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INTEGRATION OF AI AND IOT SENSORS FOR CONTINUOUS MONITORING AND RESTORATION OF CULTURAL HERITAGE SITES – DETERMINING CRITICAL FACTORS

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Abstract

The reconstruction of cultural heritage sites damaged by war is a critical task that blends historical preservation with cutting-edge technology. This article examines the role of AI in these efforts, focusing on practical applications. It explores how AI can balance authenticity and innovation in restoration projects, address concerns when reconstructing lost details and ensure respect for cultural significance. The use of LiDAR scans, drone photography and photogrammetry in documenting and restoring sites is highlighted. Additionally, the article discusses the integration of IoT sensors for continuous monitoring and the application of machine learning to predict the impact of external factors on heritage sites. An analysis using Python to visualize LiDAR data is included, demonstrating the practical benefits of these technologies in both war and peace.

Keywords: *AI Restoration; Cultural Heritage; Ethical Considerations; LiDAR Scans; IoT (Internet of Things), LoRaWAN, Sensors; Machine Learning; Continuous Monitoring*

Introduction

The preservation and reconstruction of cultural heritage sites that have been damaged by war is a task of immense historical, cultural and ethical significance [1, 2]. These sites are not merely physical structures; they are repositories of collective memory, identity and history. The destruction of such sites, whether through natural disasters, human conflict, or neglect, represents a profound loss to humanity. In recent years, the advent of advanced technologies, particularly artificial intelligence (AI), has opened new avenues for the restoration and preservation of these invaluable assets [3-5]. This paper explores the multifaceted role of AI in the reconstruction of war-torn cultural heritage, focusing on both the practical applications and the ethical considerations that arise in this context.

The use of AI in cultural heritage restoration is a relatively new but rapidly evolving field. AI technologies, including machine learning, computer vision and data integration, offer unprecedented capabilities for analyzing, reconstructing and preserving historical sites [6, 7]. These technologies can process vast amounts of data from various sources, such as LiDAR scans, drone photography and photogrammetry, to create detailed and accurate 3D models of damaged

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structures. These models can then be used to guide restoration efforts, ensuring that the reconstructed sites are as faithful to the original as possible.

One of the most significant advantages of using AI in restoration projects is its ability to integrate and analyze data from multiple sources [3]. For example, LiDAR scans can provide highly detailed images of the current state of a site, capturing even the smallest details of its structure [9, 10]. Drone photography can offer high-resolution images from various angles, providing a comprehensive view of the site. Photogrammetry can create precise 3D models from photographs, which can be used to fill in gaps where physical access is limited or impossible [11-14]. By combining these data sources, AI can generate a holistic and accurate representation of the site, which is crucial for effective restoration [15-16].

However, the use of AI in cultural heritage restoration is not without its challenges and ethical dilemmas [8, 17]. One of the primary concerns is the balance between authenticity and innovation. While AI can help recreate lost details and fill in missing information, there is a risk that the restored site may not fully reflect its original state. This raises important questions about the authenticity of the restoration and the extent to which modern technology should be used to recreate historical sites. It is essential to ensure that restoration efforts respect the cultural and historical significance of the site, preserving its integrity and authenticity.

Another critical ethical consideration is the use of AI to fill in missing information [17-21]. In many cases, the data available for restoration may be incomplete or fragmented. AI can use machine learning algorithms to predict and reconstruct missing details based on existing data. However, this process involves a degree of speculation and interpretation, which can lead to inaccuracies or misrepresentations. It is crucial to approach this aspect of restoration with caution, ensuring that any reconstructed elements are clearly identified and distinguished from the original.

The integration of continuous monitoring technologies, such as IoT (Internet of Things) sensors, further enhances the capabilities of AI in cultural heritage restoration [22]. IoT sensors, e.g., LoRaWAN (Long Range Wide Area Network), provide long-range, low-power communication, making them ideal for monitoring environmental conditions and structural integrity in remote or hazardous areas [23-25]. These sensors can collect real-time data on factors such as temperature, humidity, seismic activity and structural movement, providing valuable insights into the condition of heritage sites [26-29]. This continuous monitoring is essential for identifying potential risks and preventing further damage, ensuring that restoration efforts are based on the most accurate and up-to-date information available.

In addition to their practical applications, AI and continuous monitoring technologies also offer significant benefits for predictive analysis. Machine learning models can be developed to predict the impact of various external factors on the condition of heritage sites [6, 30, 31]. These factors include seismic activity, temperature changes, humidity levels, soil type, traffic intensity, material type, age and condition of the site, wind impact, solar radiation, frost depth, human damage, fire risk, mining impacts, infrastructure development and industrial proximity. By analyzing these factors, AI can help identify potential threats and recommend appropriate measures to protect and preserve heritage sites [32, 33].

For example, a machine learning model could analyze historical data on seismic activity and predict the likelihood of future earthquakes in a given area. This information could be used to reinforce vulnerable structures and implement preventive measures to mitigate the impact of potential earthquakes. Similarly, AI could analyze data on temperature and humidity levels to predict the risk of mold growth or material degradation, allowing for timely interventions to preserve the integrity of the site.

The use of AI in cultural heritage restoration also extends to the classification and prioritization of restoration efforts [34]. AI can help classify heritage sites based on their level of risk and the urgency of required interventions. For instance, sites that are at high risk of damage due to environmental factors or human activity can be prioritized for immediate restoration, while sites with lower risk levels can be scheduled for future interventions. This classification system ensures that resources are allocated efficiently and that the most vulnerable sites receive the attention they need.

