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Utilising non-invasive measurement methods for the inventory of endangered cultural heritage -case study of Iraq

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Abstract: Advanced non-invasive remote sensing techniques, in conjunction with advanced digital technologies designed for the acquisition and comprehensive analysis of extensive datasets, hold substantial promise for significantly augmenting the capacities associated with the documentation of cultural heritage sites. This is especially crucial when it comes to preserving endangered cultural heritage. The main goal of this article was to demonstrate instances of non-invasive approaches used to catalogue cultural heritage objects and locations in Iraq. This investigation showcased a number of examples and employed a variety of contemporary data collection and processing techniques. These included digital close-range photogrammetry, Building Information Modeling (BIM), data from crowdsourced data, and findings derived from the Mosul Project. As evident, reality underscores the presence of numerous perils endangering the preservation of tangible cultural heritage sites worldwide. Precious architectural marvels, artistic creations, and natural landmarks are at risk of permanent loss. Therefore, a prompt inventory process, along with the creation of precise digital models, ensures the protection, rescue, and potential reconstruction of these invaluable entities. The instances provided in this article proved that the application of different digitisation methods to Iraq's cultural heritage could readily serve as a model for other endangered objects and sites.

Keywords: 3D models, cultural heritage, hazard areas, Iraq, non-invasive methods, Iraq

1. Introduction

Cultural heritage comprises a collection of both intangible and tangible values, originating from the historical endeavours of humanity and transmitted across generations, reflecting the culmination of human spiritual and material activities. Artefacts within cultural heritage possess distinctiveness and historical significance, warranting legal protection [1]. Cultural and natural heritage sites elicit awe and fascination among individuals and tourists alike, serving as subjects of exploration and research to address diverse scientific and practical challenges. These cultural heritage sites transcend physical and temporal boundaries, existing

within the realms of human cognition, thereby enriching our environmental and intellectual milieu while carrying scientific, cognitive, and educational significance.

Cultural heritage serves as a significant testament to the collective human understanding of historical narratives. Regrettably, its safeguarding is not always guaranteed, as it remains susceptible to degradation resulting from both anthropogenic and natural factors. Cultural heritage frequently faces devastation attributable to myriad factors, encompassing natural phenomena such as floods, fires, and earthquakes, alongside human-induced acts, including civil conflicts and acts of terrorism [2]. The latter represent some of the most severe manifestations of criminal activities against human heritage. Protecting and preserving cultural heritage, whether in monuments, archaeological sites, cultural landscapes, or movable and immovable artefacts, often pose formidable challenges [1,3]. Since cultural heritage holds a universal significance for humanity, a collective responsibility exists to ensure its safeguarding, necessitating concerted efforts and decisive actions.

An example of the destruction of monuments can be seen in the warfare that took place during and after the Second Iraq War. The Second Iraq War, which began in 2003, profoundly devastated Iraq's cultural heritage. This impact extended during the conflict and the turbulent years that followed [4]. Several critical aspects of cultural heritage destruction during and after the war include:

