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THE USE OF 3D SCANNING AND GIS TOOLS FOR THE DIGITAL PRESERVATION OF CENTRAL ASIAN ARCHITECTURAL HERITAGE

Nodira Makhkamova[1], Khamdam Matyakubov[2], Shahzod Rakhmonov[3], Uzokova Shakhnoza[4], Mehrangiz Hojiyeva[5], Sherzod Rakhimov[6], Oybek Rakhimov[7]

[1]Department of History of Uzbekistan, Tashkent University of Information Technologies named after Muhammad Al-Khwarizmi Tashkent, Uzbekistan.
e-mail: mnadira2000@mail.ru, orcid: https://orcid.org/0009-0008-8883-6713
[2]Department of History, Urgench State University after named Abu Raykhon Beruni, Urgench, Uzbekistan. e-mail: hamdamtarix_377@mail.ru,
orcid: https://orcid.org/0000-0001-5440-0112
[3]Department of History of Uzbekistan, Tashkent University of Information Technologies named after Muhammad al-Khorazmi, Tashkent, Uzbekistan.
e-mail: wwwraxmonovvvv@gmail.com, orcid: https://orcid.org/0009-0003-8372-5241
[4]Jizzakh State Pedagogical University, Uzbekistan.
e-mail: shakhnozauzokova@gmail.com, orcid: https://orcid.org/0000-0003-2692-4669
[5]Bukhara State Medical Institute named after Abu Ali ibn Sino, Bukhara, Uzbekistan.
e-mail: hojiyeva.mehrangiz@bsmi.uz, orcid: https://orcid.org/0009-0006-0329-5539
[6]Department of Engineering and Technology of Geological Exploration Works, University of Geological Sciences, Tashkent, Uzbekistan. e-mail: sherzodraximov@gmail.com, orcid: https://orcid.org/0009-0008-7783-7825
[7]Department of History, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan. e-mail: oybekjon.9990@gmail.com,
orcid: https://orcid.org/0009-0003-9766-5307

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SUMMARY

The architectural landmarks of Central Asia are a stunning reminiscence of the cultural and historical amalgamation that took place over the Silk Road. The regions of Central Asia face an unparalleled risk of climate change, urban decay, and worse neglecting conservation attempts. New methodologies of preservation, driven by digital techniques, have been initiated to document and protect the sites of architectural importance. This paper discusses the application of 3D scanning and Geographic Information Systems (GIS) in the preservation of architecture in Central Asia. 3D scanning offers precision obtained in the high-resolution models of physical structures while GIS enables their spatial analysis within a defined temporal framework. These solutions facilitate a more holistic approach to conservation planning which supports the development of public relations, restoration works, and architectural research. The paper aims at demonstrating the potential stored within the advanced tools in the region by using case studies from Central Asia. Other existing problems regarding the use of the tools will also be presented. The architectural landmarks of the region can be sustained for posterity's reference as cultural heritage, rather than decaying structures, if the local authorities and stakeholders embrace these tools.

Key words: *digital preservation, 3d scanning, gis (geographic information systems), central asian architecture, cultural heritage, architectural conservation, laser scanning, historic documentation, spatial analysis, heritage technology*.

INTRODUCTION

Central Asia, which served as a historical crossroad of civilizations intertwined by the Silk Road, provides of some the globe's most astonishing architectural wonders. Cities like Samarkand, Bukhara, and Khiva boast of ancient mosques, madrasas, caravanserais, and mausoleums that reflect a blend of Persian, Islamic, Turkic and Mongol motifs. These structures are regionally central as they serve as ethnically emblematic and historical relics of beauty and cultures turning into memories encapsulated in places for the people.

Treasure, in form of architecture have great historical value, but most of them are at risk due to a number of reasons [3]. These factors include the natural decay of erosion and seismic activities, urbanization, lack of attention, low funds towards conserving these architectural pieces which add value to the country. In the face of imbalance between effort and reward, while having sophisticated, monumental preservation always comes to the rescue which renders a portion of devotion needed towards maintenance and survival of the building's conceptual legends. Digital preservation is now ever more important to add to the efforts, as it helps document artistic sculpture without physical intervention [2].