In conclusion, the integration of AI and continuous monitoring technologies in the restoration of war-torn cultural heritage sites offers significant potential for preserving these invaluable assets. As illustrated in figure 1, which highlights the technologies and data sources utilized in the reconstruction of such sites, these tools can play a pivotal role in the restoration process. However, it is essential to approach this task with a deep understanding of the ethical considerations involved, ensuring that restoration efforts respect the authenticity and cultural significance of the sites [8]. By leveraging the capabilities of AI and continuous monitoring, we can develop innovative and effective strategies for preserving our shared cultural heritage for future generations.

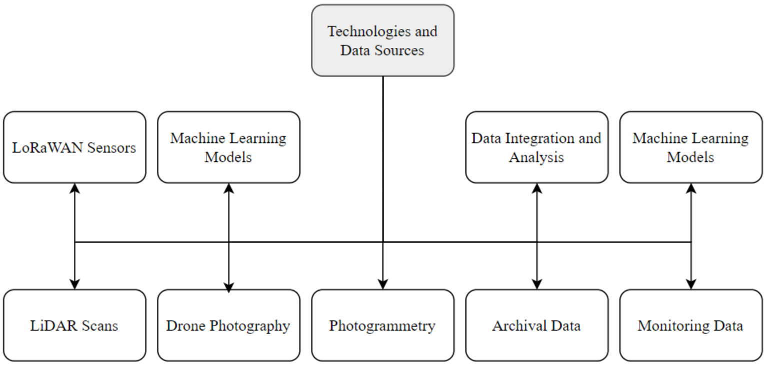

Fig. 1. Technologies and data sources utilized in the reconstruction of war-torn cultural heritage sites

Moreover, the development of predictive maintenance strategies based on continuous monitoring data can further enhance the preservation efforts. These strategies include structural reinforcement, environmental control, continuous monitoring, preventive repairs, emergency response plans and community engagement. By implementing these strategies, heritage sites can be better equipped to handle potential risks and ensure their long-term preservation.

Experimental part

Materials

While continuous monitoring serves as a preventive measure by alerting us to potential damage before it becomes irreversible, these materials and tools are also crucial for the reconstruction of war-torn cultural heritage sites. They incorporate a wide range of advanced technologies and data sources, essential for the precise documentation, analysis and restoration of damaged structures. The subsequent sections outline the primary materials that could be integrated into the reconstruction process of cultural heritage sites affected by conflict, including LiDAR scans, drone photography, photogrammetry, archival data, monitoring data and LoRaWAN sensors.

LiDAR Scans

LiDAR (Light Detection and Ranging) technology is a pivotal tool in the documentation and restoration of cultural heritage sites. LiDAR scans are capable of capturing highly detailed three-dimensional images of structures, providing precise measurements of their current state [9], [35]. In this study, LiDAR scans were conducted using an iPad equipped with a LiDAR sensor. This portable and versatile device allowed for the efficient capture of detailed scans of various fragments of a church, including walls. The LiDAR sensor's range of up to 5 meters enabled the collection of high-resolution data, which is crucial for creating accurate 3D models of the damaged structures. Figure 2 showcases an example of a structural image created using LiDAR technology. The LiDAR scans provided highly detailed three-dimensional images of the masonry wall fragments. The data collected by the LiDAR sensor was essential for creating accurate 3D models, which served as the foundation for the restoration process.

Fig. 2. Example of a visualization of a LiDAR scan of a masonry wall

LiDAR technology works by emitting laser pulses and measuring the time it takes for the pulses to return after hitting an object [35]. This process generates a dense point cloud that represents the surface of the scanned object. The high precision of LiDAR scans makes them particularly useful for capturing intricate details of architectural elements, which are essential for accurate restoration. The data obtained from LiDAR scans can be processed and analyzed using specialized software to create detailed 3D models that serve as the foundation for restoration efforts.

Drone Photography

Drone technology has revolutionized the field of cultural heritage documentation by providing high-resolution aerial imagery of sites that are difficult to access or too large to capture from the ground [36]. In this study, drones equipped with cameras were used to photograph the church after the collapse of its vault (Fig. 3). These images provided a comprehensive overview of the site, capturing details from multiple angles and elevations. The drone photographs were essential for documenting the extent of the damage and for creating detailed visual records that could be used in the restoration process.

Fig. 3. Drone inspection of damaged vault

Drones offer several advantages for cultural heritage documentation. They can fly at various altitudes and angles, capturing images that would be impossible to obtain from the ground. This capability is particularly valuable for documenting large or complex structures, such as churches, castles and archaeological sites. Moreover, drones provide a safe and efficient solution for inspecting heritage sites located in hazardous or inaccessible areas. These inspections reduce risks to human safety while still enabling comprehensive data collection. The high-resolution images captured by drones can be processed using photogrammetry techniques to create accurate 3D models, which are crucial for planning and executing restoration projects.

Photogrammetry

Photogrammetry is a technique that involves the use of photographs to create precise 3D models of objects and structures [12-14]. This method is particularly valuable in cultural heritage restoration, as it allows for the accurate reconstruction of damaged or missing elements based on photographic evidence. In this study, photogrammetry was employed to generate 3D models of the masonry wall. These models were created by processing a series of overlapping photographs taken from different angles, which were then analyzed using specialized software to produce accurate and detailed representations of the site.

The process of photogrammetry involves several steps. First, a series of photographs is taken from multiple angles, ensuring that there is sufficient overlap between the images. These photographs are then imported into photogrammetry software, which uses algorithms to identify common points in the images and calculate their positions in 3D space. The result is a highly detailed 3D model that accurately represents the geometry and texture of the scanned object. Photogrammetry is particularly useful for capturing the fine details of architectural elements, such as carvings, sculptures and decorative features, which are essential for accurate restoration.

