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Digital preservation of endangered cultural heritage in conflict zones

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Abstract. The study aimed to explore the role of digital technologies in preserving cultural heritage in conflict zones, ensuring the safety of historical and cultural identity amid warfare. The study examined the risks and digital solutions for preserving both tangible and intangible legacies during armed conflicts. Challenges arising from unstable environments, scarce technical resources, and disrupted infrastructure that hinder the use of methods such as 3D scanning, remote sensing, and digital modelling to document and reconstruct damaged sites were addressed. Ethical concerns regarding ownership and informed consent were evaluated alongside logistical issues resulting from geopolitical constraints and fragmented collaboration among local communities, governments, and international agencies. Case studies from Syria, Afghanistan, Mali, and Ukraine illustrated the application of digital tools for heritage documentation and recovery under adverse conditions. Technological innovations, including blockchain-based provenance tracking, edge computing for local data processing, decentralised storage networks, and AI-assisted predictive risk mapping, were discussed as strategies to secure and maintain digital records. The findings demonstrated that despite technical and geopolitical barriers, local stakeholders have demonstrated remarkable adaptability by using low-cost, open-source tools to continue documentation efforts. Community engagement emerged as a key enabler in digital preservation, with grassroots initiatives often leading data collection and storytelling. International partnerships were most effective, when they supported, not supplanted, local agency. Additionally, respondents emphasised the urgent need for sustainable digital infrastructure and culturally sensitive data governance models. The study also considered relevant international legal frameworks that supported proactive preservation efforts. Lastly, it advocated for integrated digital approaches that combined technological advances with community participation to protect cultural assets and support recovery efforts in conflict-affected regions, ensuring their enduring preservation

Keywords: digital modelling; decentralised storage; heritage documentation; 3D modelling; remote sensing; international law

Introduction

The challenges of digital preservation in conflict zones are complex, encompassing technical, ethical, and logistical dimensions. Technically, the unstable conditions typical of conflict environments often hinder access to necessary equipment and complicate data storage. M. Rahimi (2024) noted that although HBIM and 3D scanning offer significant potential for reconstructing damaged sites, they required specialised tools and training that were often unavailable in war-torn regions. A.Z. Sampaio *et al.* (2021) emphasised the difficulties in implementing digital documentation methods caused by the poor infrastructure and limited professional capacity on-site. According to A. Zerbini (2018), unstable internet and electricity networks made it difficult to reliably store, transmit, or manage digital data, increasing the risk of irretrievable loss during armed conflict. Ethically, digital preservation initiatives must navigate complex issues of ownership, authority, and informed

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consent. Moreover, studies examined the Endangered Archaeology in the Middle East and North Africa (EAMENA) project, which combined satellite imaging with historical mapping to track at-risk heritage sites. The project's success, however, was contingent on effective collaboration between governments, non-governmental organisations, and local actors. R. Alcala (2022) highlighted the importance of including local voices in preservation planning, as communities have deep cultural ties to the heritage in question. Without their consent and active participation, preservation efforts risk perpetuating a form of digital colonialism. L. Kelly (2021) observed that externally driven initiatives often failed, when they overlooked or undervalued indigenous knowledge systems. These ethical concerns were not merely theoretical; it influenced the legitimacy and long-term sustainability of digital preservation projects. Furthermore, the author noted that legal protections were only effective alongside local cooperation and long-term investment in preservation infrastructure. Logistically, digital heritage in conflict zones was constrained by fragmented governance and access issues. L. Rayne *et al.* (2017) observed that such collaborations were often undermined by differing agendas, a lack of trust, or ongoing instability. P. Jakubowski (2019) noted that bureaucratic delays and shifting political alliances further obstruct preservation efforts, especially, when operating across borders or within regions lacking centralised authority.

Digital technologies offer new opportunities, but also new vulnerabilities. X. Zhang *et al.* (2022) demonstrated that digital platforms can democratise access to cultural heritage, enabling global audiences to engage with endangered sites. Similarly, Y. Choi *et al.* (2021) argued that immersive tools such as virtual and augmented reality can reconstruct heritage environments with in high detail, fostering education and awareness. R. Alcala (2022) stated that over-reliance on digital formats introduced sustainability risks, especially as platforms evolved and older data formats became obsolete. These risks were compounded in conflict zones, where maintaining and updating digital systems was often impractical. Legal frameworks provided essential guidance for the protection of heritage in war. G. Baj (2021) evaluated the impact of United Nations Security Council Resolution 2347, which urged states to adopt proactive measures for cultural heritage protection. While symbolically significant, its real-world impact remained limited due to the uneven commitment of member states and the absence of enforcement mechanisms. T.G. Weiss & N. Connelly (2018) examined the legal gap concerning non-state actors, who frequently disregard international norms and pose one of the greatest threats to cultural property during armed conflict.

The study aimed to evaluate how emerging digital technologies, when supported by ethical practices, collaborative logistics, and legal protections, can form an integrated strategy for safeguarding cultural heritage in conflict zones. The study also highlighted the importance of adapting these tools to the complex and rapidly changing conditions characteristic of modern warfare.

Literature Review

Cultural heritage reflected the ways of life cultivated by a community and transmitted through generations. E. Macrì & C.L. Crsistofaro (2021) noted that it encompassed customs, practices, locations, objects, artistic expressions, and values. This element was essential in showcasing the spiritual and intellectual richness of a specific civilisation, society, or nation, as well as contributing to an individual's identity. Cultural heritage can be divided into three main categories: immovable heritage, which included monuments and archaeological sites; movable heritage, comprising items such as sculptures, paintings, manuscripts, artefacts, and other objects of historical importance; and intangible heritage, which referred to traditions, knowledge, and artistic expressions such as music, dance, language, and folklore that were transmitted across generations.

Digital technologies were a vital resource, enabling precise data collection that upholds authenticity and integrity. Z. Ye (2024) noted that advanced high-definition scanning and modelling technologies was substantial in the prevention and intervention efforts for the conservation and restoration of cultural heritage. Since the 20th century, digital technologies were central in the cultural sector. T. Gorbul & S. Rusakov (2022) emphasised that during the latter half of the century digital technologies became instrumental in cataloguing, organising, and digitising sources and artefacts of historical and cultural significance. The convergence of culture and technology has created an intriguing and complex realm referred to as digital heritage. As societies globally face the challenges of preserving their rich cultural legacies, the integration of digital tools and technologies offers both remarkable opportunities and distinct obstacles. M. Sofilkanych (2022) noted that a comprehensive framework aimed at unifying advancements in innovation was currently emerging within modern scientific discussions. U. Maraieva (2022) suggested that this paradigm saw technologies as tools, with information acting as a connecting force among humans, society, nature, and technology.