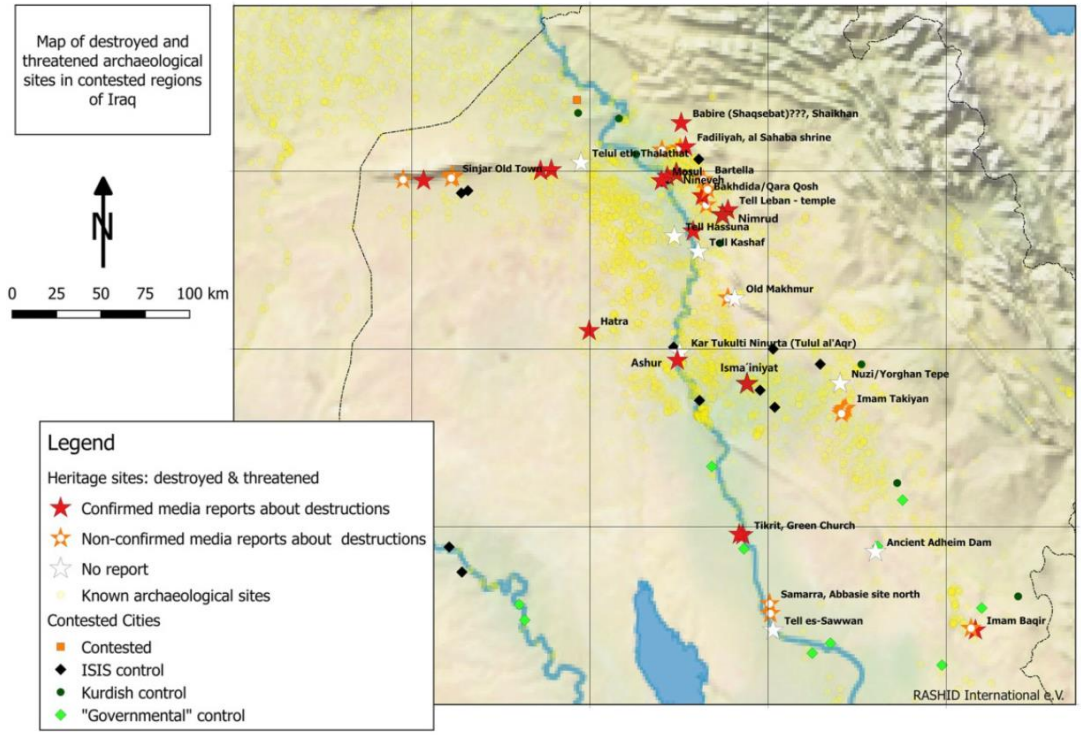
- **Looting and Pillaging:** One of the most immediate and visible forms of cultural heritage destruction occurred during the early stages of the war. Iraq's museums, archaeological sites, and historical monuments were subjected to widespread looting and pillaging. Priceless artefacts dating back thousands of years were stolen, smuggled, and sold on the black market, significantly losing cultural and historical treasures.
- **Museum Losses:** The National Museum of Iraq in Baghdad, home to an extensive collection of Mesopotamian artefacts, was heavily looted during the initial stages of the war. While some items were eventually recovered, many were lost forever. Other regional museums and historical sites across the country also suffered looting and damage.
- **Archaeological Sites**: Iraq is the cradle of civilisation, with numerous archaeological sites providing insights into human cultural development. Many sites, such as Babylon, Ur, and Nineveh, experienced damage and looting during and after the war. This destruction resulted in the loss of valuable historical context and information.
- **Neglect and Vandalism**: In the chaotic post-war environment, many cultural heritage sites and monuments were neglected and fell into disrepair. Some sites were even used for military purposes, causing further damage. Additionally, vandalism and graffiti added to the degradation of these historical sites.
- **Ongoing Threats**: Even after the formal end of the conflict, Iraq faced threats to its cultural heritage. Instability, sectarian violence, and the rise of extremist groups posed ongoing risks to historical sites and artefacts. The emergence of ISIS in 2014 led to the deliberate and systematic destruction of cultural heritage sites, such as the ancient Palmyra in Syria and historical sites in northern Iraq.

Efforts have been ongoing to mitigate the damage and preserve Iraq's cultural heritage. International organisations, including UNESCO, worked to document and recover stolen artefacts, restore damaged sites, and raise awareness about the importance of cultural preservation. However, the scale of destruction and loss has significantly impacted Iraq's cultural heritage and understanding of human history.

The most immediate and substantial threats to Iraq's cultural heritage are primarily concentrated within regions either presently or previously under the occupation of Daesh (ISIS). Specifically, these areas include Mosul and its surroundings, the Sinjar region, Anbar province, northern and eastern Salah ad-Din province, and parts of the Divala region. In contrast, the cultural heritage in the southern regions of Iraq and the north and eastern areas of the Kurdistan region faces different challenges, predominantly stemming from chronic underinvestment and economic difficulties rather than systematic destruction and looting [5].

Among the four Iraqi sites designated as UNESCO World Heritage sites (Ashur, Hatra, Samarra, Erbil Citadel), the first three are categorised by UNESCO as being 'World Heritage in Danger.' This classification signifies a significant and imminent threat to their integrity as sites of considerable cultural heritage importance. Of the 11 Iraqi sites listed on the UNESCO World Heritage Tentative List, at least two of globally significant stature, the Assyrian capital cities of Nimrud and Nineveh, have suffered severe episodes of destruction during Daesh's occupation of the Mosul region. Furthermore, the internationally renowned Mosul Museum has extensively damaged its exhibitions and collections.