Two of the most transformative technologies I have come across are 3D scanning and GIS, which stands for geographic information systems.

Advancements in technology such as LiDAR and structured light scanning facilitate the creation of detailed three-dimensional virtual models of architectural structures [6]. These digital reproductions may undergo modelling for evaluation, analysis, restoration, instructional purposes, or virtual visitation. The reproductions are snapshots of a given site for monitoring factors such as structural decay or damage over time [1].

Geographic Information Systems (GIS) refers to the methods, processes, systems, and technologies involved in the collection, maintenance, analysis, and management of spatial and geographic information [16]. Within the context of heritage conservation, GIS helps scholars and conservators visualize the interrelationships between sites, study environmental impacts, manage site information, and assist with planning restorations or tourism to the site. GIS, when used with 3D scanning, provides comprehensive preservation strategy because architectural models are integrated into their geographic and cultural context [11].

The integration of 3D scanning with the GIS system, as argued in this paper, constitutes an efficient and holistic approach towards the digitized preservation of Central Asian architectural heritages [2]. These technologies go beyond improved documentation and monitoring; they assist in the preservation of information, public engagement, and planning for sustainable developmental conservation. This paper seeks to demonstrate how digital technologies and tools can mitigate the disparity between the traditional approaches to preserving heritages in Central Asia and the more contemporary, straightforward, and on-demand accessible retrieval systems through case studies and technological implementation analyses.

BACKGROUND INFORMATION

The combination of landmarks in Central Asia is a product of the region's extensive architecture and culture history because it was influenced by many religions, construction styles, and civilizations due to trade, conquest, and migration [17]. The cities of Samarkand, Bukhara, Khiva, and Merv are fundamental to the progression and spread of Islamic art and architecture because of how they contributed to other regions in those aspects [4]. Alongside their flourishing trade, these urban centres served simultaneously as cultural sites where Persian, Turkic, Mongolian, and Arab folk blended with their own influences to create a new culture [10]. Building such as caravanserais, minarets, fortified cities, and madrasas, mausoleums were constructed, inscribed with elaborate tile work, flowing

calligraphy, colossal dome, and muqarnas. which is a form of dome decoration Islamic architecture [7]. The Timurid Dynasty's contribution also has not gone unnoticed, dedicating popular structures such as the Registan in Samarkand, which features glazed tiles in geometric and floral patterns most associated with Timurid Dynasty, showcasing extensive use of mosaic and monumental sculptural decor [14]. The Kalyan Minaret alongside Itchan Kala are now renowned structures located in Uzbekistan where more urban and religious architecture is fused, they developed this virus from Bukhara and Khiva [9]. One of the largest cities in the Islamic civilization, Merv exemplifies how the diffusion of style together with the rich collection of regional styles, interdisciplinary approaches, and scientific innovations that determine its cultural identity were incorporated eastward [15]. The art of these regions portrays trade, exchange, and interactions between cultures all over the world showcasing their generosity to the world during the Islamic period [11].

The architectural wonders mark the region's Islamic Golden Age, Kalyan Minaret in Bukhara and Registan Ensemble in Samarkand stand tall for all to see. These structures were used primarily for governance, religion, and education, but they also served as a means for the people to express their political power and cultural identity. Unluckily, many of these heritage sites are at risk of destruction due to years of natural erosion, neglect, changing city structures, war, and weathering.

In Central Asia, preservation activities in the past have focused on traditional methods ranging from manual chronicling, building, and restoration to using historically appropriate materials and techniques. In the 20th century, Soviet restoration projects within Uzbekistan and Turkmenistan aided in stabling numerous monuments. Unfortunately, these restorations were often politically motivated and led to over-repair or modification of historically accurate architectural features, cyclopean inauthenticity [12]

In relation to this, the following are the shortcomings of these methods:

- Non meticulous recording: Restoration was undertaken on numerous structures without accompanying historical documents or even detailed architectural plans.
- Limited Resources: Even in tumultuous geographically remote or politically volatile regions, funding, technical skills, and access to traditional materials was severely lacking.
- Passive Not-invasive Substantial: Lack the ability to routinely check the physical state of the structure over long periods of time or simulate the effects of environment changes.