Consequently, the incorporation of technology and information within this broader framework aimed to promote a comprehensive approach to advancement, highlighting the relationships and mutual reliance of different components in the modern, dynamic social and scientific landscape. In conflict zones, cultural heritage was particularly vulnerable to acts of deliberate destruction and looting. These actions were often used as strategic means in warfare to weaken the morale and identity of targeted populations. E. Cunliffe & L. Curini (2018) investigated the systematic

destruction of cultural heritage in conflict zones and described how such acts were used not merely as collateral damage, but as intentional methods to erase cultural identity. The study highlighted examples from Syria, Iraq, and other conflict-affected areas, where historic monuments and religious sites were specifically targeted. The study underlined the importance of timely digital documentation and the role of remote sensing technologies in capturing and preserving cultural data amid conflict. L. Hajibayova (2019) addressed the preservation of cultural memory through digital platforms, particularly emphasising the ethical dimensions of who gets to document and how heritage was represented. The author advocated for community-centred approaches that empower local populations to take part in digital preservation efforts. This study warned against top-down documentation practices that can distort or omit cultural context, stressing the need for inclusive methods that respect the diversity and complexity of local narratives. Both studies highlighted how heritage destruction in conflict zones was a deliberate and culturally devastating tactic. While E. Cunliffe & L. Curini (2018) emphasised the urgency of documentation, L. Hajibayova (2019) highlighted the need for participatory and ethical frameworks to guide digital preservation. Together, these perspectives underscored the necessity of rapid yet culturally informed responses to protect heritage under threat.

Materials and Methods

The study employed a multidisciplinary approach to investigate the digital preservation of endangered cultural heritage in conflict zones. The research was structured into three key phases: data collection and case study selection, technological assessment, policy and ethical analysis.

The study employed qualitative and quantitative data sources to examine various strategies for digital preservation. The study integrated historical records, academic literature, and policy documents to establish a comprehensive understanding of cultural heritage risks in conflict zones. Case studies from Syria, Afghanistan, Mali, and Ukraine were used as focal points for assessing digital preservation efforts. Primary case studies included analysis of such sources: Palmyra, Syria – 3D reconstruction of the Arch of Triumph following ISIS-led destruction; Bamiyan, Afghanistan – digital restoration of the Bamiyan Buddhas destroyed by the Taliban in 2001; Timbuktu, Mali – remote sensing and satellite monitoring of ancient manuscripts endangered by extremist attacks; Ukraine – emergency digitisation efforts during the 2022 war to preserve museum collections and archives. These case studies were selected due to their representation of different types of cultural heritage (monuments, manuscripts, and museum artefacts) and their exposure to various conflict-related threats.

The study assessed advanced digital tools used in cultural heritage conservation through analysis, including: 1) 3D scanning and modelling – technologies such as photogrammetry, LiDAR (Light Detection and Ranging), and HBIM (Heritage Building Information Modeling) were analysed for their effectiveness in reconstructing destroyed sites; 2) satellite monitoring and remote sensing – multi-temporal InSAR (Interferometric Synthetic Aperture Radar) techniques were examined for tracking structural integrity and documenting damage; 3) blockchain and decentralised storage – the use of blockchain for provenance tracking and decentralised networks such as IPFS (InterPlanetary File System) for secure archiving was explored; 4) AI and predictive risk mapping – machine learning algorithms and federated AI models were assessed for identifying potential threats and prioritising conservation efforts.

The study reviewed international legal frameworks, including the Convention for the Protection of Cultural Property in the Event of Armed Conflict with Regulations for the Execution of the Convention (1954) and Resolution S/RES/2347 (2017), to determine their role in cultural heritage protection. Ethical considerations such as ownership rights, community involvement, and the risks of digital colonisation were discussed. Stakeholder analysis included NGOs (Non-Governmental Organisations), governments, and local communities to evaluate collaboration challenges and solutions. Equally relevant was ethical stewardship, which required engaging local communities in decision-making processes to ensure that preservation efforts reflected the values and needs of those directly connected to their cultural heritage.

Preservation of cultural heritage in conflict zones involved a delicate balance of policy, ethics, and technological innovation. Regulatory documents provided a foundational legal framework for protecting cultural property, mandating state responsibility and international cooperation to prevent and remedy the loss of cultural assets during warfare.

Results and Discussion

The preservation of ancient books, manuscripts, archival materials, and maps in conflict zones presents unique challenges due to threats such as deliberate destruction, looting, and environmental degradation. Various technological interventions were employed to safeguard these cultural assets, ensuring their long-term accessibility and protection.

One of the most notable digitisation initiatives in conflict zones took place in Timbuktu, Mali, where thousands of historic manuscripts faced destruction at the hands of extremist groups. These manuscripts, dating back to the 13th century, contain invaluable knowledge on subjects such as astronomy, medicine, law, and philosophy. Their destruction would have resulted in an irreplaceable loss of Africa's written heritage. To safeguard these fragile documents, remote sensing

and satellite monitoring were employed to assess the condition of storage facilities and track environmental risks, such as humidity, temperature fluctuations, and structural damage (Tapete & Cigna, 2019; Spizzichino & Margottini, 2021). This real-time monitoring helped conservationists identify threats before they resulted in irreversible damage.

In response to the imminent danger posed by militant attacks, local preservationists and international organisations orchestrated a secret operation to evacuate the manuscripts. W. Zhou *et al.* (2015) noted that high-resolution scanning technologies were utilised to create digital replicas, ensuring that even if the original manuscripts were lost, their content would be preserved. The digitisation process involved specialised imaging techniques, including multi-spectral scanning, which captured faded or damaged text that would otherwise be unreadable. Once digitised, the manuscripts were smuggled out of Timbuktu in hidden compartments and transported to safer locations for preservation. These digital records were stored in decentralised databases and cloud-based repositories, ensuring accessibility, while mitigating risks associated with centralised storage failures. The integration of blockchain-based provenance tracking further secured the authenticity and ownership of these manuscripts, preventing illicit trade. This large-scale digitisation effort in Timbuktu serves as a model for heritage preservation in conflict zones, demonstrating the importance of combining technological innovation, strategic planning, and community involvement to protect endangered cultural assets (Fig. 1).

