EAI Endorsed Transactions
on Digital Transformation of Industrial Processes Research Article **EAI.EU**

Digitization of civil architecture objects during wartime using photogrammetry: A case study of Sumy State University

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Abstract

INTRODUCTION: In the context of the ongoing war in Ukraine, the preservation of architectural heritage has become critically important. In this regard, the documentation and preservation of architectural heritage have become crucial.
OBJECTIVES: The study employs drone-based aerial imaging and terrestrial photography to generate accurate 3D models of a partially destroyed historic building.
METHODS: A photogrammetric technique was employed to create an accurate 3D model of Campus K-2 of Sumy State University, destroyed by russian missiles on April 13, 2025, in Sumy, Ukraine. A comprehensive approach for involving photogrammetric reconstruction, texture processing, and building information modeling (BIM) integration was described. The research also outlines the challenges of restoring during wartime, discusses data acquisition and processing workflow, and evaluates the effectiveness of low-cost equipment and open-source software in achieving high-quality results.
RESULTS: The resulting digital model captures structural deformations and facade details. The implemented approach enables documentation and monitoring of damaged structures. It also provides valuable fundamentals for the studied object's future restoration, structural analysis, and memorialization.
CONCLUSION: The research shows photogrammetry as a fast, reliable tool for documenting cultural heritage in wartime and emphasizes its social value for education and preservation. It also suggests adding protective architectural features to reconstructed heritage buildings to improve resilience in conflict zones.

Keywords: digital reconstruction, cultural heritage preservation, resilient infrastructure design, sustainable reconstruction of war-damaged sites, digital documentation for historical memory, post-conflict recovery planning

Received on 10 July 2025, accepted on 31 July 2025, published on 04 August 2025

doi: 10.4108/dtip.9697

1. Introduction

In the context of the ongoing war in Ukraine, the problem of documenting, preserving, and protecting architectural heritage has become particularly urgent, as the loss of historical sites harms the cultural identity and memory of cities [1].

Critical is the prompt documentation of the condition of damaged cultural heritage sites for their subsequent restoration and reconstruction [2]. The relevance of the research topic is confirmed by a number of scientific studies that highlight various aspects of documentation, preservation, and virtual modeling of cultural heritage, especially in the context of modern threats.

Photogrammetry has emerged as a key technology for rapidly and accurately recording damaged structures [3]. This method allows the creation of high-resolution 3D digital

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models based on photographic data collected from aerial and ground-based sources. It is especially valuable in wartime conditions, where access to sites is often limited, and traditional documentation techniques are impractical.

Based on the latest research data [4–13], a comprehensive global overview of photogrammetry applications by sector is summarized in Figure 1.