Alongside these factors, the absence of precise digital documentation means that once a structure is either damaged or destroyed, its design, context and history will be permanently lost without any possibility of recovery.

New digital technologies have developed new methods for preserving and studying architectural heritage. LiDAR (Light Detection and Ranging) and structured light scanning are examples of 3D scanning technologies that capture high-resolution geometric data of architectural surfaces and structures. These technologies produce detailed digital models that can be used for:

- Virtual reconstruction and visualization,
- Structural analysis and monitoring,
- Archival documentation, and
- Interactive public education [5].

GIS integrates spatially correlated data sets with 3D scanning data, thereby supplementing the latter's capabilities. GIS can incorporate environmental (temperature, erosion, vegetation growth) and anthropogenic (tourism, urbanization) data into architectural models. In cultural heritage applications, GIS has proven especially useful for:

- Mapping the distribution and vulnerability of heritage sites
- Assessing the impact of environmental or human-induced risks, and
- Supporting multi-layered conservation planning [13].

The combination of 3D scanning and GIS form a powerful digital preservation toolkit that overcomes in each case the precision, replicability, and accessibility challenges posed by traditional techniques to scholars, conservators, and policymakers [18].

LITERATURE SURVEY

Review of Various Central Asian Locations with The Use Of 3D Scanning and GIS Tools for Heritage Preservation

Central Asia is a region with a deep cultural heritage and the technological advancement of 3D scanning and GIS has opened up new vistas for its preservation [8]. Many important sites have served as case studies for the effective application of these technologies for documentation purposes. In Uzbekistan, some of the most important works include the historic cities of Samarkand and Bukhara, which have been at the cutting edge of technological advances. There are several cross-border projects such as the one with University of Tsukuba and UNESCO where TLS and photogrammetry along with GIS were used to develop accurate 3D representations of famous ancient buildings. Among these were the Registan Ensemble and the Po-i-Kalyan Complex. The models have been used not only for restoration and architectural analysis but also for enabling virtual tourism and education.

Equally important, the ancient city of Merv in Turkmenistan has undergone digital documentation using LiDAR scanning, drone imaging, and GIS analysis through CyArk. These technologies permitted the construction of complete digital records of the site's mudbrick structures, which, in particular, helped in monitoring preservation and planning essential change strategies. In Kazakhstan, the Otrar Oasis has been studied employing GPR, UAV photogrammetry, and GIS tools such as ArcGIS for mapping the subsurface features and reconstructing the layouts of ancient cities spatially. This perspective brought new understanding of the historical settlement patterns which, and policies for the protection of the heritage sites could be developed.

The Silk Roads Heritage Corridors project has integrated architecture analysis with 3D structured light scanning and GIS databases frameworks aims to preserve Khiva, Uzbekistan digitally. The intricate architectural data obtained from Khiva proved useful in designing development restoration plans for sustainable preservation supervised by UNESCO. Additionally, the archaeological region of the Issyk-Kul Basin in Kyrgyzstan which houses notable petroglyphs and burial mounds was drone mapped together with the use of GIS. The landscape archaeology framework was improved through the creation of digital elevation models (DEMs) which aided in urban planning and provided analysis for averting environmental degradation [13].

Moreover, these case studies focus on the role of 3D scanning and GIS technologies in enhancing the ethnicity culture of Central Asia and their accompanying advantages. It emphasizes the boundless potential for documenting sensitive heritage locations while casting a focus on tertiary education as well as eco-friendly tourism.

Assessment of Results and Consequences Derived with These Instruments Regarding the Preservation Process

The previous case studies have achieved all of these goals by applying 3D scanning and GIS tools:

- Greater Accuracy: DMDs (Digital Deformation Models) in particular, due to the millimetric precision of their measurements, are unrivalled for the monitoring of displacements, cracks, and deformations.

- Complex Contactless Reconstruction: Scanning allows for the reconstruction of detailed surfaces and inscriptions without any direct handling, thus reducing damage risks.