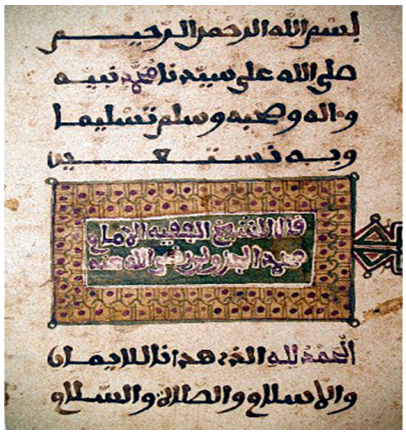

Figure 1. A page from one of the manuscripts. Photo by Seydou Camara via Art Daily
Source: based on H. Neuendorf (2014)

Original manuscripts were saved from destruction, when Islamist militants occupied the ancient city of Timbuktu in 2012. When Islamist militants occupied Timbuktu during the Northern Mali conflict in 2012, Abdel Kader Haidara mobilised 32 of the city's libraries to secretly smuggle their collections of ancient manuscripts on African history, mathematics, chemistry, and law to the capital Bamako. The smugglers risked their lives to preserve the world-renowned artefacts for future generations. Figure 2a showed an example of a manuscript from the IFYL collection, noting the powdery dry mould on the leather binding wrap and part of the information that has already started fading, while Figure 2b showed the digitalisation processes.

Figure 2. Preservation efforts: degraded IFYL manuscript and ongoing digitisation process
Note: a – example of a manuscript from the IFYL collection; b – digitalisation process
Source: based on I. Straughn (2017)

During the 2022 war in Ukraine, cultural institutions faced an urgent need to protect fragile archival collections, as libraries, museums, and historical archives became vulnerable to destruction due to bombings, looting, and infrastructure collapse. Recognising the risks, Ukrainian cultural organisations, in collaboration with international partners, rapidly implemented portable digitisation kits to preserve valuable documents, books, and maps (Boronos *et al.*, 2018). A key innovation in these efforts was the use of low-tech, solar-powered digitisation devices, which enabled scanning and documentation in areas with unreliable electricity supply. These portable units enabled local librarians, historians, and volunteers to digitise thousands of manuscripts and archival materials under challenging conditions. Special care was taken to handle rare and delicate documents, many of which required non-invasive imaging techniques, such as high-resolution

photography and multispectral scanning, to capture faded text and fragile ink.

To prevent data loss in case of physical destruction, the digital copies were immediately uploaded to cloud-based repositories and stored in decentralised storage networks (DSNs), such as IPFS and Filecoin. These systems ensured that even if local servers were compromised, the data would remain accessible from multiple locations worldwide. This distributed approach not only enhanced security, but also made the digital archives resistant to cyberattacks and accidental erasure. One of the defining aspects of Ukraine's emergency digitisation efforts was the role of grassroots participation. Local communities, including students and volunteers, were trained in document scanning and digital archiving. This decentralised, community-led approach ensured the preservation of cultural records despite wartime disruptions. The Ukrainian initiative highlighted how technological innovation, decentralised storage, and civic engagement can collaborate to safeguard national heritage in conflict zones (Fig. 3).

Figure 3. An example of digital preservation of Ukraine's scientific heritage of the late 19th and early 20th centuries

Source: based on N. Khalak (2016)

Figure 3 demonstrated a rich visual narrative that encapsulated a slice of Ukraine's cultural and intellectual history from the late 19th and early 20th centuries. It was a collection that brought together historical photographs, manuscripts, and scanned publications associated with the Shevchenko Scientific Society in Lviv. The collection presented an array of materials, including portraits of individuals in both everyday and formal attire, documents of scholarly work, and pages from old books and journals. Handwritten texts and title pages highlighted the era's vibrant academic discourse, while maps and manuscripts reflected the breadth of research in fields such as geography, ethnography, literature, and history. Overall, this composition was a visual summary of a significant period in Ukrainian scientific and cultural heritage, offering a glimpse into the past through its carefully preserved archival artefacts. Figure 4 depicted the handover of a scanner to the Kyiv-Pechersk Lavra for the digitisation of its archive, supported by UNESCO and the Austrian government.

Figure 4. Delivery of a specialised scanner to Kyiv-Pechersk Lavra for archive digitisation with support from UNESCO and the Government of Austria

Source: based on Yu. Koganov (2023)

M. Danti *et al.* (2017) noted that the ongoing conflict in Syria has led to the destruction and looting of historical archives, prompting urgent digitisation efforts using 3D imaging and AI-assisted restoration. Libraries and cultural institutions employed photogrammetry and LiDAR scanning to create high-resolution digital reconstructions of damaged manuscripts, maps, and historical documents. These technologies were used for precise replication of lost or deteriorated artefacts, preserving their details for future study and restoration. G. Asmolov (2022) and M. Dynel (2024) emphasised that to combat the illegal trade of looted documents, blockchain-based provenance tracking was implemented, ensuring authenticity and preventing unauthorised sales. By assigning immutable digital records to each scanned document, institutions can verify ownership and trace the movement of cultural assets. Additionally, federated AI models have enabled international collaboration in restoring archival data. In contrast to centralised databases, federated learning enables joint analysis and improvement digital records, while maintaining data security and privacy (Cigna *et al.*, 2014; Luo *et al.*, 2019). These technological advancements provided a sustainable solution for preserving Syria's documentary heritage amid ongoing conflict and displacement.

The digital preservation of endangered cultural heritage in conflict zones was a pressing concern, particularly as armed conflicts threaten the integrity of historical sites and artefacts. This response synthesises various case studies and technological solutions that have emerged during the period of 2015-2020, illustrating the multifaceted approaches to safeguarding cultural heritage amidst crises. One prominent case study was the 3D reconstruction of the Arch of Triumph in Palmyra, Syria, and the Bamiyan Buddhas in Afghanistan (Fig. 5). These efforted utilise advanced technologies such as AI-driven 3D modelling and photogrammetry to create accurate digital representations of these significant cultural landmarks. The reconstruction of the Palmyra Arch, for instance, served not only as a means of preserving the memory of the structure, but also as a tool for education and awareness about the cultural heritage that has been lost due to conflict.