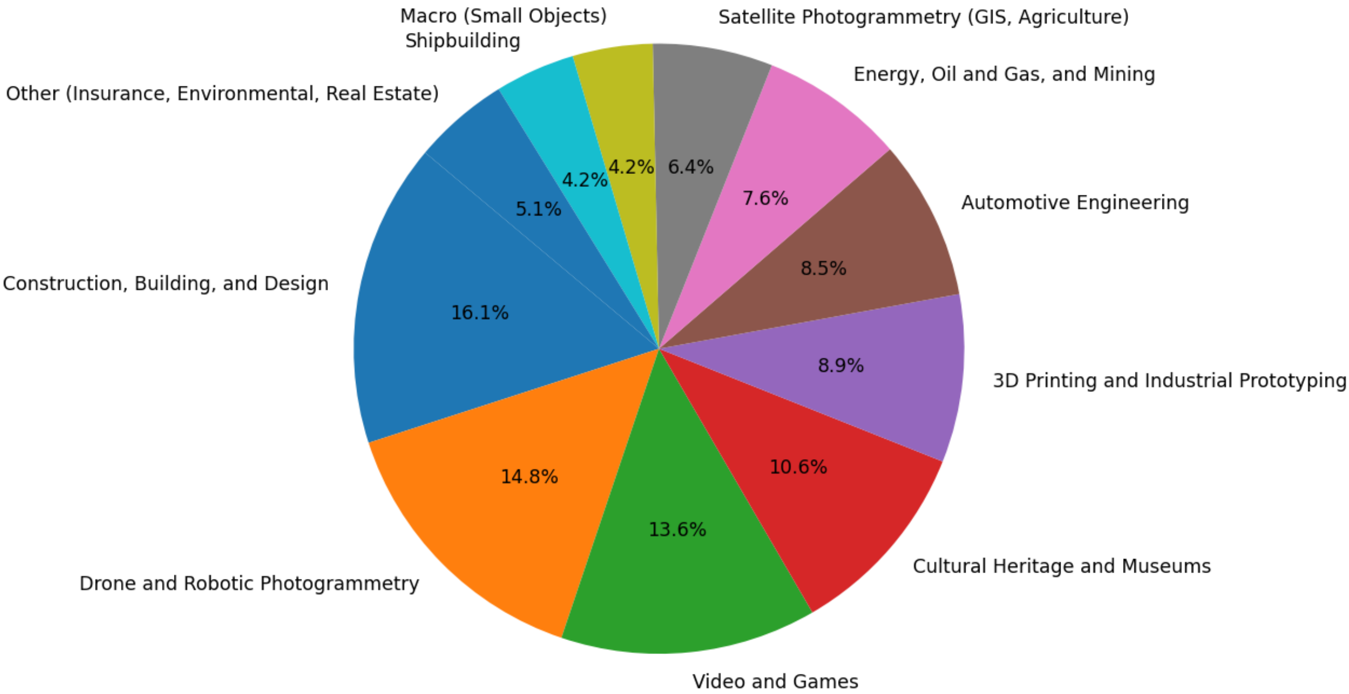

Figure 1. An overview of photogrammetry applications by sector

The research aims to demonstrate how photogrammetric techniques can be effectively applied during wartime for structural analysis, heritage preservation, and post-war reconstruction planning.

The research also explores integrating protective design principles into restoration, offering a comprehensive approach that balances historical fidelity with contemporary security requirements.

2. Literature Review

The significance of the researched issue is emphasized by numerous scientific publications worldwide. In particular, Ivanysko et al. [14] examined the challenges and threats to the sustainability of cultural practices in Ukraine during the war. This article effectively illustrates the challenges to sustainable cultural practices (from destroying tangible heritage sites to disrupting cultural processes, destabilizing cultural identity, and erosion of national memory).

Ferdani et al. considered 3D reconstruction and validation of historical background for immersive VR applications [15]. After, Rodriguez-Garcia et al. [16] systematized approaches to the virtual reconstruction of cultural heritage in a virtual reality (VR) environment.

Methods of 3D modeling of architectural heritage using aerial photography are described in [17–28]. A comprehensive analysis of the results obtained and their advantages and disadvantages is summarized in Table 1. It reflects recent experience in digital photogrammetry and laser scanning in documenting cultural heritage sites. It also represents the possibilities of applying photogrammetry for architectural education and practice.

Thus, unmanned aerial vehicles (UAVs) have emerged as a significant tool in cultural heritage preservation and documentation [29]. The reviewed studies reveal a broad spectrum of applications, methodological innovations, and technological integrations that underline the growing relevance of UAV-based photogrammetry in heritage research.

The primary applications include comparative assessments of UAV photogrammetry against traditional techniques such as terrestrial laser scanning (TLS) and ground-based photogrammetry. UAV-based data are increasingly integrated with digital systems such as building information modeling (BIM), enhancing the management and interpretation of historical sites [30]. Moreover, UAVs have proven valuable in documenting damaged, deteriorated, or inaccessible structures [31].

The main advantages of photogrammetry in digitizing architecture objects include the high flexibility and mobility of UAV systems, enabling access to complex or hazardous areas [32]. UAV photogrammetry is generally recognized for its cost-effectiveness and efficiency, particularly compared to resource-intensive methods. The ability to capture high-resolution imagery from multiple angles generates detailed and accurate 3D reconstructions [33].