- Enhanced Collaboration: Global policy makers and researchers across the globe are now able to freely access and digitally preserve information stored in heritage databases, which greatly assists in collaborative planning towards holistic conservation.

- Simulation: 3D information enables authorities to forecast the impact of earthquakes, flooding, or even tourism and take pre-emptive measures to safeguard the sites.

- Greater Public Support: There has been a marked increase in the public's educational awareness due to the popularity of virtual reconstructions and interactive 3D models of sites which leads to greater support for preservation initiatives.

A case in point: In Shah-i-Zinda, the restoration team was able to design and perform virtual simulations of the repairs using digital design documents resulting in greatly reduced expenses, time, and historical damage.

Comparison of the Effectiveness of Using These Tools Versus Traditional Preservation Methods

Criteria	Traditional Methods	3D Scanning & GIS Tools
Accuracy	Relies on manual measurements and sketches; subject to human error	High precision digital capture of geometry and details
Accessibility	On-site presence required; limited data sharing	Remote access and global collaboration possible
Intervention	Often invasive; risks damage during documentation	Non-invasive; reduces physical contact with fragile elements
Monitoring	Difficult to detect gradual changes	Enables time-lapse comparisons and condition monitoring
Cost & Time	Long-term manual work; high labour costs	High initial setup, but efficient over time
Preservation of Data	Analog records may degrade or be lost	Digital archives can be stored, replicated, and restored

Despite the importance of past techniques especially concerning physical restoration work and historical rendering, traditional methods take precedence, whereas, on the other hand, tools focused on computation result in greater accuracy, scale, and strength. Also, in their synergy, these two elements allow for the safeguarding of both the physical and non-physical components of heritage in a holistic manner.

CHALLENGES AND LIMITATIONS

In the Central Asian region, the application of 3D scanning and GIS technologies poses unique challenges despite the advancements in the digital preservation of cultural heritage. The shortcomings include the underdeveloped use of technology at institutions in the region as a result of limited contextual and regional factors.

Many heritage sites across Central Asia are situated in rural regions or remote politically sensitive zones. Access to these areas can be hampered by bureaucratic barriers, foreign researcher restrictions, poor infrastructure, or impenetrable borders. These dynamics, witnessed in parts of Kyrgyzstan and Tajikistan, Turkmenistan and Tajikistan, pose serious challenges towards achieving the intended purpose of digital preservation.

The combination of arid and mountainous regions that define Central Asia's diverse geography and rich topography serve as serious obstacles while undertaking on-site data collection. Scanning and equipment operability are subject to severe interference from extreme temperatures, dust, and changes in sunlight

throughout the day. Moreover, fieldwork opportunities can be frequently limited by seasonal weather conditions.

Remarkable advancement in 3D scanning technologies, such as LiDAR systems, and drone-mounted photogrammetry setups incur great expenditure while simultaneously requiring constant maintenance. Several local institutions lack adequate funding to maintain or purchase the equipment. Moreover, advanced computing infrastructures for storage and processing data are often lacking at regional universities or heritage offices.

In Central Asia, the approaches of combining 3D scanning and GIS with their respective cultural heritages is virtually unexplored, resulting in a lack of trained professionals. There tends to be an adequate supply of information technology and surveying, yet digital heritage recording, data analysis, elaborate interpretation, and analysis of preservation is not well developed, which in turn creates reliance on foreign teams and hinders local preservation ownership. In the case of the region's digital heritage projects, most are funded by international grants or are part of short-term collaborative research initiatives. These collaborations are usually project-centred and short-term, which makes it hard to foster sustainable locally driven ecosystems of digital preservation. While creating digital records is the first milestone, maintaining their accurate information and long-term usability requires stringent data management. Unfortunately, the archiving region lacks uniform procedures for metadata, digital archives, and cross-organizational cooperation standards. As a result, the possibility of integrating or reusing the data into future projects is significantly strained [16].