Figure 5 illustrated the beginning of the process, where professional and open-domain images were first collected and classified based on their orientation and distribution patterns. Shown in grey was the part from dense multi-view 3D reconstruction, and in red were the parts from panoramic image-based modelling. Dense multi-view 3D reconstruction was then applied to these image sets, processing them in chunks to generate point clouds. From these reconstructions, the positions of the professional panoramic images were accurately retrieved. In Figure 6, the generated mesh was imported into 3D modelling software, where the panoramic images were projected onto it using central projections from the determined positions. The mesh was graphically aligned with the projections, hence two distinct meshes can be created: a high and low-poly version. These meshes were subsequently resampled into one closed solid mesh using tools such as Mesh Mixer. The refined model was then re-imported into the photogrammetry program for texturing, and the final step involved post-processing the texture, where colour balance and contrast were optimised to achieve the appropriate representation of the Arch of Triumph as shown in Figure 6.

Figure 5. The destroyed Arch of Triumph in Palmyra, a projection of a panorama and the reconstructed model
Source: based on W. Wahbeh & S. Nebiker (2017)

Figure 6. The final model of the Arch of Triumph and the used panoramas
Source: based on W. Wahbeh & S. Nebiker (2017)

The triptych in Figure 7 portrayed the rise and fall of the Bamiyan Buddhas in Afghanistan. On the left, one of the two colossal sixth-century statues stands intact, carved directly into the cliff face and gasing over the valley. The centre image depicts the moment of their violent destruction in March 2001, as explosives tear

through the ancient stone, sending plumes of dust and rubble into the air. The final panel revealed the empty niche left behind: a gaping void where a piece of Gandharan art once stood, its absence marked by the outlines of shattered rock and the small figures of local observers, who now confront the stark reality of cultural loss. Together, these three images chronicle the creation, destruction, and lingering absence of a cultural treasure lost to ideological violence. The Bamiyan Buddhas, which were destroyed by the Taliban in 2001, have been the subject of digital reconstruction efforts that aimed to restore their presence in the cultural landscape, thereby promoting a sense of continuity and resilience among affected communities (Danti *et al.*, 2017).

Figure 7. The Great Buddha of Bamiyan before the destruction (left), the explosion of March 2001 (centre) and the hole left in the cliff after the destruction (right)

Source: based on A. Gruen *et al.* (2003)

Figure 8 demonstrated the installation at the Bamiyan cliff site, in which a highluminosity projector mounted on a temporary scaffold casts a full-scale, golden-hued image of one of the destroyed Buddha statues onto the rock face where the original once stood. The projected figure, rendered in warm tones of amber and ochre, recreates the Buddha's serene countenance and draped monastic robes with remarkable clarity, while the surrounding darkness underscored both the monument's absence and its enduring cultural resonance.

Figure 8. Holographic reconstruction of the Great Buddha of Bamiyan: 175-foot installation at the site of the destroyed monument

Source: based on E. Chan (2015)

In addition to 3D modelling, satellite monitoring was substantial in the recovery of Mali's Timbuktu manuscripts, which have faced significant threats from extremist groups. Scientists D. Spizzichino & C. Margottini (2021) demonstrated that multi-temporal InSAR techniques can effectively track environmental changes and detect potential structural damage to the buildings housing these historic manuscripts.

Similarly, D. Tapete & F. Cigna (2019) highlighted that satellite imagery was necessary for assessment of the condition of vulnerable cultural archives, ensuring that critical interventions were made to preserve these invaluable documents. Moreover, researchers noted that the use of remote sensing technologies enabled the assessment of the condition of these manuscripts and the monitoring of their storage environments. V. Boronos *et al.* (2018) noted that during the 2022 conflict in Ukraine, satellite monitoring was key in tracking the looting and destruction of museums, archives, and historical sites. High-resolution satellite imagery was used to document damage to cultural institutions, providing visual evidence that helped inform rescue and recovery operations. This was particularly important for libraries and museums housing rare books and maps, which needed urgent digitisation efforts. Satellite-based environmental monitoring was also crucial in assessing fire risks and infrastructure vulnerabilities at storage facilities, ensuring proactive conservation measures could be implemented before irreversible losses occurred. Ukraine's emergency digitisation efforts during the 2022 crisis further highlighted the importance of digital preservation in conflict situations. As the war escalated, cultural institutions faced immense challenges, prompting rapid digitisation initiatives to safeguard collections and maintain access to cultural heritage. The Ukrainian government and various NGOs mobilised resources to implement portable digitisation kits, enabling local communities to participate in the preservation of their cultural heritage. This community-led approach not only empowered individuals, but also promoted a sense of ownership and responsibility towards cultural heritage, which was crucial in post-conflict recovery. K. Themistocleous *et al.* (2020) emphasised that in Syria, satellite monitoring has been extensively used to track damage to libraries, religious manuscripts, and heritage archives, especially in cities such as Aleppo and Palmyra. This technology was used to analyse before-and-after satellite images to identify illegal excavation activities and the movement of looted artefacts (Luo *et al.*, 2019). W. Zhou *et al.* (2015) stated that by employing advanced multi-temporal InSAR techniques, researchers can detect changes in the structural integrity of buildings housing these manuscripts, thereby informing conservation strategies and ensuring their protection. This approach exemplified how remote sensing can be integrated into cultural heritage management, providing valuable data for decision-making processes (Elfadaly *et al.*, 2018).

T. Greene (2023) noted that technological solutions such as blockchain for immutable provenance tracking have also emerged as vital tools in the preservation of cultural heritage. Projects such as "Salsal: Blockchain verification service for cultural artefacts" were a Web3-based verification-as-a-service model designed for cultural heritage organisations. It was used to upload images and descriptions of artefacts, which were then evaluated by experts. Once validated, artefacts can be minted as Non-Fungible Tokens (NFTs), creating immutable records on the blockchain that document authenticity and ownership. This was particularly relevant in conflict zones, where looting and illicit trafficking of cultural property were prevalent. R. Marigliano *et al.* (2024) emphasised that by providing a reliable means of documenting the provenance of artefacts, blockchain can help deter illegal activities and promote ethical practices in cultural heritage management. Moreover, the integration of AI-driven technologies in the preservation of cultural heritage has opened new avenues for innovation. For instance, machine learning algorithms can analyse vast datasets to identify patterns and predict potential threats to cultural sites (Cigna *et al.*, 2014).