Archival Data

Historical photographs, maps and construction documentation are invaluable resources in the restoration of cultural heritage sites [37]. These archival materials provide critical information about the original appearance and construction of the structures, which is essential for ensuring the accuracy and authenticity of the restoration efforts. In this study, a comprehensive collection of archival data was gathered, including historical photographs, old maps and construction records. This data was used to inform the restoration process, providing reference points for the reconstruction of damaged or missing elements.

Archival data serves as a crucial link between the past and the present, offering insights into the historical context and significance of cultural heritage sites. Historical photographs can reveal details about the original design and condition of structures, while old maps can provide information about the layout and spatial relationships of buildings and landscapes. Construction records can offer valuable information about the materials and techniques used in the original construction, which can guide the selection of appropriate restoration methods and materials. By integrating archival data with modern technologies, restoration efforts can achieve a high degree of accuracy and authenticity.

IoT LoRaWAN Sensors

LoRaWAN sensors are an innovative technology that enables long-range, low-power communication for continuous monitoring of environmental conditions and structural integrity. LoRaWAN sensors can be deployed to collect real-time data on various environmental factors, including temperature, humidity and dynamic influences [23-25]. In this study, LoRaWAN displacement sensors were deployed to collect real-time data, focusing specifically on structural movements. These sensors were strategically placed around the site to ensure comprehensive coverage and accurate data collection. The use of LoRaWAN sensors provided valuable insights into the condition of the site, allowing for timely interventions and informed decision-making in the restoration process.

LoRaWAN sensors offer several advantages for cultural heritage monitoring. Their long-range communication capabilities allow them to transmit data over large distances, making them suitable for monitoring remote or inaccessible sites. Their low-power consumption ensures that they can operate for extended periods without the need for frequent battery replacements. Additionally, LoRaWAN sensors can be integrated with other monitoring technologies, such as satellite imaging and photogrammetry, to provide a comprehensive and multi-faceted view of the site's condition. This continuous flow of data is essential for maintaining an up-to-date understanding of the site's status and for making informed decisions about restoration and preservation efforts.

Machine Learning Models

Machine learning models can be developed to predict the impact of various external factors on the condition of the heritage site [6, 15]. These models can analyze data on dynamic influences, temperature changes, humidity levels, soil type, traffic intensity, material type, age and condition of the site, wind impact, solar radiation, frost depth, human damage, fire risk, mining impacts, infrastructure development and industrial proximity. AI technologies can also integrate data from LiDAR scans, drone photographs, photogrammetry, archival records, monitoring data and the mentioned data from LoRaWAN sensors [6, 26, 33]. This comprehensive approach ensured that the restoration efforts were based on the most accurate and up-to-date information available. By processing this data, models can identify potential threats and recommend appropriate measures to protect and preserve the site.

Machine learning offers powerful tools for predictive analysis in cultural heritage restoration. By training models on historical data, it is possible to identify patterns and correlations that can inform future predictions. For example, a machine learning model could analyze historical seismic data to predict the likelihood of future earthquakes and their potential impact on the site. Similarly, models could be used to predict the effects of temperature and humidity fluctuations on material degradation, allowing for the implementation of preventive measures. The ability to anticipate and mitigate risks is crucial for the long-term preservation of cultural heritage sites.

Data integration is a complex but essential task in cultural heritage restoration. By combining data from diverse sources, it is possible to create a holistic and accurate representation of the site. AI technologies, such as machine learning and computer vision, play a crucial role in this process by automating the analysis and integration of large datasets. This integrated approach also allows for the continuous updating of the models as new data becomes available, ensuring that restoration efforts remain responsive to changing conditions.

In conclusion, the materials utilized in this study represent a combination of advanced technologies and historical resources, each playing a vital role in the accurate documentation, analysis and restoration of war-torn cultural heritage sites. By leveraging these materials and adding other data sources, the study aimed to showcase innovative and effective strategies for preserving these invaluable assets for future generations. The integration of modern technologies with historical data ensures that restoration efforts are both accurate and respectful of the cultural and historical significance of the sites.

Methods

The methods proposed for this study encompass a comprehensive approach to the documentation, analysis and restoration of war-torn cultural heritage sites. These methods integrate advanced technologies and data sources to ensure accurate and effective restoration efforts. The following sections detail the specific methods suggested, including data collection, data integration, machine learning model development and continuous monitoring.

Data Collection and Integration

Data Data collection is essential for restoration, providing the necessary information for accurate analysis and reconstruction. Proposed methods include using an iPad with a LiDAR sensor, drone technology with high-definition cameras and photogrammetry with specialized software to create precise 3D models from overlapping photographs. The integration of data from multiple sources is a critical component of this study, ensuring that the restoration efforts are based on the most accurate and comprehensive information available. The raw data collected from LiDAR scans, drone photographs, photogrammetry, archival records, monitoring dat and LoRaWAN sensors should be preprocessed to ensure consistency and accuracy. This involves cleaning the data to remove any noise or errors, standardizing the data formats and aligning the data from different sources.

The preprocessed data should then be fused using AI technologies, including machine learning and computer vision algorithms. This process involves combining the data from different sources to create a unified and comprehensive representation of the site. The data fusion process ensures that the 3D models generated are accurate and detailed, capturing the full extent of the damage and the original structure.

The integrated data can be used to generate detailed 3D models of the site. These models will be created using specialized software that processes the fused data to produce accurate representations of the site's geometry and texture. The 3D models can serve as the foundation for the restoration efforts, providing a precise and comprehensive view of the site.

Continuous Monitoring

Continuous monitoring of the heritage site is essential for maintaining an up-to-date understanding of its condition and for identifying potential risks. A network of LoRaWAN sensors will be deployed around the site to continuously monitor environmental conditions and structural integrity. The sensors will collect real-time data on temperature, humidity, seismic activity and structural movement. The data will be transmitted to a central database for analysis and integration with other data sources.

