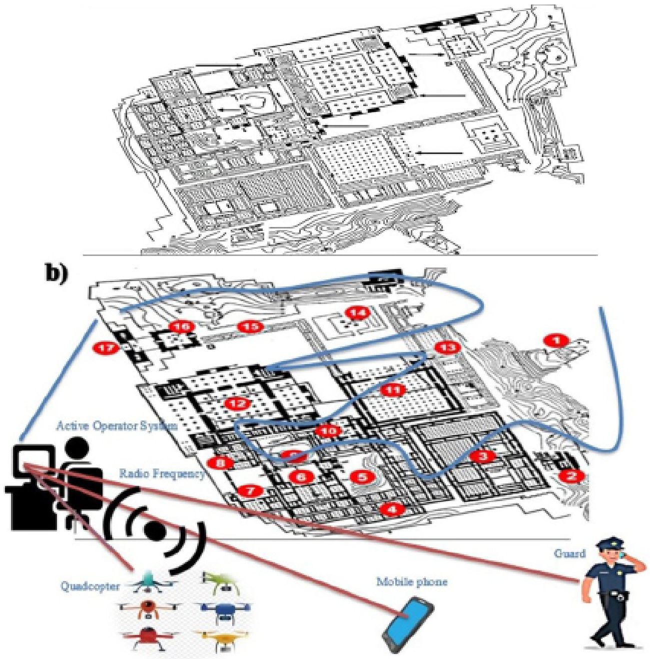

Figure9.
a) schematic representation of the Persepolis environment, illustrating the layout and key areas of interest for security monitoring. b) A plan outlining the protection of the FOS connected to both a quadcopter and a mobile phone. This setup allows for real-time monitoring and instant alerts to inform security personnel of any suspicious activity in the area

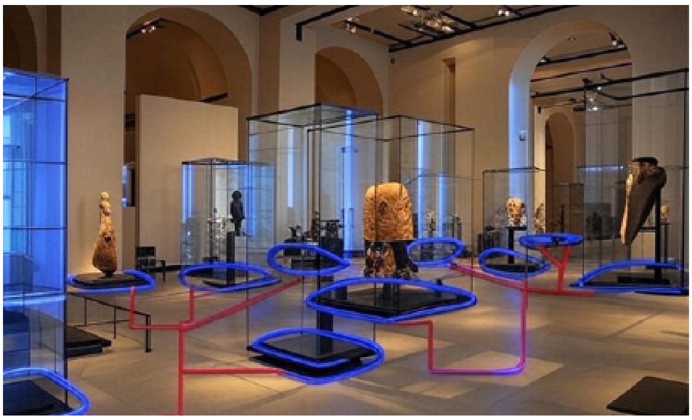

Figure10.
Schematic of FOS protection in the Louvre Museum sample area in Paris, where blue fiber optic cables are placed on the surface and directly exposed to acoustic waves from disturbing agents, while gray cables are buried underground, where strain changes are minimal and negligible compared to those in cables located around ancient objects

Figure 10 illustrates a comprehensive schematic of the advanced optical fiber configuration employed for disturbance detection. This system detects and accurately localizes acoustic waves by monitoring their effective frequency, which is captured by strategically arranged sensing fibers in a circular layout. As these fibers rotate, they transmit real-time signals to an active monitoring system, enabling precise identification of the acoustic disturbance's source. Beyond simple detection, the system also provides valuable contextual information about the surrounding environment—for instance, identifying zones with increased human activity.

This is achieved by analyzing variations in the optical phase shifts of the fibers, which are directly correlated with the intensity of ambient acoustic events. In essence, these phase shifts serve as dynamic indicators of human presence, allowing security personnel to prioritize and focus monitoring efforts in areas requiring heightened attention. Fiber Optic Sensor (FOS) systems offer several critical advantages over traditional security solutions. They exhibit exceptional sensitivity and accuracy in detecting minute disturbances, ensuring reliable performance even in acoustically complex or noisy environments. Their immunity to electromagnetic interference and ambient noise makes them particularly suitable for outdoor and large-scale heritage site applications. Furthermore, FOS systems support uninterrupted, 24/7 monitoring with minimal human intervention, effectively reducing operational costs and the likelihood of human error. However, some limitations must be acknowledged: the initial deployment cost of FOS systems is considerably higher than that of conventional approaches, which can pose financial barriers, particularly in resource-limited contexts. Additionally, these systems require specialized expertise for installation, calibration, and maintenance, introducing a level of technical complexity that may not be readily manageable in all settings. In contrast, traditional systems—while often less accurate and more prone to false alarms—are generally simpler to install and maintain. Despite these challenges, FOS systems stand out as highly reliable, scalable, and technologically advanced solutions for security applications where precision, continuous coverage, and robustness are critical.

Conclusion

This study presents and validates a novel distributed fiber optic sensor (FOS) framework designed for the intelligent and automated protection of cultural heritage assets, encompassing both museum-held artifacts and open-air archaeological sites. Employing advanced interferometric configurations—including Mach-Zehnder, Sagnac, and Michelson—the proposed system exhibits exceptional sensitivity to external perturbations such as vibrations and acoustic signals, thereby enabling accurate, real-time detection and localization of potential threats. Through an integrated methodology that combines laboratory experiments, numerical simulations, and conceptual site-specific implementations—exemplified by case studies at Persepolis and the Louvre Museum—the research demonstrates the system's practical feasibility, adaptability to diverse heritage contexts, and potential for scalable deployment. Notably, the incorporation of AI-based signal classification significantly enhances the system's capacity to discriminate between anthropogenic intrusions and ambient environmental noise, thereby reducing false positives and improving overall operational reliability. Beyond intrusion monitoring, the FOS system provides situational awareness by identifying zones of elevated human activity, facilitating the strategic allocation of security resources. Its inherent immunity to electromagnetic interference, resilience under varying environmental conditions, and capability for continuous, non-invasive monitoring offer distinct advantages over conventional surveillance technologies—especially in contexts where minimal physical intervention is paramount. Although the initial installation costs and requirement for specialized technical expertise pose challenges, these limitations are counterbalanced by long-term benefits, including reduced dependence on human surveillance, improved detection accuracy, and wide-area coverage. Future research should prioritize the refinement of machine learning algorithms for acoustic pattern recognition, cost-reduction strategies for implementation in resource-constrained regions, and integration with GIS-based spatial analytics for comprehensive heritage site monitoring. In sum, the deployment of distributed FOS technologies constitutes a significant advancement in the field of cultural heritage preservation. By synergizing high-resolution optical sensing with intelligent analytics, this approach offers a minimally invasive, technologically sophisticated, and sustainable solution for the safeguarding of humanity's most vulnerable and invaluable cultural legacies.

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Data Availability

The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the corresponding author upon reasonable request.

Conflict of Interest

The results obtained in this research do not conflict with any individual or organization.

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Authors' Participation

All authors contributed equally to the analytical and numerical calculations and have read and approved the final manuscript.

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