(**a**)



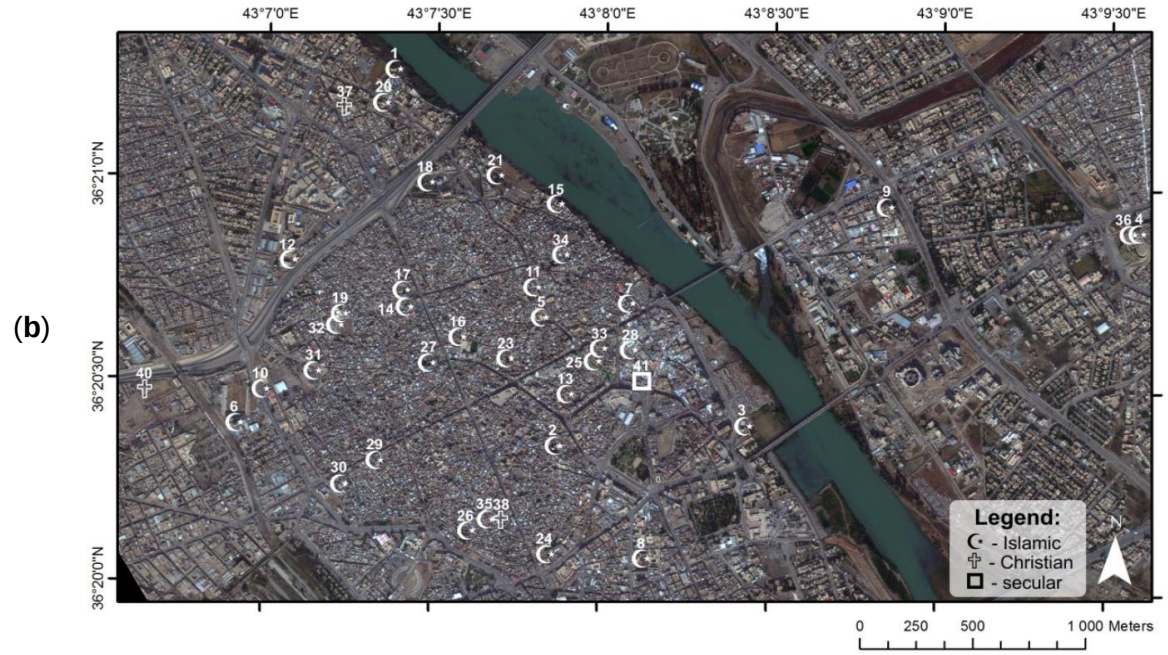


Figure 1. (a) Map of destroyed and threatened archaeological sites in contested regions of Iraq as of June 2016, (b) Satellite image of Mosul from November 2013 with heritage sites destroyed as of August 2015, marked by religious denomination [5].

Additionally, Daesh has engaged in the deliberate obliteration or severe damage of numerous cultural sites that hold profound significance for the various ethnic and religious groups residing in northern and western Iraq. These include churches, shrines, mosques, minarets, and tombs, as part of their campaign to eradicate the rich cultural and religious diversity that has historically characterised this region of the Middle East.

The losses include the 2003 looting of the Iraq National Museum in Baghdad and the large-scale looting of archaeological sites throughout Iraq. In the ancient past, Iraq was the birthplace of cities and writing. Iraq continued to be a centre of world civilisation as the homeland of the Sumerian, Assyrian, and Babylonian empires and the capital of the early Islamic Abbasid empire.

The article aims to show the possibilities of using modern measurement methods and ways of data acquisition on the example of selected 2D and 3D inventories of Iraq's valuable cultural heritage objects and sites.

2. The state-of-the-art digitalisation methods

Various 3D reconstruction techniques such as computer vision, computer graphics or close-range photogrammetry have been widely used for these applications to accomplish the architectural documentation and visualisation of cultural heritage artefacts. Contemporary photogrammetric measurement technologies enable comprehensive photogrammetric documentation through the utilisation of both passive (image-based) and active (range-based) measurement techniques for the creation of 3D geometric representations and architectural documentation, encompassing orthoimages, cross-sectional views, vector drawings, and digital surface object models. These methods typically rely on a variety of optical sensors and, in particular, on RGB cameras, Terrestrial Laser Scanners, or multispectral cameras [6].

The choice of a suitable method or sensor for the reconstruction of 3D shapes is contingent upon various factors, including the purpose of the inventory, the volume of the object, the intricacy of its architectural design, the ease of access to the object, and the requisite temporal

constraints and precision requirements [3,7]. In documenting historical structures such as old buildings, historic walls, or analogous objects, commonly employed techniques encompass image-based methods (e.g., Structure-from-Motion/Photogrammetry) and range-based techniques (such as Terrestrial Laser Scanning).