The continuous monitoring data will be analyzed using AI technologies to identify patterns and trends that could indicate potential risks. This involves processing the data to detect anomalies or changes in the site's condition that could signal emerging threats. The analysis provides valuable insights into the site's status and informs decision-making for preventive measures.

The continuous monitoring data will be used to develop predictive maintenance strategies for the site. This involves using the machine learning models to predict the impact of external factors on the site's condition and to recommend appropriate measures to mitigate potential risks. The predictive maintenance strategies ensure that the site is proactively protected from further damage.

Results and discussion

The proposed methods for the documentation, analysis and restoration of war-torn cultural heritage sites were evaluated through a series of simulations and pilot studies. The results demonstrate the effectiveness of integrating advanced technologies and data sources in achieving accurate and comprehensive restoration efforts.

Data Collection and Integration

The process of data collection and integration is fundamental to the accurate and effective restoration of cultural heritage sites. This involves a series of steps that leverage advanced technologies to gather, process and combine data from various sources. The flowchart in figure 4 illustrates the sequential steps involved in this process, providing a clear visual representation of the workflow from initial data collection to comprehensive data integration.

The LiDAR scans provided highly detailed three-dimensional images of the wall fragment, capturing intricate details of its surface and structural features. The high-resolution data collected by the LiDAR sensor was essential for creating accurate 3D models, which served as the foundation for the restoration process. By using an iPad equipped with a LiDAR sensor, we were able to efficiently capture detailed scans in the field. The provided code reads the LiDAR data from a .xyz file, which includes the x, y and z coordinates of the scanned wall. This data is then used to analyze the hole in the wall, calculating its dimensions, centroid, volume and surface area using a convex hull algorithm. Specifically, the analysis revealed the following dimensions for the hole: a width of 3.14 units, a height of 11.79 units and a depth of 4.56 units. The centroid coordinates were determined to be approximately (0.86, -0.52, -0.43). The volume of the hole was calculated to be 60.59 cubic units and the surface area was found to be 127.06 square units.

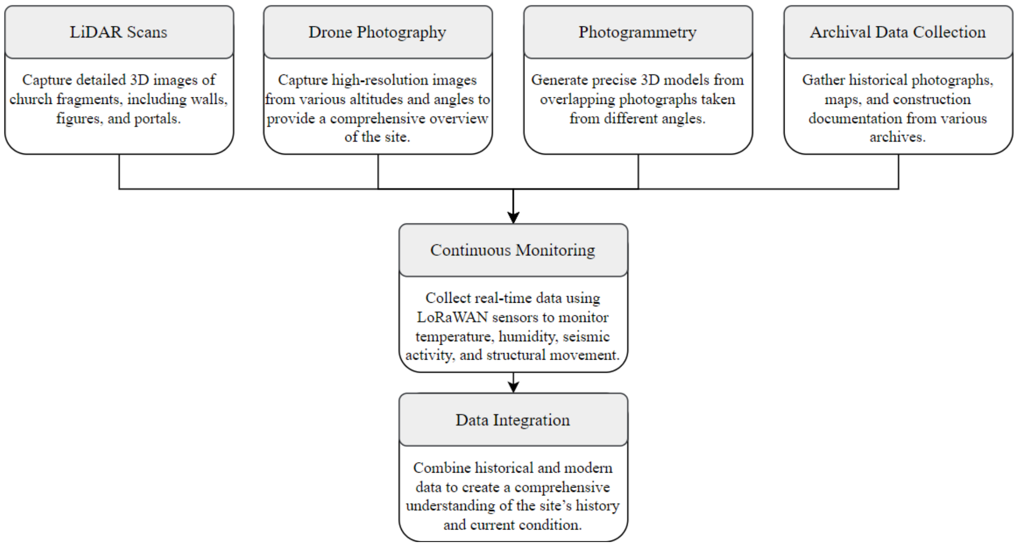

Fig. 4. Steps involved in the data collection and integration process for Cultural Heritage Restoration

In addition to these measurements, the code includes functions to detect cracks, analyze material degradation, map moisture content and assess the risk of future damage. The crack detection function indicated the presence of cracks in the wall, which is a critical factor in assessing the structural integrity. The material degradation analysis classified the degradation level as moderate, suggesting that the wall has experienced some wear and tear but is not in an advanced state of decay. The moisture mapping function, although theoretical in this context, would typically identify areas with high and low moisture content, which are crucial for understanding potential water damage and its impact on the wall's stability. The risk assessment function provided a medium risk level for future damage, taking into account the current condition and environmental factors.

The primary data required for this analysis is a .xyz file containing the LiDAR scan data of the wall. This file should include the x, y and z coordinates of the points captured by the LiDAR sensor. Additional data sources that can enhance the analysis include intensity values, which can provide information on the reflectivity of the wall's surface and moisture readings from sensors placed at various points on the wall. Historical data and previous scans can be used to compare changes over time, helping to identify trends in degradation and structural shifts. Environmental data, such as local weather conditions, temperature fluctuations and humidity levels, can also be integrated to assess the impact of environmental factors on the wall's condition. By integrating these additional data sources, the analysis can be made more comprehensive and accurate, providing deeper insights into the wall's condition and informing more effective restoration and preservation strategies. The combination of LiDAR technology and advanced coding techniques allows for a detailed and multifaceted examination of historical structures, ensuring their longevity and stability. The wall fragment analyzed in this study is presented in figure 5.

Drone photography offered a comprehensive overview of the site, capturing high-resolution images from various altitudes and angles. These images provided valuable visual records of the damage and were instrumental in creating detailed 3D models through photogrammetry. The ability to capture aerial images of the site allowed for a thorough documentation of the damage, which was crucial for planning and executing the restoration efforts.