Table 1. UAV-based 3D modeling for cultural heritage (in alphabetical order of the first author)

Author(s)	Main impact	Advantage(s)	Disadvantage(s)
Bolognesi et al. [17]	Comparison of UAV and ground-based photogrammetry	High accuracy, efficiency	Limitations when photographing facades
Hu and Minner [18]	System review for cities and heritage	Interdisciplinarity	Surface technical detailing
Jiménez-Jiménez et al. [19]	Quality of budget drone models	Economic accessibility	Less texture detail, noise
Orihuela and Molina-Fajardo [20]	UAV for BIM	BIM integration, heritage preservation	Restrictions for dense urban development
Petráček et al. [21]	Autonomous shooting of dark objects	Access to hard-to-reach areas	Lighting restrictions, global positioning system (GPS) dependence
Rinaudo et al. [22]	Early use of UAVs in heritage	High mobility, regular monitoring	Restrictions in difficult terrain
Samadzadegan et al. [23]	Multi-angle shooting with ±1 cm accuracy	Spatial coverage, detailed geometry	Relatively large number of images, complicated processing
Srinivasan et al. [24]	Development of a hexacopter for cultural infrastructure	High stability in difficult weather conditions, customization to tasks	Specializing in environmental monitoring
Tong et al. [25]	Comprehensive roof and facade covering	Data complexity, accuracy	Coordination of different methods is required
Tytarenko I. et al. [26]	UAV photogrammetry for damaged objects	High detail of facades, a focus on partially destroyed objects	Local focus, limited comparative database
Ulvi [27]	Comparison of UAV photos with TLS	UAV flexibility, accessibility	Less accurate than TLS during detailization
Yang et al. [28]	Bibliometric review of 3D clouds	Generalization of approaches	Lack of practical cases

Customization of UAV systems further enhances their applicability across diverse environmental and architectural conditions. Additionally, the interoperability of UAV-generated data with multidisciplinary platforms, such as BIM or geographic information system (GIS), supports broader applications in conservation planning and urban heritage analysis [34].

Particularly, despite the strengths, UAV systems exhibit several limitations. These include reduced effectiveness in densely built or vegetated environments, challenges in capturing vertical or narrow features, and dependence on optimal lighting and weather conditions. Accuracy limitations related to TLS in fine-detail analysis are also noted [31, 35].

Furthermore, the data's complexity and volume present processing, storage, and interpretation challenges. A lack of standardized methodologies and consistent comparative datasets is cited as a barrier to reproducibility and benchmarking in UAV-based heritage research [36].

In summary, UAV-based 3D modeling represents a transformative approach in cultural heritage documentation. Its strengths in terms of accessibility, affordability, and high-resolution data acquisition make it a valuable complement to existing methods.

However, technical, environmental, and methodological challenges remain, highlighting the need for continued research and the development of standardized workflows to fully harness the potential of UAV technologies in heritage science.

Notably, accurate 3D replicas of objects created using photogrammetry contribute to advancing technical protection measures for buildings by constructing specialized protective structures.

Particularly, the behavior of reinforced concrete structures of modular shelters under explosion conditions was studied by Novhorodchenko et al. [37]. As a result, ways for ensuring the protective performance of shelters under the impact of an explosion were proposed.

Anas et al. [38] studied reinforced concrete structures for blast protection. For this purpose, numerical modeling was used under various impact scenarios. As a result, the blast load capacity of reinforced concrete shelters was predicted.

Zhydkova et al. [39] proposed solutions for equipping protective shelters in the basements of residential buildings, considering safety and structural standards.

In the article [26], the authors stated that "further research will be conducted on the application of photogrammetry to digitize architectural heritage objects (e.g., Manor of Sukhanovych-Sumovskych of the Institute of Applied Physics of the National Academy of Sciences of Ukraine), as well as modern objects (e.g., Congress Center and Campus of Sumy State University) destroyed by russian missiles on April 13, 2025, in Sumy, Ukraine". Therefore, this article considers the application of photogrammetry to digitize Campus K-2 of Sumy State University.

3. Research Methodology

The object of the study was Campus K-2 of Sumy State University (Figure 2a), destroyed by russian missiles on April 13, 2025, in Sumy, Ukraine (Figure 2b).

For your information, after a missile strike on the historic area of the city of Sumy, the Sukhanov–Sumovskyi estate, the buildings, and the Congress Center of Sumy State University located in the city center were significantly damaged.

a

b

Figure 2. Campus K-2 of Sumy State University before (a) and after (b) destruction

One of the most effective methods for spatial recording and documenting the condition of architectural objects is photogrammetry, a modern technique for creating 3D models of objects based on photographs, which is an efficient tool for documenting damage.