As highlighted by B.M. Garcia (2021), this proactive approach was used to implement preventive measures, thereby contributing to the resilience of cultural heritage against the impacts of conflict and environmental changes. In conclusion, the digital preservation of endangered cultural heritage in conflict zones was a complex and multifaceted process that required the integration of advanced technologies, community engagement, and international collaboration. The case studies of Syria, Afghanistan, Mali, and Ukraine illustrated the diverse strategies employed to safeguard cultural heritage amidst crises.

Edge computing can be deployed in conflict zones to process data locally. For example, a Raspberry Pi-based system paired with a LiDAR scanner can perform 3D scans and process satellite images on site. A pertinent example is the study conducted on the Koszalin city walls in Poland by P. Kędziorski *et al.* (2024), where researchers explored the efficacy of affordable LiDAR systems for 3D modelling and degradation assessment of heritage buildings. In this study, the research team employed mobile devices equipped with LiDAR capabilities, such as the Apple iPad Pro, to capture detailed 3D scans of the city walls. The process involved two phases: initial evaluation of the measurement accuracy and subsequent assessment of the detection of structural degradations. The findings indicated that while low-cost LiDAR solutions were suitable for small-scale documentation, their accuracy diminishes, when applied to larger, more complex structures compared to traditional terrestrial laser scanning (TLS) methods. Nevertheless, the study suggested that these accessible technologies can reduce costs and enhance the reach of heritage conservation efforts, especially when complemented by further development of mobile applications. This solution minimised dependency on cloud services and supports rapid documentation even when connectivity was unstable. Figure 10 depicted the result of the design of a rendered 3D model of the complete system.

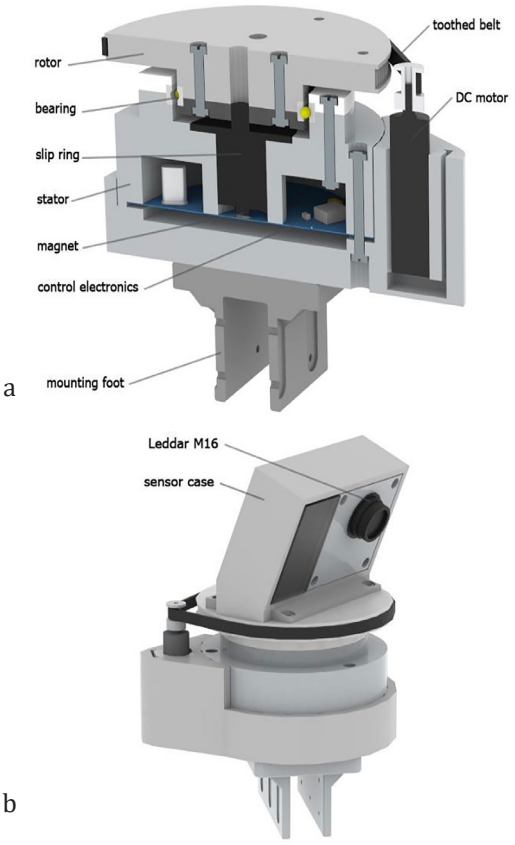

Figure 10. The 3D model of the designed 3D LIDAR sensor
Note: a – the sectional image of the structure, stator, without sensor; b – the complete unit
Source: based on T. Bécsi *et al.* (2017)

Federated learning enabled multiple institutions, such as museums and NGOs, to train shared AI models without centralising sensitive data. In practice, collaborative AI systems can analyse satellite imagery to detect patterns of looting, while preserving the privacy of each participant's data. This method increased the quality of predictive analytics without exposing information to cyber risks. Moreover, the establishment of collaborative frameworks for cross-border preservation was crucial in addressing the transnational nature of cultural heritage. R. Doszhan (2023) noted that many cultural sites and artefacts were not confined to national borders; thus, international cooperation was essential for their protection. Collaborative frameworks can facilitate knowledge sharing, resource mobilisation, and joint initiatives among countries facing similar challenges in cultural heritage preservation. For instance, regional partnerships can be formed to address the illicit trafficking of cultural property, which often throve in conflict zones (Zhang *et al.*, 2022). Such collaborations can also enhance the capacity of local institutions to manage and protect cultural heritage, ensuring that preservation efforts were sustainable and contextually relevant.

Quantum-resistant encryption can protect from future advances in computing. Lattice-based cryptography within blockchain ledgers can secure provenance records of repatriated artefacts. This technique created digital archives that remained secure even as quantum computing develops. Low-tech digitisation kits equipped with solar-powered components provided a practical solution in remote, off-grid areas. Portable devices integrated with terrestrial LiDAR backpacks, for example, enable local communities to digitise manuscripts or record oral histories without reliance on external power sources. Such kits broaden access to preservation technologies in resource-limited settings.

Digital twins that incorporate IoT sensor integration can be used to create updatable virtual models of heritage sites. Sensors placed on a structure can monitor parameters such as vibration or humidity, and the real-time data feeds into a digital replica, for instance, of Yemen's Old City of Sana'a to signal potential damage. This arrangement supported early intervention by those responsible for conservation. Decentralised storage networks (DSNs) distributed digital heritage data across peer-to-peer systems such as IPFS or Filecoin. By storing 3D models of heritage sites on these networks, the risk of data loss was reduced if centralised servers were compromised. This distributed approach was resistant to both cyberattacks and physical damage.

Holographic preservation and augmented reality (AR) can reconstruct lost artefacts for educational use. Initiatives such as UNESCO's #Unite4Heritage used AR to overlay digital reconstructions onto physical ruins, thereby reuniting displaced communities with a visible reminder of their past (Shang *et al.*, 2017). AI-powered predictive risk mapping combined conflict reports, climate models, and heritage inventories to identify sites at imminent risk. For instance, a tool such as Project Mosul's RiskMap can prioritise areas that required urgent digitisation and intervention before damage occurs.

Crowdsourced verification platforms that incorporate gamification engage volunteers around the world in validating heritage data. Platforms such as MicroMappers enabled users to tag satellite imagery of damaged sites, accelerating the data-checking process, while raising public awareness about heritage preservation. Predictive risk mapping using conflict data analytics was a promising direction for enhancing the protection of cultural heritage. B.M. Garcia (2021) emphasised that by integrating data on conflict dynamics, social unrest, and environmental factors, stakeholders can develop comprehensive risk assessments that identified vulnerable cultural sites. Such predictive models can inform proactive measures to safeguard cultural heritage, enabling targeted interventions in high-risk areas. A. Gravagnuolo *et al.* (2021) determined that the application of participatory mapping techniques can facilitate community engagement in identifying potential threats to cultural heritage,

thereby promoting a sense of ownership and responsibility among local populations. This collaborative approach not only enhanced the effectiveness of preservation efforts, but also strengthened community resilience in the face of conflict.