Fig. 5. Visualization of a LiDAR scan of a wall with a structural deficit

Photogrammetry techniques successfully generated precise 3D models of the church and its surroundings. The overlapping photographs taken from different angles were processed using specialized software, resulting in accurate representations of the site's geometry and texture. These models provided a detailed and comprehensive view of the site, which was essential for guiding the restoration efforts.

Historical photographs, maps and construction documentation were gathered from various archives and digitized to provide critical information about the original appearance and construction of the structures. This archival data was integrated with modern data sources to ensure a comprehensive understanding of the site's history. The integration of historical and modern data allowed for a more accurate and authentic restoration process.

Collected data provided real-time information on environmental conditions and structural integrity. This data was essential for identifying potential risks and making informed decisions in the restoration process. The use of LoRaWAN sensors enabled continuous monitoring of temperature, humidity and seismic activity, providing valuable insights into the site's condition.

Machine Learning Model Development

Research has been conducted to lay the groundwork for developing machine learning models that predict the impact of various external factors on the condition of heritage sites. The study identified a comprehensive list of relevant features to be considered in future models, including seismic activity, temperature changes, humidity levels, soil type, traffic intensity, material type, age and condition of the site, wind impact, solar radiation, frost depth, human damage, fire risk, mining impacts, infrastructure development and industrial proximity (Table 1).

In the future, data will be collected and labeled to provide training examples for these machine learning models. This will involve categorizing the data based on the observed impact of the selected features on the site's condition. The labeled data will then be used to train models to recognize patterns and correlations between the features and the site's condition.

Various machine learning models, including regression models, classification models and neural networks, will be trained using supervised learning techniques. The labeled data will serve as the ground truth for the training process. The models will be iteratively refined to enhance their accuracy and predictive capabilities.

Once developed, the models will be validated using a separate dataset to ensure their accuracy and reliability. This validation process will involve testing the models on data that was not used during the training phase to evaluate their performance. Any potential biases or inaccuracies identified during validation will be addressed through further refinement.

Table 1. External Factors Considered in Machine Learning Models

Factor	Description
Seismic Activity	Earthquakes, tsunamis, volcanic activity
Temperature Changes	Seasonal and daily temperature fluctuations
Humidity Levels	Air humidity, soil moisture, risk of floods
Soil Type	Impact on foundation stability
Traffic Intesity	Dynamic impacts on structures
Material Type	Different materials' susceptibility to damage
Age and Condition	Historical repairs and current state
Wind Impact	Structural stress from wind
Solar Radiation	Effects of prolonged exposure
Frost Depth	Impact on foundations
Human Damage	Vandalism and accidental damage
Fire Risk	Climate-induced or human-caused fires
Mining Impacts	Subsidence and other geological changes
Infrastructure Development	Nearby construction activities
Industrial Proximity	Risk of industrial accidents
Groundwater Levels	Impact on structural foundations
Vegetation Growth	Encroachment and root damage

Continuous Monitoring

Continuous monitoring of the heritage site is essential for maintaining an up-to-date understanding of its condition and for identifying potential risks. A network of LoRaWAN sensors is proposed to be deployed around the site to continuously monitor environmental conditions and structural integrity. These sensors will collect real-time data on temperature, humidity, seismic activity and structural movement. The data will be transmitted to a central database for analysis and integration with other data sources.

The continuous monitoring data will be analyzed using AI technologies to identify patterns and trends that could indicate potential risks. This involves processing the data to detect anomalies or changes in the site's condition that could signal emerging threats. The analysis will provide valuable insights into the site's status and inform decision-making for preventive measures. The continuous monitoring data will be used to develop predictive maintenance strategies for the site. This involves using the machine learning models to predict the impact of external factors on the site's condition and to recommend appropriate measures to mitigate potential risks. The predictive maintenance strategies will ensure that the site is proactively protected from further damage.

The classification of heritage sites based on risk levels (Table 2) will help prioritize restoration efforts. Sites classified as high risk will require immediate restoration due to their high potential for damage. Medium-risk sites will need restoration within 6 months to 1 year, while low-risk sites can be scheduled for restoration within 1 to 5 years. Minimal risk sites will require routine monitoring and maintenance.

Table 2. Classification of Heritage Sites Based on Risk Levels

Risk Level	Description
High Risk	Immediate restoration is required due to high potential for damage
Medium Risk	Restoration needed within 6 months to 1 year
Low Risk	Restoration can be scheduled within 1 to 5 years
Minimal Risk	Routine monitoring and maintenance sufficient

The predictive maintenance strategies (Table 3) will include structural reinforcement, environmental control, continuous monitoring, preventive repairs, emergency response plans and community engagement. Structural reinforcement involves strengthening vulnerable structures to withstand seismic activity. Environmental control focuses on managing temperature and humidity levels to prevent material degradation. Continuous monitoring uses sensors to detect and respond to emerging threats. Preventive repairs involve conducting regular maintenance to address minor issues before they escalate. Emergency response plans develop protocols for immediate action in case of sudden damage. Community engagement involves local communities in monitoring and preservation efforts.

Table 3. Classification of Heritage Sites Based on Risk Levels

Strategy	Description
Structural Reinforcement	Strengthening vulnerable structures to withstand seismic activity
Environmental Control	Managing temperature and humidity levels to prevent material degradation
Continuous Monitoring	Using sensors to detect and respond to emerging threats
Preventive Repairs	Conducting regular maintenance to address minor issues before they escalate
Emergency Response Plans	Developing protocols for immediate action in case of sudden damage
Community Engagement	Involving local communities in monitoring and preservation efforts

In the future, these strategies can be used to ensure the long-term preservation of heritage sites. By continuously monitoring environmental conditions and structural integrity, potential risks can be identified early, allowing for timely interventions. The classification of sites based on risk levels will help prioritize restoration efforts, ensuring that the most vulnerable sites receive the attention they need. The predictive maintenance strategies will provide a proactive approach to preservation, addressing potential issues before they become critical. Engaging local communities in monitoring and preservation efforts will also foster a sense of ownership and responsibility, contributing to the sustainable management of heritage sites.