Therefore, all the damages were documented with the support of the Department of Culture, Tourism and Religions and the Department of Urban Planning and Architecture of the Sumy Regional State Administration. Accurate 3D models of the respective objects were created based on the taken photographs.

Using photogrammetry combined with aerial photography by UAVs enables the rapid and highly accurate acquisition of detailed information about the condition of architectural objects, even in challenging environments such as combat zones or restricted-access areas.

The damage documentation was carried out using photogrammetry, aerial photography, and ground-based photographic recording.

A DJI Mavic 3 Pro UAV (Figure 3) was used to capture the area from various heights and angles.

a b

Figure 3. UAV (a) and workplace (b) for photogrammetry

The drone is equipped by a triple-camera system: a primary 20 MP Hasselblad camera with a 4/3” complementary metal oxide semiconductor (CMOS) sensor, a medium telephoto 48 MP (1/1.3” CMOS) lens with 3x optical zoom, and a long telephoto 12 MP lens with 7x optical zoom, all stabilized by a 3-axis gimbal. It offers a maximum flight time of up to 43 min, a top speed of 19 m/s, and a control range of up to 15 km via the OcuSync 3+ transmission system.

The drone is also equipped with an omnidirectional obstacle avoidance system featuring 8 sensors for safe flight, supports video recording up to 5.1K at 50 fps and 4K at 120 fps, and includes the DJI RC controller with an 8-inch display and a microSD slot supporting up to 512 GB.

A professional camera for detailed documentation of the facades with cross-angle shots to enhance the accuracy of geometric reconstruction in the digital model.

The next stage involved processing the photographs using Lightroom for sorting and quality assurance, then generating a 3D model with the specialized software 3DF Zephyr. This enabled the generation of three-dimensional point clouds of the objects, followed by final model processing in Blender and subsequent integration of the model into BIM software, such as Revit. A step-by-step software application is presented in Figure 4.

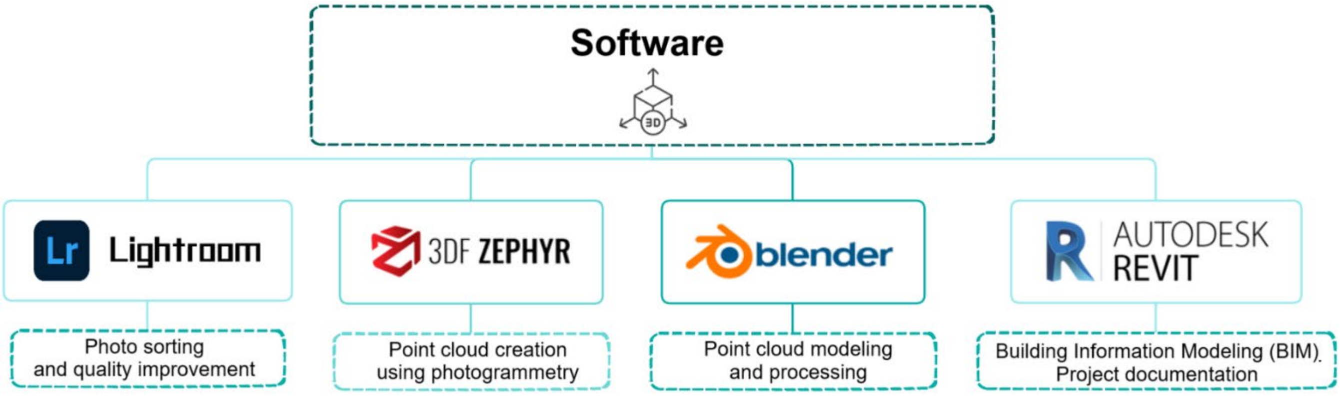

Figure 4. A flowchart of software application

The created 3D model should accurately reflect the scale and nature of the damage and serve as a basis for analyzing the condition of the damaged heritage sites and planning restoration works.

A detailed flowchart of the research methodology is as follows (Figure 5):

(i) Step 1 – Definition of the Research Object:
- Target: Campus K-2 of Sumy State University, partially destroyed during a missile strike on April 13, 2025.
- Justification: The building is a historical architectural monument and a cultural heritage site. Its documentation is critical for future restoration.