Biometric authentication systems enhanced the security of digital archives. By employing iris or fingerprint scanning, access to sensitive records such as those maintained by the Iraqi Museum can be restricted to authorised personnel only, thereby reducing the risk of unauthorised data breaches. Innovations in material science also contributed to a hybrid approach that protected both physical and digital records. For instance, nano-coated storage drives or ceramic nanodots can encode 3D scan data into heat-resistant plaques. These materials helped ensure that digital backups survive extreme conditions, such as fires or explosions. Swarm robotics involved the use of autonomous drone swarms to document sites that were too dangerous for human teams. Synthetic media techniques used AI-generated voice cloning to reconstruct oral histories that were fragmented or lost. Projects that restored recordings damaged during conflict not only preserved the content of these narratives, but also maintained the cultural practices associated with them. Ethical AI audits provided an essential check on algorithms used in heritage preservation. By establishing audit frameworks modelled after initiatives such as MIT's Moral Machine, stakeholders can review AI outputs for cultural bias and ensure that digital reconstructions accurately reflected the intended heritage narratives without imposing external interpretations (Brogan, 2016; For driverless cars, a moral dilemma…, 2017).

The protection of cultural heritage in conflict zones required a combination of modern technologies, strategic planning, and community involvement. Digitisation, including multispectral scanning and cloud storage, enabled preservation of vulnerable documents even under the threat of war. Successful examples in Mali and Ukraine demonstrated the effectiveness of mobile equipment, decentralised archives, and grassroots initiatives in safeguarding cultural assets. These approaches ensured the long-term accessibility and authenticity of historical materials.

Conclusions

The digital preservation of endangered cultural heritage in conflict zones was essential for protecting both physical monuments and the associated traditions of affected communities. The study highlighted the transformative role of 3D scanning, remote sensing, and blockchain-based records in documenting and safeguarding cultural heritage, when direct access to sites was restricted by violence or instability. The use of advanced imaging technologies enabled researchers to create high-resolution digital replicas of heritage sites, ensuring their long-term preservation and accessibility for future generations. Despite these advancements, challenges persist, including technical limitations, inadequate infrastructure, and restricted access to specialised equipment. Many conflict-affected regions struggle with unstable electricity supplies and limited internet connectivity, making real-time documentation and data storage difficult. However, case studies from Palmyra, Bamiyan, Timbuktu, and Ukraine demonstrated that a combination of local digitisation initiatives and international collaboration can effectively mitigate these challenges. By providing digital tools and preservation training, heritage documentation efforts became more sustainable and reflective of the cultural identity of affected populations. The documentation of written monuments, such as manuscripts in Timbuktu and Ukraine, has further revealed the critical importance of safeguarding textual heritage alongside architectural relics. Digitising fragile manuscripts not only protected them from physical destruction, but also ensured continued scholarly access and cultural relevance, particularly for communities, whose identities were closely tied to these historical texts. Furthermore, investments in technology transfer, digital repositories, and capacity-building initiatives will contribute to the resilience of heritage preservation efforts. Establishing secure, decentralised archives will ensure that digitised cultural records remain accessible and protected from cyber threats or physical destruction. Further expansion of international partnerships and interdisciplinary collaborations will be critical in strengthening digital preservation initiatives. By integrating technological innovation with community engagement, cultural heritage can be maintained as a vital resource for historical memory, education, and cultural continuity, even amid the disruptions of armed conflict.

Further research should explore scalable and context-sensitive preservation strategies, particularly those that integrate indigenous knowledge systems and prioritise underrepresented heritage forms.

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Conflict of Interest

None.

References

[1] Alcala, R. (2022). Cultural evolution: Protecting "digital cultural property" in armed conflict. *International Review of the Red Cross*, 104(919), 1083-1119. doi: 10.1017/s181638312200008x.

[2] Asmolov, G. (2022). The transformation of participatory warfare: The role of narratives in connective mobilization in the Russia-Ukraine war. *Digital War*, 3, 25-37. doi: 10.1057/s42984-022-00054-5.