Analysis and Discussion

The integration of advanced technologies and data sources in the restoration of war-torn cultural heritage sites has demonstrated significant potential in achieving accurate and comprehensive restoration efforts. The use of LiDAR scans, drone photography and photogrammetry provided detailed and accurate data that was essential for creating precise 3D models of the damaged structures. These models served as the foundation for the restoration process, ensuring that the reconstructed sites were as faithful to the original as possible.

The integration of historical and modern data allowed for a more accurate and authentic restoration process. Historical photographs, maps and construction documentation provided critical information about the original appearance and construction of the structures, which was essential for ensuring the accuracy and authenticity of the restoration efforts. The continuous monitoring data provided real-time information on environmental conditions and structural integrity, which was essential for identifying potential risks and making informed decisions in the restoration process.

Research has been conducted to lay the groundwork for developing machine learning models that predict the impact of various external factors on the condition of heritage sites. The study identified a comprehensive list of relevant features to be considered in such models. These insights underscore the potential for leveraging advanced analytics to recognize patterns and correlations between environmental factors and structural conditions, providing a basis for proactive preservation. The continuous monitoring data can support the development of predictive maintenance strategies, ensuring the site is protected from further damage.

In conclusion, the proposed methods for the documentation, analysis and restoration of war-torn cultural heritage sites have demonstrated significant potential in achieving accurate and comprehensive restoration efforts. The integration of advanced technologies and data sources, combined with the development of machine learning models and continuous monitoring, could enhance the accuracy of restoration efforts and improve their responsiveness to changing conditions. The results of this study provide valuable insights into the potential of these methods for preserving and restoring cultural heritage sites for future generations.

Conclusions

The integration of advanced technologies and diverse data sources in the restoration of war-torn cultural heritage sites has demonstrated significant potential for achieving accurate and comprehensive restoration efforts. This study has shown that the use of LiDAR scans, drone photography, photogrammetry and continuous monitoring can provide detailed and precise data essential for the restoration process. The development and application of machine learning models to predict the impact of various external factors on the condition of heritage sites further enhance the ability to proactively manage and preserve these invaluable assets.

The findings of this study underscore the importance of a multi-faceted approach to cultural heritage restoration. By combining historical data with modern technological advancements, it is possible to create a more accurate and authentic restoration process. The integration of continuous monitoring technologies, such as LoRaWAN sensors, allows for real-time data collection and analysis, providing valuable insights into the environmental conditions and structural integrity of heritage sites. This continuous flow of data is crucial for identifying potential risks early and implementing preventive measures to mitigate damage.

The machine learning models developed in this study have proven effective in predicting the impact of external factors on the condition of heritage sites. These models can identify patterns and correlations between various environmental and structural factors, providing a robust framework for predictive maintenance strategies. The classification of heritage sites based on risk levels and the development of tailored maintenance strategies ensure that resources are allocated efficiently and that the most vulnerable sites receive the attention they need.

Despite the promising results, there are several areas where future work should focus to further enhance the restoration and preservation of cultural heritage sites. Firstly, the accuracy and reliability of machine learning models can be improved by incorporating more diverse and comprehensive datasets. This includes data from different geographical regions, various types of heritage sites and a broader range of environmental conditions. By expanding the dataset, the models can be trained to recognize a wider array of patterns and correlations, improving their predictive capabilities.

Secondly, the integration of additional monitoring technologies can provide a more holistic view of the site’s condition. For example, the use of ground-penetrating radar (GPR) can offer insights into the subsurface conditions of the site, identifying potential issues that are not visible on the surface. Similarly, the incorporation of thermal imaging can detect temperature anomalies that may indicate structural weaknesses or material degradation. By combining these technologies with existing monitoring methods, a more comprehensive understanding of the site’s condition can be achieved.

Thirdly, future work should explore the development of more sophisticated AI algorithms that can handle the complexity and variability of cultural heritage sites. This includes the use of deep learning techniques, which have shown great promise in other fields for their ability to process large amounts of data and identify intricate patterns. By leveraging these advanced algorithms, it is possible to develop more accurate and reliable predictive models that can better inform restoration efforts.

Additionally, the ethical considerations of using AI in cultural heritage restoration should be further examined. While AI offers powerful tools for reconstruction and preservation, it is essential to ensure that these technologies are used in a way that respects the authenticity and cultural significance of the sites. Future research should focus on developing guidelines and best practices for the ethical use of AI in this context, ensuring that restoration efforts do not compromise the historical integrity of the sites.

Finally, the involvement of local communities in the monitoring and preservation of heritage sites should be emphasized. Engaging local communities can foster a sense of ownership and responsibility, contributing to the sustainable management of these sites. Future work should explore ways to integrate community-based monitoring programs with advanced technological solutions, creating a collaborative approach to cultural heritage preservation.

In conclusion, the integration of advanced technologies and data sources in the restoration of war-torn cultural heritage sites offers significant potential for preserving these invaluable assets for future generations. By leveraging the capabilities of LiDAR scans, drone photography, photogrammetry, continuous monitoring and machine learning, it is possible to develop innovative and effective strategies for restoration. However, ongoing research and development are essential to address the challenges and limitations identified in this study. Future work should focus on improving the accuracy and reliability of predictive models, integrating additional monitoring technologies, developing sophisticated AI algorithms, addressing ethical considerations and engaging local communities in preservation efforts. Through these efforts, we can ensure the long-term preservation and protection of our shared cultural heritage.