(ii) Step 2 – Data Collection Preparation:
- Goal: Plan comprehensive image acquisition of the damaged building.
- Tools Prepared:
  – UAV (DJI Mavic 3 Pro) for aerial imagery;
  – digital single-lens reflex (DSLR) camera for detailed facade imagery at oblique angles;
  – Software: Adobe Lightroom (preprocessing), 3DF Zephyr (3D model generation), Blender (geometry refinement), and Autodesk Revit (BIM integration).

(iii) Step 3 – Image Acquisition:
- Techniques:
  – UAV-based photogrammetry: Aerial photos taken at multiple altitudes and angles;
  – Terrestrial photogrammetry: High-resolution images of building facades from the ground.
- Conditions: Fieldwork performed in a post-conflict zone with limited accessibility and safety constraints.

(iv) Step 4 – Image Preprocessing:
- Software: Adobe Lightroom.
- Action:
  – Selection and quality control of images;

– Adjustment of lighting and contrast for photogrammetric consistency.

(v) Step 5 – 3D Model Generation:
- Software: 3DF Zephyr.
- Process:
  – Structure-from-Motion (SfM) technique used to reconstruct dense point clouds;
  – Mesh generation and texturing of aligned photos.

(vi) Step 6 – Model Refinement and BIM Integration:
- Refinement: Imported into Blender for post-processing (geometry cleaning, smoothing, filling gaps).
- Integration: Exported and imported into Autodesk Revit for semantic enrichment (BIM) and further planning.

(vii) Step 7 – Structural Analysis and Visualization:
- Deliverables:
  – High-resolution 3D model of the damaged building;
  – Visualization from multiple angles/sides.
- Analysis:
  – Identification of cracks, facade deformations, and collapse areas;
  – The model is used as a basis for restoration.

(viii) Step 8 – Future Use Planning:
- Applications:
  – Memorialization, virtual tours, restoration training;
  – Integration into post-war urban recovery strategies;
  – Protective architectural retrofitting.