[3] Baj, G. (2021). Beyond Resolution 2347 (2017): The search for protection of cultural heritage from armed non-state groups. *Constitutional Review*, 7(1), 153-187. doi: 10.31078/consrev716.
[4] Bécsi, T., Aradi, S., Fehér, Á., & Gáldi, G. (2017). Autonomous vehicle function experiments with low-cost environment sensors. *Transportation Research Procedia*, 27, 333-340. doi: 10.1016/j.trpro.2017.12.143.
[5] Boronos, V., Plikus, I., Aleksandrov, V., & Antoniuk, N. (2018). Digital transformation of Ukraine: Challenges of theory and practice in implementation of digital quality of life. *Economic Annals-XXI*, 172(7-8), 38-43. doi: 10.21003/ea.v172-07.
[6] Brogan, J. (2016). Should a self-driving car kill two jaywalkers or one law-abiding citizen? *Slate*. Retrieved from https://surl.li/olqdwq.
[7] Chan, E. (2015). Rebirth of the Buddha of Bamiyan: Chinese millionaires create amazing 175ft hologram of iconic statue deliberately destroyed by the Taliban. *MailOnline*. Retrieved from https://www.dailymail.co.uk/news/peoplesdaily/article-3124580/Chinese-millionaires-create-amazing-175-foot-3-D-hologram-Afghan-Buddha-statue-destroyed-Taliban-bomb-blast.html.
[8] Choi, Y., Yang, Y.-J., & Sohn, H.-G. (2021). Resilient cultural heritage through digital cultural heritage cube: Two cases in South Korea. *Journal of Cultural Heritage*, 48, 36-44. doi: 10.1016/j.culher.2021.01.007.
[9] Cigna, F., Lasaponara, R., Masini, N., Milillo, P., & Tapete, D. (2014). Persistent scatterer interferometry processing of COSMO-SkyMed stripmap HIMAGE time series to depict deformation of the historic centre of Rome, Italy. *Remote Sensing*, 6(12), 12593-12618. doi: 10.3390/rs61212593.
[10] Convention for the Protection of Cultural Property in the Event of Armed Conflict with Regulations for the Execution of the Convention. (1954, May). Retrieved from https://www.unesco.org/en/legal-affairs/convention-protection-cultural-property-event-armed-conflict-regulations-execution-convention.
[11] Cunliffe, E., & Curini, L. (2018). ISIS and heritage destruction: A sentiment analysis. *Antiquity*, 92(364), 1094-1111. doi: 10.15184/aqy.2018.134.
[12] Danti, M., Branting, S., & Penacho, S. (2017). The American schools of Oriental research cultural heritage initiatives: Monitoring cultural heritage in Syria and Northern Iraq by geospatial imagery. *Geosciences*, 7(4), article number 95. doi: 10.3390/geosciences7040095.
[13] Doszhan, R. (2023). Multi-vector cultural connection in the conditions of modern globalisation. *Interdisciplinary Cultural and Humanities Review*, 2(1), 27-32. doi: 10.59214/2786-7110-2023-2-1-27-32.
[14] Dynel, M. (2024). Do we know whether to laugh or cry? User responses to @Ukraine's dark-humour meme. *Journal of Creative Communications*, 19(3), 243-258. doi: 10.1177/09732586241239908.
[15] Elfadaly, A., Attia, W., Qelichi, M.M., Murgante, B., & Lasaponara, R. (2018). Management of cultural heritage sites using remote sensing indices and spatial analysis techniques. *Surveys in Geophysics*, 39, 1347-1377. doi: 10.1007/s10712-018-9489-8.
[16] For driverless cars, a moral dilemma: Who lives and who dies? (2017). *The Associated Press*. Retrieved from https://www.nbcnews.com/tech/innovation/driverless-cars-moral-dilemma-who-lives-who-dies-n708276.
[17] Garcia, B.M. (2021). Integrating culture in post-crisis urban recovery: Reflections on the power of cultural heritage to deal with crisis. *International Journal of Disaster Risk Reduction*, 60, article number 102277. doi: 10.1016/j.ijdrr.2021.102277.
[18] Gorbul, T., & Rusakov, S. (2022). Cultural heritage in the context of digital transformation practices: Experience of Ukraine and the Baltic states. *Baltic Journal of Economic Studies*, 8(4), 58-69. doi: 10.30525/2256-0742/2022-8-4-58-69.
[19] Gravagnuolo, A., Micheletti, S., & Bosone, M. (2021). A participatory approach for "circular" adaptive reuse of cultural heritage. Building a heritage community in Salerno, Italy. *Sustainability*, 13(9), article number 4812. doi: 10.3390/su13094812.
[20] Greene, T. (2023). Researchers develop blockchain verification service for cultural artifacts. *Cointelegraph*. Retrieved from https://cointelegraph.com/news/researchers-develop-blockchain-verification-service-for-cultural-artifacts.
[21] Gruen, A., Remondino, F., & Zhang, L. (2003). Image-based automated reconstruction of the Great Buddha of Bamiyan, Afghanistan. In *2003 conference on computer vision and pattern recognition workshop*. Madison: IEEE. doi: 10.1109/CVPRW.2003.10003.
[22] Hajibayova, L. (2019). An investigation of cultural objects in conflict zones through the lens of TripAdvisor reviews: A case of South Caucasus. *Journal of Information Science*, 46(5), 710-722. doi: 10.1177/0165551519867545.
[23] Jakubowski, A. (2019). International protection of cultural heritage in armed conflict: Revisiting the role of safe havens. *Indonesian Journal of International Law*, 16(2), 169-190. doi: 10.17304/ijil.vol16.2.748.
[24] Kędziorski, P., Jagoda, M., Tysiąc, P., & Katzer, J. (2024). An example of using low-cost LiDAR technology for 3D modeling and assessment of degradation of heritage structures and buildings. *Materials*, 17(22), article number 5445. doi: 10.3390/ma17225445.