The region suffers significantly from a lack of educational curricula and training schemes focused on basic educational tools which should include workshops, classes, and even study-abroad programs on digital tools of heritage. This change can be brought forth through collaborations with foreign institutions. Knowledge transfer and providing custom to toolkits region need can be estimated through institutes like UNESCO and ICOMOS.

Other countries geographically located next to each other should be able to collaborate and share resources. In that context, creating centralized digital heritage hubs equipped with scanning facilities, GIS labs, and archival resources would allow these institutions to work more effectively. In addition, these centres can serve as repositories for data, leading to these centres functioning as training and research hubs. Moreover, lower-cost and open-source alternatives to sophisticated scanning equipment (like smartphone photogrammetry or handheld scanners) can be utilized as preliminary tools to document community-driven small-scale initiatives. Likewise, certain GIS software applications such as QGIS provide a free counterpart to costly proprietary systems. Cultural ministries and governments need to ensure the integration of information technologies and digital preservation systems into national policies related to heritage preservation. The development of legal frameworks to foster data sharing, cross-border collaboration, and the creation of digital archives will help many long-term plans. Educating the public and local communities with virtual exhibits, digital reconstructions, and other campaigns that focus on education help gather support towards active preservation. Such strategies help the formal projects and help change peoples' perception towards the undertaking to increase collective responsibility. Crowdsourced documentation or mapping initiatives are great examples of Citizen Science.

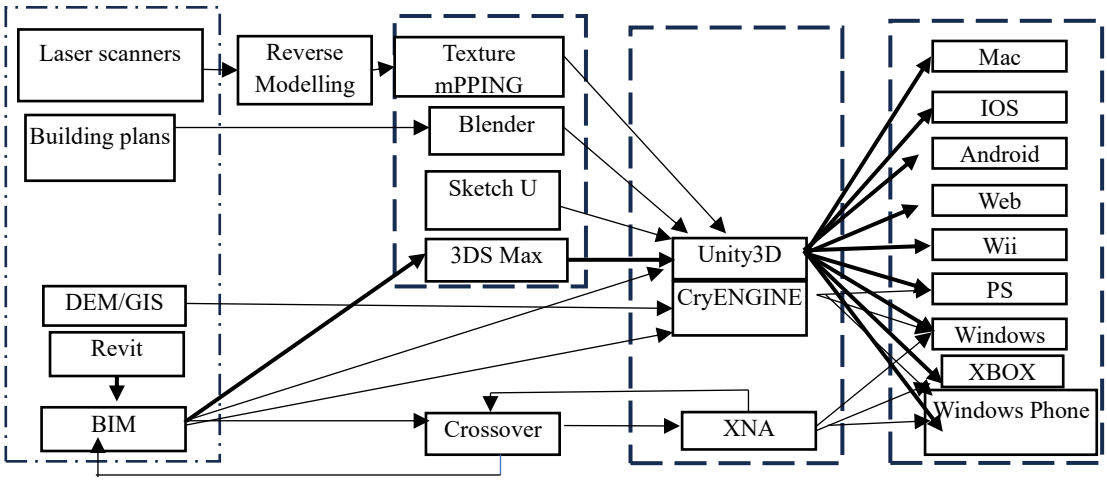

Figure 1. Extending 3D -GIS district model bim building model of cultural heritage

In cultural heritage preservation, an interactive extended 3D model integrated with GIS functionalities provides a comprehensive representation of historical sites, alongside artifacts that can be appreciated spatially in figure1. The risk assessment and conservation strategies can be documented in detail due to the spatial analysis features of GIS and the advanced 3D modelling capabilities.

RESULT AND DISCUSSION

The rapid development of technology is broadening the possible uses of 3D scanning and GIS frameworks in the digital preservation of heritage sites. New advancements in artificial intelligence, cloud data technologies, and immersive media, including virtual and augmented reality, will greatly enhance the functioning of these tools.

Through the integration of artificial intelligence with GIS, predictive modelling can enable simulacra for the long-term structural decay, environmental impacts, or effects of urbanization on a heritage site. With these models, pre-emptive measures for intervention rather than restoration would be possible. In the same way, drone or IoT (Internet of Things) sensor remote real-time monitoring linked to GIS platforms could enable managers to monitor offshore deterioration or unauthorized alteration activities geographically.