To enhance the documentation of historical towers, ancient walls, or other cultural heritage artefacts, conventional practices involve the application of image-based techniques such as Structure-from-Motion (SfM) and photogrammetry, in addition to range-based methods such as terrestrial laser scanning (TLS) [8–13]. The assessment of structural integrity and the object's condition can be facilitated through remote sensing and electromagnetic sensors, which capture spectral reflectance data across various wavelength ranges. These methodologies enable the acquisition of data and information about the object that may not be discernible to the naked eye.

The outcomes of photogrammetric surveys employing TLS and SfM encompass several valuable products, including base maps, vector drawings, point clouds, digital object models, and 3D models, along with orthoimages captured across diverse spectral ranges. Geographic information systems (GIS), along with building information modelling (BIM) and historical building information modelling (HBIM), are frequently employed for the storage, management, and analysis of this data [3].

The next chapter will provide examples of how the above measurement techniques can be used to investigate and generate architectural documentation.

3. The example of Iraq's cultural heritage objects in hazard

3.1. The Project Mosul – Rekrei

Rekrei (formally known as Project Mosul) constitutes a crowdsourced initiative designed to amass photographic records of monuments, museums, and artefacts that have suffered damage due to natural calamities or human activities [14]. These collected data are then harnessed to generate three-dimensional representations, thereby contributing to the preservation of our universally shared human heritage on a global scale.

This project is dedicated to the preservation of lost cultural heritage through the methodology of digital restoration. The project employs photogrammetric techniques to construct three-dimensional representations of heritage sites lost worldwide by leveraging crowdsourced photographs from experts, tourists, or individuals possessing digital imagery.

In response to the destruction of cultural heritage in northern Iraq, Project Mosul was established by Matthew Vincent and Chance Coughenour, two researchers based in Europe. It operates as a volunteer-driven endeavour, mobilising global volunteers to restore our collectively shared heritage in the face of its unwarranted demise. UNESCO has characterised recent acts of cultural destruction as a "cultural tragedy" and sternly condemned by ICOMOS. Moreover, incidents of looting and the illicit sale of cultural heritage from regions such as Iraq and Syria have transpired beyond physical destruction. However, individuals do not need to feel helpless or remain passive observers. Additionally, cultural heritage is susceptible to threats, as evidenced by the devastating consequences of the earthquake in Nepal.

Figure 2. The 3D model of the (a) Nobleman, (b) Mihrab of the mosque Banat Al Hasan, (c) Jami Sheykh Shatt and (d) Lion from Mosul [14].

As the project has expanded its international reach, it has evolved. “Rekrei,” which translates to “recreate” in Esperanto, a language designed for international universality, now encapsulates its mission. Building upon the initial workflow, which entails utilising crowdsourced images for virtual artefact reconstruction via photogrammetry, the project’s web-based platform is continuously evolving to make more effective use of publicly accessible web data, thereby providing new avenues of assistance to its volunteers.

As part of this project, the Rekrei Online Platform was established. The online platform is the primary repository for the organisation and management of digital images employed in photogrammetric reconstructions. Within this online environment, volunteers engage in three primary tasks. Firstly, users identify geographical locations worldwide where heritage has been lost due to natural phenomena or human actions. These specified locations are the principal divisions for structuring the project’s activities. The second task involves uploading images depicting these designated locations, accessible to anyone who has registered an account on the website. The third and final task entails organising images from each location into pertinent groups for subsequent reconstruction efforts (based on the combined SfM/MVS approach). Images may belong to multiple groups, as an image can encompass one or more components necessitating inclusion in photogrammetric processing. Similarly, certain monuments may prove too significant for comprehensive processing within photogrammetric

software or may not be entirely covered by available digital imagery. Dividing such monuments into smaller groups allows for the reconstruction of individual parts, which can be merged later if additional imagery becomes accessible. Sometimes, these monuments may undergo manual reconstruction by digital artists, who base their work on the provided photographs. Given that the reconstructions mentioned above are not intended for rigorous scientific analysis but primarily function as visual representations of lost heritage, any method for recovering such heritage is considered valid.

3.2. Al-Hadba' Minaret In Mosul – Lost Heritage In Conflict Zones

One important aspect related to the preservation, protection and restoration of threatened or damaged cultural heritage is the attempt to recreate the 3D shape and preserve spatial data according to GIS/BIM/HBIM standards. Historical architectural heritage structures demand continuous maintenance, repair, and restoration efforts. Several studies have employed Geographic Information System (GIS) technology to map and monitor indicators of cultural heritage deterioration [15]. However, when dealing with managing architectural heritage on a large scale, particularly to meet the requirements of conservation engineering and provide comprehensive documentation of building attributes and structures, GIS alone often proves insufficient [16]. Building Information Modelling (BIM)[17] can be a valuable addition and complementary tool to GIS in such scenarios. Originating from the management needs of the architectural and engineering sectors, BIM offers an integrated representation of both the physical and functional characteristics of a building. This representation is established through 3D survey techniques, which may include photogrammetry, Terrestrial Laser Scanning (TLS), classical surveying methods, and their synergistic integration.