[25] Kelly, L. (2021). Lessons learned on cultural heritage protection in conflict and protracted crisis. *Institute of Development Studies.* doi: 10.19088/k4d.2021.068.
[26] Khalak, N. (2016). Ukrainian scientific heritage of the late 19th and early 20th century preservation: Digitisation of archival materials and scientific publications Shevchenko Scientific Society in Lviv (EAP900). *British Library*. doi: 10.15130/EAP900.
[27] Koganov, Yu. (2023). Supporting the digitization of museum collections and documentary heritage in Ukraine. *UNESCO*. Retrieved from https://www.unesco.org/en/articles/supporting-digitization-museum-collections-and-documentary-heritage-ukraine.
[28] Luo, L., *et al.* (2019). Airborne and spaceborne remote sensing for archaeological and cultural heritage applications: A review of the century (1907-2017). *Remote Sensing of Environment*, 232, article number 111280. doi: 10.1016/j.rse.2019.111280.
[29] Macrì, E., & Cristofaro, C.L. (2021). The digitalisation of cultural heritage for sustainable development: The impact of Europeana. In P. Demartini, L. Marchegiani, M. Marchiori & G. Schiuma (Eds.), *Cultural initiatives for sustainable development. Contributions to management science* (pp. 373-400). Cham: Springer. doi: 10.1007/978-3-030-65687-4_17.
[30] Maraieva, U. (2022). On the formation of a new information worldview of the future (literature review). *Futurity Philosophy*, 1(1), 18-29. doi: 10.57125/FP.2022.03.30.02.
[31] Marigliano, R., Ng, L.H.X., & Carley, K.M. (2024). Analyzing digital propaganda and conflict rhetoric: A study on Russia's bot-driven campaigns and counter-narratives during the Ukraine crisis. doi: 10.21203/rs.3.rs-3997295/v1.
[32] Neuendorf, H. (2014). Timbuktu manuscripts rescued from Jihadist destruction go on view. *Artnet*. Retrieved from https://news.artnet.com/art-world/timbuktu-manuscripts-rescued-from-jihadist-destruction-go-on-view-201806.
[33] Rahimi, M. (2024). *A comprehensive analysis of privacy and data protection in conflict-affected areas: Revising human rights and humanitarian law to address the challenges of surveillance technologies*. (Master's thesis, Utrecht University, Utrecht, The Netherlands).
[34] Rayne, L., Bradbury, J., Mattingly, D., Philip, G., Bewley, R., & Wilson, A. (2017). From above and on the ground: Geospatial methods for recording endangered archaeology in the Middle East and North Africa. *Geosciences*, 7(4), article number 100. doi: 10.3390/geosciences7040100.
[35] Resolution S/RES/2347 "On the Protection of Cultural Heritage in Armed Conflicts". (2017, March). Retrieved from https://docs.un.org/en/S/RES/2347%20(2017).
[36] Sampaio, A.Z., Gomes, A.M., Sánchez-Lite, A., Zulueta, P., & González-Gaya, C. (2021). Analysis of BIM methodology applied to practical cases in the preservation of heritage buildings. *Sustainability*, 13(6), article number 3129. doi: 10.3390/su13063129.
[37] Shang, L.W., Siang, T.G., bin Zakaria, M.H., & Emran, M.H. (2017). Mobile augmented reality applications for heritage preservation in UNESCO world heritage sites through adopting the UTAUT model. *AIP Conference Proceedings*, 1830(1), article number 030003. doi: 10.1063/1.4980928.
[38] Sofilkanych, M. (2022). The formation of a new information culture of the future: The socio-philosophical content. *Futurity Philosophy*, 1(1), 56-67. doi: 10.57125/FP.2022.03.30.05.
[39] Spizzichino, D., & Margottini, C. (2021). Satellite monitoring of geo-hazards affecting cultural heritage. In E. Stegmeijer & L. Veldpaus (Eds.), *A research agenda for heritage planning* (pp. 133-143). Cheltenham, Northampton: Edward Elgar Publishing. doi: 10.4337/9781788974639.00023.
[40] Straughn, I. (2017). A new chapter in the story of Timbuktu's manuscripts: Sample digitisation of materials from the Infa Yattara Family Library. *Endangered Archives*. Retrieved from https://blogs.bl.uk/endangeredarchives/2017/05/timbuktu_manuscripts.html.
[41] Tapete, D., & Cigna, F. (2019). COSMO-SkyMed SAR for detection and monitoring of archaeological and cultural heritage sites. *Remote Sensing*, 11(11), article number 1326. doi: 10.3390/rs11111326.
[42] Themistocleous, K., Hadjimitsis, D., Schreier, G., Krauss, T., & Kontoes, H. (2020). The contribution of the Excelsior Project for cultural heritage. *Proceedings of SPIE*, 11534, article number 1153410. doi: 10.1117/12.2574004.
[43] Wahbeh, W., & Nebiker, S. (2017). Three dimensional reconstruction workflows for lost cultural heritage monuments exploiting public domain and professional photogrammetric imagery. In *ISPRS annals of the photogrammetry, remote sensing and spatial information sciences. 26th international CIPA symposium* (Vol. IV-2/W2, pp. 319-325). Ottawa, Canada. doi: 10.5194/isprs-annals-IV-2-W2-319-2017.
[44] Weiss, T.G., & Connelly, N. (2018). Protecting cultural heritage in war zones. *Third World Quarterly*, 40(1), 1-17. doi: 10.1080/01436597.2018.1535894.
[45] Ye, Z. (2024). Theoretical mechanism and implementation path of digital technology enabling cultural heritage protection. *China Finance Economic Review*, 13(1), 112-128. doi: 10.1515/cfer-2024-0006.

[46] Zerbini, A. (2018). Developing a heritage database for the Middle East and North Africa. *Journal of Field Archaeology*, 43(1), 9-18. doi: 10.1080/00934690.2018.1514722.
[47] Zhang, X., Zhang, A., Xu, J., & Ma, R. (2022). Documentation and inheritance of ancient opera stage based on multidisciplinary approach and digital technology. *Buildings*, 12(7), article number 977. doi: 10.3390/buildings12070977.
[48] Zhou, W., Chen, F., & Guo, H. (2015). Differential radar interferometry for structural and ground deformation monitoring: A new tool for the conservation and sustainability of cultural heritage sites. *Sustainability*, 7(2), 1712-1729. doi: 10.3390/su7021712.

Цифрове збереження культурної спадщини, що перебуває під загрозою зникнення, в зонах конфліктів

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Анотація. Метою дослідження було вивчення ролі цифрових технологій у збереженні культурної спадщини в зонах конфліктів, забезпечення безпеки історичної та культурної ідентичності в умовах воєнних дій. У дослідженні проаналізовано ризики та цифрові рішення для збереження як матеріальної, так і нематеріальної спадщини під час збройних конфліктів. Були розглянуті виклики, що виникають через нестабільне середовище, обмежені технічні ресурси та зруйновану інфраструктуру, які перешкоджають використанню таких методів, як 3D-сканування, дистанційне зондування та цифрове моделювання для документування та реконструкції пошкоджених об'єктів. Етичні проблеми, пов'язані з правом власності та інформованою згодою, оцінювалися разом з логістичними питаннями, що виникають внаслідок геополітичних обмежень і фрагментарної співпраці між місцевими громадами, урядами та міжнародними організаціями. Тематичні дослідження з Сирії, Афганістану, Малі та України проілюстрували застосування цифрових інструментів для документування та відновлення спадщини в несприятливих умовах. Технологічні інновації, зокрема відстеження походження на основі блокчейну, периферійні обчислення для локальної обробки даних, децентралізовані мережі зберігання та прогнозне картування ризиків за допомогою штучного інтелекту, обговорювалися як стратегії захисту та збереження цифрових записів. Результати дослідження показали, що, незважаючи на технічні та геополітичні бар'єри, місцеві зацікавлені сторони продемонстрували неабияку адаптивність, використовуючи недорогі інструменти з відкритим вихідним кодом для продовження зусиль із документування. Залучення громад виявилося ключовим фактором у збереженні цифрової спадщини, причому низові ініціативи часто очолювали збір даних і розповідь історій. Міжнародні партнерства були найефективнішими, коли вони підтримували, а не підміняли місцеві організації. Крім того, респонденти наголосили на нагальній потребі у створенні сталої цифрової інфраструктури та моделей управління даними з урахуванням культурних особливостей. У дослідженні також розглянуто відповідні міжнародні правові рамки, які підтримують проактивні зусилля зі збереження даних. Насамкінець, воно закликає до інтегрованих цифрових підходів, які поєднують технологічні досягнення з участю громадськості для захисту культурних цінностей і підтримки зусиль з відновлення в регіонах, що постраждали від конфлікту, забезпечуючи їхнє тривале збереження

Ключові слова: цифрове моделювання; децентралізоване зберігання; документація про спадщину; 3D-моделювання; дистанційне зондування; міжнародне право