In 3D scanning, the prospective advancement of portable and fully autonomous scanning systems will make them more accessible to field researchers and provide thorough documentation even in hard to access or dangerous places. Also, automated classifying of architectural elements captured in scans (sematic segmentation) will further enhance analysis, historical reconstruction, and integration with BIM systems.

The use of 3D scanning and GIS technologies is not restricted to preservation. They hold great potential in transforming academic research, educational outreach, and cultural tourism in Central Asia.

Digital archives enable the disembodied examination of heritage sites, thereby enhancing multidisciplinary approaches within architecture, archaeology, history, and digital humanities. The integration of GIS with data spatial analysis and 3D modelling yields insights into settlement patterns, trade routes, and religious influences that remain obscured in traditional records.

Digital 3D representations of architectural structures can be utilized by primary and secondary educational institutions, museums, and universities to stimulate interest in learning. The provision of 3D models and virtual field trips has the potential to appeal to youth audiences and foster cultural awareness. Access to heritage sites is particularly advantageous through online databases and mobile applications for diasporic communities and people with mobility restrictions.

The use of 3D models and GIS mapping within virtual and augmented reality content creates opportunities for the enrichment of site visitors' experiences through multilingual audiovisual history interpretations. These technologies support the reduction of foot traffic in areas of historical sensitivity and aid in the preservation of ancient structures by redirecting tourists from vulnerable zones. Through contemporary digital tourism services, lesser-known sites can be showcased to foster a more balanced distribution of economic benefits to the region.

Whereas these opportunities increase public participation with culture and history, the growing ease of accessing sites through the internet poses a risk of oversimplifying cultural narratives. Ensuring balanced drawbacks and benefits serves as an important issue for advocating cultural heritage and guarantees responsible stewardship over heritage that is preserved digitally.

When the works are part of overseas organizations or international research groups, questions arise more often about the custodianship of digital representations of the culture's heritages. Central Asia is one of the regions with no local community or administrative consent, participation, or approval where data can be collected, stored, published, or monetized. Protecting the sovereignty over that data and clarifying the policies for the controlling and sharing of such data are crucial.

The omission of data rarely results in errors in historical representation; however, digital reconstructions tend to do so quite often. Models based on incomplete data or uncertain designs tend to yield far-fetched results. The automated processes used for reconstruction must be plainly marked so that hypothetical specimens are not miscast as historical remnants. Guidelines on ethics need to place stronger emphasis on transparency, precision, and scholarly meticulousness.

Certain sites, for example, funerary or religious structures, may possess community or spiritual value and therefore require respectful treatment. The digitization and public display of human remains or sacred spaces must be thoroughly examined alongside local stakeholders. Stakeholder participation should span all phases of digital heritage projects.

The digital divide may deepen because only institutions with financial or technical resources will be able to access available tools, which will create a Split between urban and rural institutions or among different countries. Inclusive access, training, and equitable distribution of results need to be provided.