The potential of cultural heritage modelling is significantly augmented through the fusion of 3D geometric models depicting the current physical state of a historic building and a GIS database collating data concerning its historical development, material composition, and conservation status. Consequently, this integrated approach gains prominence in cultural heritage preservation and documentation.

An example of the inventory and reconstruction of the shape of the destroyed HBIM standard of Al-Hadba' Minaret in Mosul, based on archival data, crowdsourcing data and data acquired through photogrammetric measurements of the preservation condition of the site, can be seen in the results of the work presented by Al-Muqdadi and Ahmed (Fig. 3) [18].

Figure 3. Al-Hadba's 3D reconstruction workflow from crowdsourced photogrammetry to HBIM [18].

Reconstructing damaged heritage structures typically involves a combination of speculations, expert judgment, and informed decision-making. In the case of Al-Hadba, a significant challenge arose due to the absence of adequate documentation despite the structure's well-known historical significance. This challenge is particularly evident in the considerable discrepancies concerning the height of the minaret. Despite a meticulous examination of all available scientific resources, including their credibility, measurement

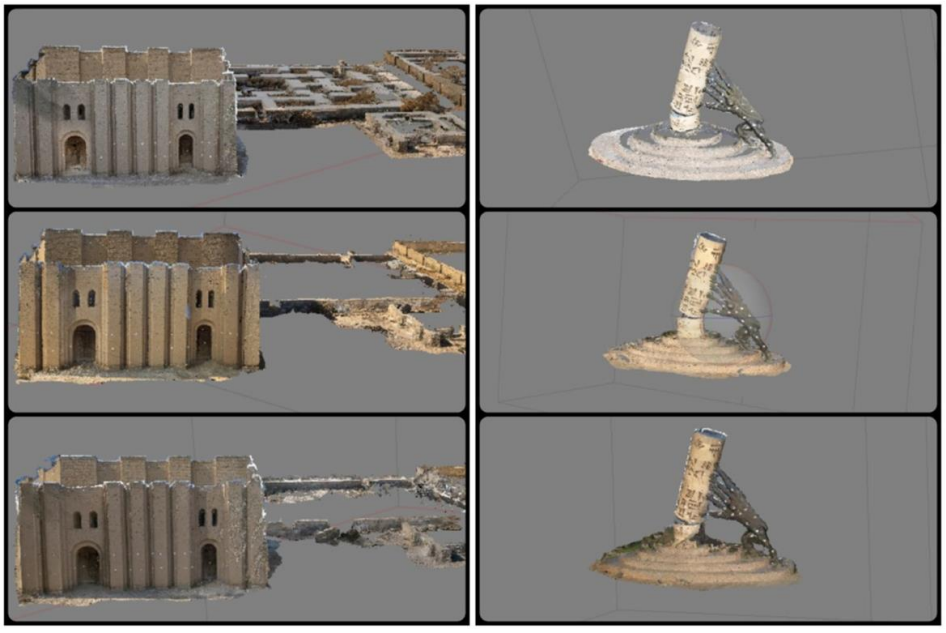
methods, and the year of measurement, arriving at a definitive conclusion proved challenging due to the destruction of the minaret's central shaft.

Fortunately, the remaining base of Al-Hadba played a pivotal role in augmenting the subsequent reconstruction efforts. Establishing a model reference system through on-site measurements substantially improved the precision of the Al-Hadba model and facilitated the resolution of the height dispute. The resulting point cloud data underscored the minaret's height as of 2012 (the year most images were captured) at 48.55 meters. The existing disparity within the literature regarding this height may be attributed to the ongoing and progressive leaning of the minaret's trunk, resulting in fluctuations in its overall height.

The concept of the practical application of Historic Building Information Modelling (HBIM) for reconstructing damaged heritage sites in conflict zones, utilising crowdsourced images as a primary data source. The research focused on implementing cost-effective and freely accessible data acquisition methods for the digital reconstruction of Al-Hadba's minaret, destroyed in 2017 during armed conflict. The resulting model encompasses a comprehensive dataset, including construction drawings, perspectives, and metadata. This database can be leveraged in various ways, such as for visualisation, 3D printing, virtual tours, and potential physical reconstruction efforts. In the future, the pilot case study of Al-Hadba will serve as a valuable foundation for further research to develop accessible and scalable approaches for documenting heritage at risk, particularly in conflict-prone regions.