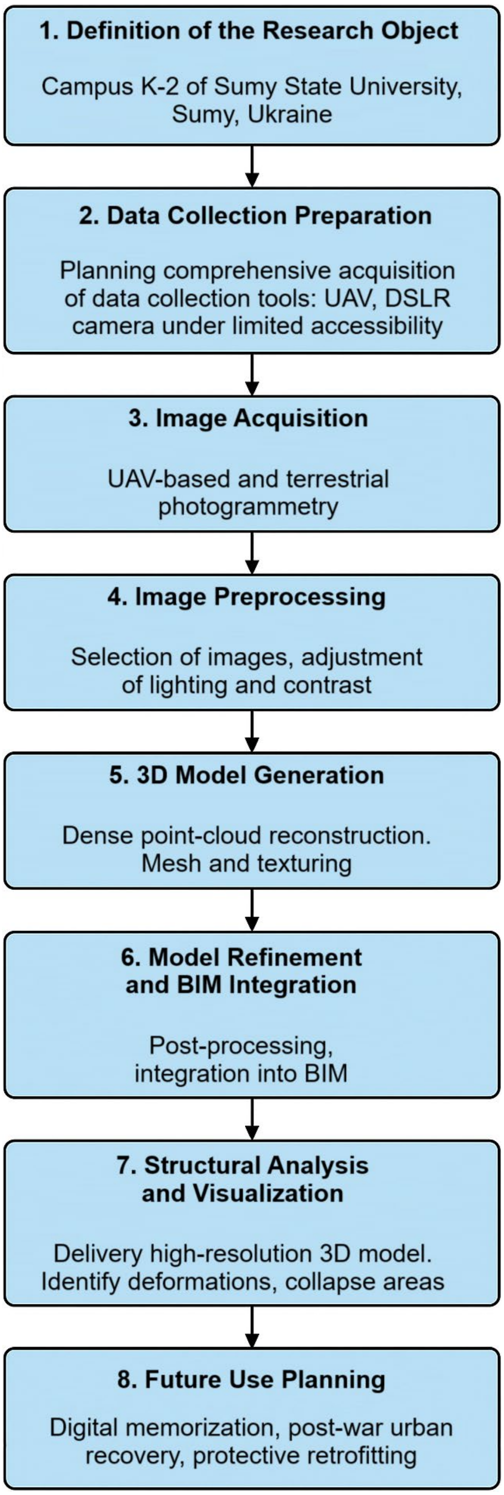

Figure 5. The main stages of the research methodology

To ensure the reproducibility of the photogrammetric reconstruction and modeling workflow, the following details regarding the dataset composition, capture configuration, and processing parameters can be followed for the image acquisition data: UAV model – DJI Mavic 3 Pro; flight altitude ranges – 15–50 m; camera specs – 20 MP Hasselblad, 48 MP medium telephoto, and 12 MP zoom; image format – *.dng for UAV, *.cr2 for DSLR; capture time – 2.5 hours total; weather – clear sky, low wind.

4. Results

The photogrammetric scanning made it possible to create an accurate 3D model of the damaged object – Campus K-2 of Sumy State University – an architectural object and a historic building of the District Court.

The obtained point cloud captured the building's geometry, the extent of the damage, the nature of the deformations in the load-bearing structures, and the details of the facade's decoration, which is essential for further restoration.

The generated model contains high-quality textures and geometry, allowing for the assessment of the extent of material damage and the documentation of cracks and collapses. This provides the possibility to analyze the object's technical condition and prepare recommendations for conservation or restoration.

As a result, the scanned digital model of the historic damaged building Campus K-2 of Sumy State University is presented in Figure 6.

To ensure the reliability and geometric accuracy of the generated 3D model of Campus K-2, a set of ground control points (GCPs) was established before the image acquisition process. A total of 12 GCPs were evenly distributed around the perimeter and facade and measured using a 1.7–2.5 cm accuracy.

After model reconstruction, the 3D coordinates of these GCPs were extracted from the model and compared to their true positions. The deviations were calculated in all three spatial dimensions X, Y, and Z. Average deviations by these axes are $\Delta X = 1.7$ cm, $\Delta Y = 2.1$ cm, and $\Delta Z = 2.5$ cm, respectively.

Therefore, 3D root mean square error (RMSE)

$$3D_{RMSE} = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \quad (1)$$

equals to 3.7 cm.

The obtained accuracy is within acceptable limits for architectural documentation and structural assessment, especially considering the constraints of a wartime, e.g., partially destroyed environment.

The created 3D model provides a highly accurate reproduction of the scale and geometry of the damages, which is critically essential for a comprehensive technical analysis of the damaged cultural heritage object. The model serves as a basis for conducting structural analysis of the monument's condition, allowing for identifying zones with the highest levels of degradation and determining damage mechanisms.

The use of three-dimensional digital representation facilitates the optimization of the restoration planning process by modeling intervention options, assessing their effectiveness, and monitoring restoration parameters. Additionally, the digital model integrates into GIS and BIM systems, enabling coordinated interaction among the various disciplines involved in the restoration project and enhancing the accuracy and speed of technical decision-making.

Photogrammetry data can be integrated into monitoring systems for cultural heritage sites, providing regular and accurate information on their deformation, damage, or other changes over time. This enables the creation of effective early warning systems for risks and the planning of preventive conservation measures. The obtained 3D models are also used to develop interactive tours and virtual exploration of heritage sites for restricted or hard-to-reach areas.

The data are also used in memorialization programs, preserving historical memory in digital format and promoting cultural heritage to a broad audience. Furthermore, photogrammetric materials are integrated into educational courses and research projects, providing visual support and enhancing the quality of the learning process. The preservation and archiving of these data create a long-term database for analyzing object changes over time and supporting informed decision-making in restoration and cultural heritage conservation.

a

b

Figure 6. Digital models of the damaged Campus K-2 of Sumy State University: a – roadside view; b – alley-side view

The obtained 3D scanning results highlight the importance of rapid documentation of the condition of architectural heritage after damage for its further study and restoration.

The obtained data on the scale and nature of the damage emphasize the need not only for the restoration of historical objects but also for the implementation of protection systems adapted to conditions of military threats.

One promising solution is the integration of special protective rooms, e.g., safe spaces [40], into restored historic buildings, similar to Israeli mamad shelters, which are individual safe rooms in residential buildings. These structures, made of reinforced concrete, are capable of withstanding shelling and explosions that cause damage from shrapnel, thereby protecting people's lives during attacks.