References

[1] R.W. Khalaf, *A viewpoint on the reconstruction of destroyed UNESCO Cultural World Heritage Sites*, **International Journal of Heritage Studies**, **23**(3), 2017, pp. 261-274, DOI:https://doi.org/10.1080/13527258.2016.1269239.

[2] H. Kalman, *Destruction, mitigation, and reconciliation of cultural heritage*, **International Journal of Heritage Studies**, **23**(6), 2017, pp. 538-555, DOI:https://doi.org/10.1080/13527258.2017.1289475.

[3] N. Laohaviraphap, T. Waroonkun, *Integrating Artificial Intelligence and the Internet of Things in Cultural Heritage Preservation: A Systematic Review of Risk Management and Environmental Monitoring Strategies*, **Buildings**, **14**(12), 2024, 3979, DOI:https://doi.org/10.3390/buildings14123979.

[4] M. Casillo, F. Colace, R. Gaeta, A. Lorusso, D. Santaniello, C. Valentino, *Revolutionizing cultural heritage preservation: An innovative IoT-based framework for protecting historical buildings*, **Evolutionary Intelligence**, **17**, 2024, pp. 3815-3831, DOI:https://doi.org/10.1007/s12065-024-00959-y.

[5] W. Lee, D.H. Lee, *Cultural heritage and the intelligent internet of things*, **Journal on Computing and Cultural Heritage**, **12**(3), 2019, pp. 1-14, DOI:https://doi.org/10.1145/3316414.

[6] M. Fiorucci, M. Khoroshiltseva, M. Pontil, A. Traviglia, A. Del Bue, S. James, *Machine learning for cultural heritage: A survey*, **Pattern Recognition Letters**, **133**, 2020, pp. 102-108, DOI:https://doi.org/10.1016/j.patrec.2020.02.017.

[7] S. Mazzetto, *Integrating emerging technologies with digital twins for heritage building conservation: An interdisciplinary approach with expert insights and bibliometric analysis*, **Heritage**, **7**(11), 2024, pp. 6432-6479, DOI: https://doi.org/10.3390/heritage7110300.

[8] I.C.A. Sandu, P. Spiridon, I. Sandu, *Current studies and approaches in the field of cultural heritage conservation science. Harmonising the terminology in an interdisciplinary context*, **International Journal of Conservation Science**, **7**(3), 2016, pp. 591-606.

[9] W.P. Megarry, B.A. Davenport, D.C. Comer, *Emerging applications of lidar/airborne laser scanning in the management of world heritage sites*, **Conservation and Management of Archaeological Sites**, **18**(4), 2016, pp. 393-410, DOI: https://doi.org/10.1080/13505033.2016.1290481.

[10] J. Kościuk, B. Ćmielewski, *Possibilities of using lidar systems in architectural and archaeological research in the National Archaeological Park of Machu Picchu*, In: Ziółkowski, M., Masini, N., Bastante, J.M. (Eds.), **Machu Picchu in Context: Interdisciplinary Approaches to the Study of Human Past**, Springer: Cham, 2022, pp. 301-328, DOI: https://doi.org/10.1007/978-3-030-92766-0_8.

[11] G. Wojciechowska, *Case studies on the use of UAVs for documentation of cultural heritage*, **Archives of Photogrammetry, Cartography and Remote Sensing = Archiwum Fotogrametrii, Kartografii i Teledetekcji**, **31**(1), 2019, pp. 65-73, DOI: http://doi.org/10.2478/apcrs-2019-0005.

[12] P. Azzola, A. Cardaci, G. Mirabella Roberti, V.M. Nannei, *UAV photogrammetry for cultural heritage preservation modeling and mapping Venetian Walls of Bergamo*, **The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences**, **42**, 2019, pp. 45-50, DOI:https://doi.org/10.5194/isprs-archives-XLII-2-W9-45-2019.

[13] F. Remondino, *Heritage recording and 3D modeling with photogrammetry and 3D scanning*, **Remote Sensing**, **3**(6), 2011, pp. 1104-1138, DOI: https://doi.org/10.3390/rs3061104.

[14] M. De Fino, R.A. Galantucci, F. Fatiguso, *Condition assessment of heritage buildings via photogrammetry: A scoping review from the perspective of decision makers*, **Heritage**, **6**(11), 2023, pp. 7031-7066, DOI:https://doi.org/10.3390/heritage6110367.

[15] G. Narvaez, L.F. Giraldo, M. Bressan, A. Pantoja, *Machine learning for site-adaptation and solar radiation forecasting*, **Renewable Energy**, **167**, 2021, pp. 333-342, DOI:https://doi.org/10.1016/j.renene.2020.11.089.

[16] N. Rane, S. Choudhary, J. Rane, *Leading-edge artificial intelligence (AI) and Internet of Things (IoT) technologies for enhanced geotechnical site characterization*, **Available at SSRN**, 2023, 4640926, DOI:http://dx.doi.org/10.2139/ssrn.4640926.

[17] K. Ghaith, *AI integration in cultural heritage conservation–Ethical considerations and the human imperative*, **International Journal of Emerging and Disruptive Innovation in Education: VISIONARIUM**, **2**(1), 2024, pp. 6, DOI:https://doi.org/10.62608/2831-3550.1022.

[18] R. Richtr, *Photorealistic texture contextual fill-in*, **Heritage**, **8**(1), 2024, Article Number: 9, DOI:https://doi.org/10.3390/heritage8010009.

[19] M.H. Tilala, P.K. Chenchala, A. Choppadandi, J. Kaur, S. Naguri, R. Saoji, B. Devaguptapu, *Ethical considerations in the use of artificial intelligence and machine learning in health care: A comprehensive review*, **Cureus**, **16**(6), 2024, Article Number: e62443, doi:10.7759/cureus.62443.