3.3. Low-cost sensors and techniques – the example of the Tell Harmel and Salvation the Culture in Iraq

When carrying out an inventory of damaged cultural heritage in post-conflict or post-disaster areas, making quick and simultaneous low-cost measurements and obtaining source data is essential. Therefore, a group of methods and sensors categorised as low-cost or consumer-grade can be used. An example of using such methods and sensors was presented in a publication by Abad et al. [19].



(**a**) (**b**)

Figure 4. (a) Texturing step of Tell Harmel from Canon, iPhone, and HTC respectively: (b) Texturing step of Salvation the Culture from Canon, iPhone, and HTC respectively [19.

This research focuses on using low-cost digital cameras to preserve two distinct case study areas, each of significant cultural and historical importance in Iraq. The first case study pertains to Tell Harmel, a vital repository of Iraqi cultural heritage. In contrast, the second case study concerns a renowned architectural monument that holds contemporary cultural significance in Iraq, referred to as “Salvation the Culture in Iraq.”

The primary objective of this study was to employ an automated documentation approach based on close-range photogrammetry techniques and a bundle block adjustment mathematical model. These devices were employed to assess the feasibility of using consumer-grade smartphones, specifically the iPhone 6 and HTC M8, in generating precise 3D models via the Structure from Motion (SFM) algorithm. Subsequently, the research findings were thoroughly analysed to ascertain the viability of using such smartphones to document cultural heritage and architectural landmarks. A comparative evaluation of accuracy was undertaken, contrasting the smartphone-based approach with a more accurate methodology employing a DSLR camera, specifically the Canon 5D Mark III, to illustrate the robustness of the proposed technique.

Furthermore, the research incorporated a validation process involving reference targets and statistical analyses. The outcomes of this validation process demonstrated highly promising results, reaffirming the efficacy and reliability of the methodology in documenting and preserving cultural heritage and architectural monuments. The outcomes derived from the initial investigation conducted in the first study area, specifically Tell Hermel, indicate that the model generated using the Canon camera exhibited the highest level of accuracy, characterised by a Root Mean Square Error (RMSE) of 6.9 mm. In contrast, the models produced using the iPhone and HTC smartphones demonstrated comparatively lower levels of accuracy, yielding RMSE values of 28 mm and 67 mm, respectively. Likewise, in the context of the second case study involving the cultural monument “Save the Culture in Iraq,” the RMSE associated with the Canon camera-derived model was measured at 4.1 mm, denoting superior accuracy. Conversely, the RMSE values for the models generated using iPhones and HTC smartphones were 6.2 mm and 6.8 mm, respectively, reflecting diminished precision compared to the Canon camera-based model.

Based on the analyses presented, it can be concluded that using low-cost methods and sensors allows architectural documentation to be geared to a lower level of accuracy. Nevertheless, considering that modern smartphones are equipped with cameras with good parameters, it can be concluded that such a solution will find particular application in the inventory of historic buildings in hazardous areas or areas of armed conflict.

4. Conclusion

Contemporary non-invasive remote sensing techniques, coupled with advanced digital technologies designed for the acquisition and analysis of extensive datasets, have the potential to substantially enhance the capabilities for documenting cultural heritage sites. This is particularly important for the documentation of endangered cultural heritage.

The objective of this article was to illustrate instances of non-invasive methodologies employed in the inventory of cultural heritage objects and sites within the vicinity of Iraq’s cultural heritage sites. Numerous instances were showcased within this investigation, and an array of contemporary data acquisition and processing methodologies were employed. These encompassed digital close-range photogrammetry, Building Information Modelling (BIM), crowdsourced data, and findings derived from the Mosul Project.

As evident, the prevailing reality underscores the presence of numerous perils endangering the preservation of tangible cultural heritage sites worldwide. Priceless

architectural masterpieces, artistic creations, and natural landmarks risk permanent loss. Hence, an expeditious inventory process, coupled with the development of precise digital models, assures the safeguarding, rescue, and potential reconstruction of these invaluable entities. The examples presented in this article of trying to apply different digitisation techniques to Iraq's cultural heritage could easily be used for other endangered objects and sites.

Conflicts of Interest: The authors declare no conflict of interest.

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