Implementing such protective systems in restored historic sites, such as the historic building K-2 of Sumy State University, will allow the combination of architectural heritage value with modern safety requirements. These solutions can be realized as separate rooms or corridors reinforced within the building structure, preserving the historic appearance of the facades while creating a safe space for people, as presented in [41].

The social value of the carried-out research is highlighted by a number of posts in Ukrainian media sources: https://cm.sumdu.edu.ua/en/science/heritage

Thus, the combination of photogrammetric documentation, historical reconstruction, and the integration of protective structures enables the formation of a new approach to architectural heritage restoration that considers modern trends and ensures the resilience of the urban environment against terrorist acts and military threats.

The research highlights the need to combine heritage documentation with forward-looking protective strategies in the broader context of post-conflict recovery. Reinforced safe spaces within restored heritage buildings could represent an innovative approach to reconciling cultural preservation with human safety under modern threats [42].

Based on a comprehensive analysis, a radar chart for visualizing the main characteristics of photogrammetry with related advantages is presented in Figure 7, with relative indicators, summarized in Table 2.

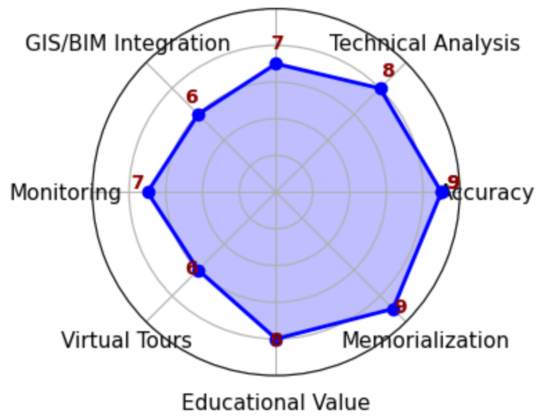

Figure 7. Photogrammetry applications and strengths

Table 2. Relative impact of photogrammetry

Parameter	Value*	Description

Accuracy	9	High reproduction accuracy
Technical analysis	8	Strong capabilities for technical analysis
Restoration planning	7	Highly suitable for restoration planning
GIS/BIM integration	6	Moderate integration with GIS and BIM systems
Monitoring	7	Effective monitoring of the objects' conditions
Virtual tours	6	Utilization for the creation of virtual tours
Educational value	8	Relatively high role in education activities
Memorialization	9	High potential role in memorialization

* from 0 (no impact) to 10 (highest impact).

Overall, this study contributes to the sustainable recovery of war-affected urban environments by offering a replicable, scalable, and socially valuable digital heritage protection framework aligned with the UN Sustainable Development Goals.

5. Discussion

The image overlap rate in the photogrammetric processing exceeded 80% (front) and 70% (side), satisfying recommended best practices for (SfM) reconstruction.

The accuracy assessment of the 3D reconstruction was performed by comparing the reconstructed coordinates of the GCPs, extracted from the 3D point cloud, with their measured real-world coordinates.

Quantitative metrics for validation of the 3D model accuracy are summarized in Table 3.

Table 3. Accuracy assessment of the 3D model

Parameter	Value	Description
Number of GCPs	12	GCPs measured with GNSS
RMSE in X-direction, cm	1.7	Horizontal error (east-west axis)
RMSE in Y-direction, cm	2.1	Horizontal error (north-south axis)
RMSE in Z-direction, cm	2.5	Vertical error
Total 3D RMSE	3.6	Combined spatial root mean square error
Mean deviation of architectural features, %	4.5	Compared to field measurements of 10 features
Average front image overlap, %	80	UAV image overlap along flight direction
Average side image overlap, %	70	Side overlap between image strips

These results demonstrate high spatial fidelity, especially considering the wartime environment and the use of a compact UAV system. Particularly, in the research work by Jiménez-Jiménez et al. [19], RMSE = 5–10 cm using budget drones; Samadzadegan et al. [23] – 1 cm with controlled multi-angle UAV imaging and intensive GCP usage.

To further validate the textural quality and structural accuracy, a comparison was made between several architectural details (window frames, facade cornices, door widths) measured in the field and corresponding features in the digital model. The average deviation across these features was below 5%, indicating satisfactory model precision for restoration planning purposes.