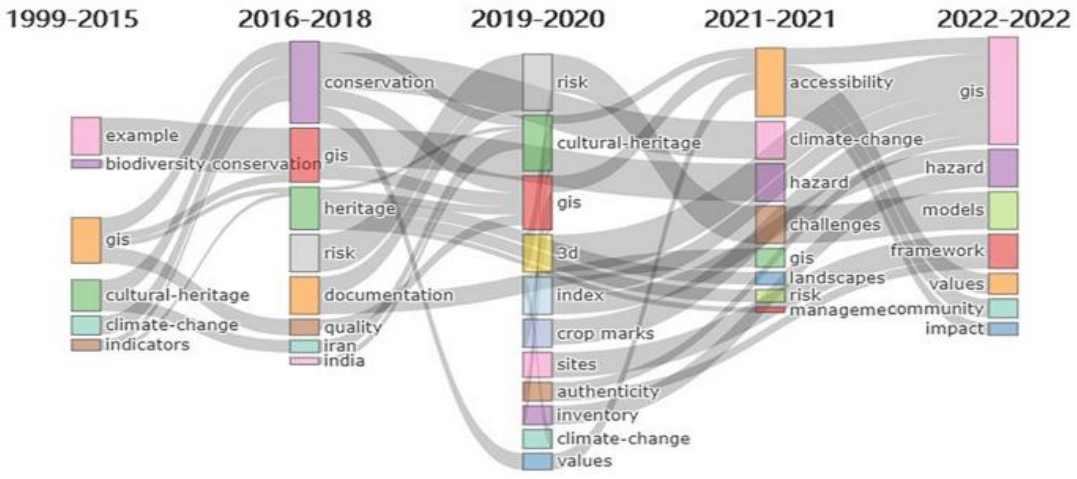

Figure 2. Emerging trends in 3D and GIS modelling on cultural heritage conservation

The integration of 3D and GIS has greatly transformed approaches toward cultural preservation. Perhaps the most notable advancement is the addition of AI and machine learning, which allows for automated feature extraction, damage assessment, and deterioration predictive modelling. Moreover, remote access to 3D models and geospatial data stored in the cloud is supporting international collaboration and engagement with such projects. Through the use of reality capture technologies, including LiDAR and photogrammetry, the costs associated with high-resolution documentation of remote or endangered sites

has made these technologies more accessible and widespread. Applications utilizing 3D and GIS data serve Augmented Reality (AR) and Virtual Reality (VR) educational purposes for virtual tourism as well as community engagement programs, thus blurring the line between reality and the digital world. Advanced, historically accurate site and architectural modelling now made possible through semantic modelling and HBIM (Heritage Building Information Modelling) enable more detailed construction narratives in the context of the architecture's evolution. All of these efforts converge toward digital conservation, greatly improving its accuracy, accessibility, and ecological impact regardless the global location.

CONCLUSION

This article analysed the impact of the modern methods of 3D scanning and GIS technologies on the preservation efforts of the architectural wonders of Central Asia. The first part focused on describing the various types of architecture found in the region, trying to trace the "silo" thinking, which must have been associated with the methods of documenting and preserving the culture, as it relies heavily on traditional means, into the region's rich culture, showing how the modern technology is changing the documentation and the preservation of the heritage.

The region's architectural digital documentation, analysis, and monitoring have benefitted from the application of 3D scanning and GIS for the Shah-i-Zinda, Merv, Khiva, and other major landmarks. The paper also discusses the problems associated with the lack of training, funding, documentation, and data management, as well as training and organizational issues. These technological restrictions result in inefficient resource allocation, poor data governance, and ineffective data utilization. Lastly, it examined the potential outcomes of digitally disruptive technologies on education, research, tourism, and cultural heritage and the ethics surrounding these innovations.

Applying 3D scanning and GIS tools as part of cultural heritage preservation activities marks a new era in and step forward concerning optimization and integration. Unlike traditional practices, these technologies provide passive and much richer data with exceptional detail spatially. In Central Asia, for example, architectural artifacts tend to be at risk from environmental and human activities—what makes them remotely located, delicate, and prone to damage. These digital technologies can assist in implementing active measures that ensure the preservation of these artifacts in a sustainable manner. In addition, they provide new opportunities for public interaction, academic participation, cultural tourism, and educational development.

Through the use of 3D scanning and GIS technologies, evolving accurate requisite documentation and spatial data, realistic predictive modelling, and immersive interpretation, cultural identities are not only preserved but enhanced.

Achieving the goal requires a combined effort. Local governments, educational and cultural institutions, as well as international institutions, should join together to enhance the level of investment in local enabling technologies, access control infrastructures, and define digital preservation policies and practices.

Further Research should focus on:

- Taking measures to create affordable and easily replicable digital procedures applicable in minimal resource settings;
- Incorporation of AI and machine learning into study and reconstruction processes.
- Investigating the socio-cultural implications of virtual heritage on communal identity and participatory citizenship.
- The architectural legacy of Central Asia is not only an archive of the bygone; it is a pillar for cultural adaptability for the forthcoming. Digital preservation is not an alternative anymore, it is imperative. So, we must act now before the history that is invaluable gets lost forever.

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