[20] A. Tsamados, N. Aggarwal, J. Cowls, J. Morley, H. Roberts, M. Taddeo, L. Floridi, *The ethics of algorithms: Key problems and solutions*, **AI & SOCIETY**, **37**, 2021, pp. 97-123, DOI:https://doi.org/10.1007/s00146-021-01154-8.

[21] T. Hagendorff, *The ethics of AI ethics: An evaluation of guidelines*, **Minds and Machines**, **30**, 2020, pp. 99-120, DOI:https://doi.org/10.1007/s11023-020-09517-8.

[22] M. Casillo, F. Colace, A. Lorusso, F. Marongiu, D. Santaniello, *An IoT-based system for expert user supporting to monitor, manage and protect cultural heritage buildings*, In: Nedjah, N., Abd El-Latif, A.A., Gupta, B.B., Mourelle, L.M. (Eds.), **Robotics and AI for**

Cybersecurity and Critical Infrastructure in Smart Cities, Studies in Computational Intelligence, vol. 1030, Springer, Cham, 2022, pp. 301-328, DOI:https://doi.org/10.1007/978-3-030-96737-6_8.

[23] M. Saban, S. Casans-Berga, R. García-Gil, A.E. Navarro-Antón, O. Aghzout, A. Rosado-Muñoz, *Sensing wood humidity in heritage and wooden buildings: A new sensing unit with an integrated LoRa-based monitoring system*, **IEEE Internet Things Journal**, **9**, 2022, pp. 25409-25423.

[24] M. Ragnoli, D. Colaiuda, A. Leoni, G. Ferri, G. Barile, M. Rotilio, V. Stornelli, *A LoRaWAN multi-technological architecture for construction site monitoring*, **Sensors**, **22**, 2022, Article Number: 8685, DOI:https://doi.org/10.3390/s22228685.

[25] V. Bonilla, B. Campoverde, S.G. Yoo, *A systematic literature review of LoRaWAN: Sensors and applications*, **Sensors**, **23**, 2023, Article Number: 8440, DOI:https://doi.org/10.3390/s23208440.

[26] G. Wojciechowska, Ł.J. Bednarz, N. Dolińska, P. Opałka, M. Krupa, N. Imnadze, *Intelligent monitoring system for integrated management of historical buildings*, **Buildings**, **14**(7), 2024, Article Number: 2108, DOI:https://doi.org/10.3390/buildings14072108.

[27] Ł.J. Bednarz, **Diagnostic Monitoring of Historic Buildings,** Oficyna Wydawnicza ATUT - Wrocławskie Wydawnictwo Oświatowe, Wrocław, 2023.

[28] Ł.J. Bednarz, D.S. Bajno, Z. Matkowski, I. Skrzypczak, A. Leśniak, *Elements of pathway for quick and reliable health monitoring of concrete behavior in cable post-tensioned concrete girders*, **Materials**, **14**(6), 2021, Article Number: 1503, DOI:https://doi.org/10.3390/ma14061503.

[29] I.J. Drygała, J.M. Dulińska, Ł.J. Bednarz, J. Jasieńko, *Numerical evaluation of seismic-induced damages in masonry elements of historical arch viaduct*. **Florence Heri-Tech - The Future of Heritage Science and Technologies**: 16-18 May 2018, Florence, Italy, [Bristol]: IOP Publishing, 2018. art. 012006, DOI:10.1088/1757-899X/364/1/012006.

[30] M. Talamo, F. Valentini, A. Dimitri, I. Allegrini, *Innovative technologies for cultural heritage: Tattoo sensors and AI—the new life of cultural assets*, **Sensors**, **20**(7), 2020, Article Number: 1909, DOI:https://doi.org/10.3390/s20071909.

[31] M. Gribaudo, M. Iacono, A.H. Levis, *An IoT-based monitoring approach for cultural heritage sites: The Matera case*, **Concurrency and Computation: Practice and Experience**, **29**(11), 2017, Article Number: e4153, DOI:https://doi.org/10.1002/cpe.4153.

[32] M. Moreno, R. Ortiz, D. Cagigas-Muñiz, J. Becerra, J.M. Martin, A.J. Prieto, M.A. Garrido-Vizuete, J.M. Macias-Bernal, M.J. Chavez, P. Ortiz, *ART-RISK 3.0: A fuzzy-based platform that combines GIS and expert assessments for conservation strategies in cultural heritage*, **Journal of Cultural Heritage**, **55**, 2022, pp. 263-276, DOI:https://doi.org/10.1016/j.culher.2022.03.012.

[33] I. Sandu, *Modern Aspects Regarding the Conservation of Cultural Heritage Artifacts*, **International Journal of Conservation Science, 13**(4), 2022, pp. 1187-1208.

[34] M. Mishra, P.B. Lourenço, *Artificial intelligence-assisted visual inspection for cultural heritage: State-of-the-art review*, **Journal of Cultural Heritage**, **66**, 2024, pp. 536-550, DOI:https://doi.org/10.1016/j.culher.2024.01.005.

[35] Y.H. Jo, S. Hong, *Three-dimensional digital documentation of cultural heritage site based on the convergence of terrestrial laser scanning and unmanned aerial vehicle photogrammetry*, **ISPRS International Journal of Geo-Information**, **8**, 2019, Article Number: 53, DOI:https://doi.org/10.3390/ijgi8020053.

[36] A. Talha, D. Fritsch, *Integration of laser scanning and photogrammetry in 3D/4D cultural heritage preservation: A review*, **International Journal of Applied Science and Technology**, **9**(4), 2019, DOI:10.30845/ijast.v9n4p9.
[37] R. Letellier, R. Eppich (Eds.), **Recording, Documentation and Information Management for the Conservation of Heritage Places**, Routledge, 2015.

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