While photogrammetry has proven to be a cost-effective and accessible method for documenting damaged architectural heritage, other 3D documentation techniques offer distinct advantages and limitations that should be considered depending on the application context (Table 4).

Table 4. Comparison summary of 3D documentation techniques

Technique	Accuracy, cm	Portability	Cost	Textural quality	Suitability in conflict zones
Photogrammetry (UAV + terrestrial)	2–4	High	Moderate	High	High
Terrestrial laser scanning (TLS)	≤ 0.5	Low	High	Moderate	Limited
Structured light scanning (SLS)	0.1	Very low	High	Very high	Poor
UAV-based LiDAR	5–15	Moderate	Very high	Low	Moderate

Given the time-sensitive and logistically constrained context of war-damaged heritage sites, UAV photogrammetry offers an optimal balance of accessibility, efficiency, and visual documentation capability. Unlike TLS or LiDAR, photogrammetry can be rapidly deployed without extensive infrastructure or specialized personnel, making it an ideal solution for emergency response and conflict-area heritage preservation.

Integrating protective features, such as internal safe rooms or reinforced zones, into restored cultural heritage buildings should align with structural design standards and preservation principles. In this regard, relevant design standards and guidelines are as follows:

1) EN 1991-1-7 (Eurocode 1): "Accidental Actions", including explosion and impact resistance;

2) FEMA 453: "Risk Management Series" for designing buildings to resist terrorist attacks;

3) UFC 3-340-02 (US DoD): Structures to Resist the Effects of Accidental Explosions";

4) Ukrainian DBN V.2.2-5:2023: "Civil Defense Protective Structures", relevant for the development of safe spaces (shelters) within civilian buildings.

6. Conclusions

This study confirms the effectiveness of photogrammetry as a rapid, accessible, and accurate method for documenting war-damaged architectural heritage in conflict zones.

The partially destroyed Campus K-2 case study of Sumy State University demonstrates that high-resolution 3D models can be successfully generated using a combination of UAV-based aerial surveys and terrestrial photography, even under limited access and security constraints.

The digital model reflects the extent and nature of structural damage and preserves critical architectural details for future analysis, restoration planning, and educational use. Integrating photogrammetry with BIM environments enhances its applicability for long-term monitoring, virtual preservation, and public memory initiatives.

Thus, the obtained results demonstrate a potential contribution to sustainable development, particularly in protecting cultural heritage, advancing digital technologies for safe urban planning, post-war city reconstruction, disseminating inclusive educational tools, and more.

Remarkably, incorporating FEM-based structural simulation into the current digital reconstruction workflow would allow for further quantitative assessment of safety, proactive retrofitting planning, and the design of integrated protective structures. This integration will be vital for aligning cultural preservation efforts with modern standards for urban resilience, civil defense, and public safety in post-conflict recovery zones.

Therefore, further studies will be focused on the following:

– integrating photogrammetric 3D models into finite element analysis (FEA) for evaluating structural integrity and simulating load behavior under post-damage conditions.

– conducting blast and dynamic load simulations to assess potential retrofitting strategies and protective design scenarios for restored heritage structures;

– developing a streamlined workflow for photogrammetry-to-FEM conversion, enabling interdisciplinary applications in engineering safety analysis and restoration planning.

Further research will also be focused on the virtual reconstruction of the obtained 2D and 3D images of damaged objects using machine learning techniques with the application of artificial intelligence systems.

Abbreviations

BIM	Building Information Modeling
CMOS	Complementary Metal Oxide Semiconductor
GCP	Ground control point
GNSS	Global navigation satellite system
DSLR	Digital single-lens reflex
FEA	Finite element analysis
FEM	Finite element modeling
GIS	Geographic information system
GPS	Global positioning system
LiDAR	Light detection and ranging
RMSE	Root mean square error
SfM	Structure-from-Motion
SLS	Structured light scanning
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
VR	Virtual Reality

Acknowledgement

The study was carried out within the R&D project "Scientific Foundations of the Virtual Reconstruction of Destroyed Cultural Heritage Objects for the Recovery Strategy in Ukraine" (state reg. no. 0125U000440). The authors appreciate the support of the Department of Culture, Tourism and Religions of the Sumy Regional State Administration.

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