Digital Reconstruction of Fragmented Cultural Heritage Assets

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The most peculiar characteristic of a cultural heritage is represented by its uniqueness. To ensure that an object is preserved against environmental deterioration, vandal attacks, and accidents, modern Cultural Heritage documentation involves 3D scanning technologies. In the case of fragmented artifacts, the digitization process represents an essential prerequisite for facilitating an accurate 3D reconstruction.

cultural heritage 3D scanning digital reconstruction 3D reconstruction

1. Introduction

Modern Cultural Heritage documentation involves interdisciplinary research teams from various fields. The three-dimensional documentation of both cultural heritage sites and artefacts has become a common task in archaeological and restoration processes [1]. This digital documentation process that makes use of modern scanning equipment and software enables the acquisition of precise digital models of both the archaeological sites and artefacts to define digital replicas. Three-dimensional scanning is frequently used for the documentation of Cultural Heritage (CH), as it is capable of defining accurate measurements compared to other digitization methods (photogrammetry, as an example) [2]. The accuracy evaluation of photogrammetry has been analyzed using a custom machine gauge [3] and a coordinate measuring machine (CMM). The trueness and precision of photogrammetry has been analyzed using CMM in other research domains, such as dental implants [4] and industrial applications [5].

Digital Cultural Heritage documentation involves a wide variety of technologies that provide heterogeneous data regarding file structure and file format. Because of this, depending on the final output of the 3D model, there are various standard file type conversion steps that are required to ensure that the output 3D dataset can be integrated within either digital applications such as virtual reality (VR), augmented reality (AR), mixed reality (MR), or computer-aided manufacturing processes (CAM).

One of the most important challenges related to the preservation of cultural and historical heritage is associated with the rapid decay of exterior monuments due to environmental deterioration, as well as vandal attacks [6]. Unfortunately, in many areas around the world, archaeological heritage has been affected by both natural hazards and anthropic destruction. The negative impact of social non-involvement in the protection of archaeological sites has had an impact in multiple countries. Romanian archaeology did not benefit from a specific legislation from its beginning, and until January 2000, as presented by Dorel Micle, even though Romania has been a member of the European Convention concerning archaeological heritage (signed at La Valetta on 16 January 1992) ever since 1997, it was only in 2000 that the government enacted the first law concerning the protection of archaeological heritage. This had an impact regarding the prevention of archaeological treasure hunting, but as presented within this research article aimed at the promotion of the Dacian ornamental shields, various Dacian archaeological sites have been targeted by treasure hunters with metal detectors up until this period, as well as after 2000, in remote areas such as the Dacian Hillfort from Piatra Roșie [7].

Due to various degradation aspects previously presented, CH artefacts are frequently broken into fragments when they are discovered. The traditional manual reconstruction may induce additional damage to the CH fragmented artefacts; therefore, the use of computer-aided techniques for reassembly and digital reconstruction provides several advantages over traditional techniques [8]. The main advantage is represented by the output 3D models that can be used for a wide variety of applications, both digital, such as: VR [9], AR [10], and MR [11], but also regarding the development of tangible replicas using computer-aided manufacturing (CAM) and rapid prototyping (RP) techniques such as casting [12], additive manufacturing [13], laser synthetization, and laser cladding [2].

As presented by Parfenov V. et al., in this context, the need to reconstruct damaged and stolen cultural heritage objects, and to gradually replace them with replicas represents one of the most important aspects on the agenda. This idea of replacing originals with copies is not new, and it causes an ambiguous attitude in society. As an example, the authors have presented the famous masterpiece of Michelangelo—a marble sculpture of David, which has remained for almost 370 years in Piazza della Signoria in Florence, and was copied in 1873 when the original statue was moved for eternal storage in the Gallery of Academy of Fine Arts in the city [6].

Modern technologies that integrate 3D scanning technology and CAM represent an attractive alternative to the traditional manual reconstruction approaches. The main advance of 3D scanning is that it is a contactless method that does not have any negative impact on the original cultural heritage elements [14].

With a wide variety of 3D scanning technologies, determining which solution is optimal is influenced by numerous aspects that are related to the digitization of objects or monuments. As presented by Di Angelo L. et al., there is no 3D scanner on the market that meets all of the technical and economic constraints; therefore, they have developed an Analytic Hierarchy Process method to determine the best 3D scanner for cultural heritage applications [15].

Faithful 3D reconstructions can be defined using 3D scanned datasets of various objects and monuments if there are enough information to define the whole 3D digital reconstruction. To facilitate the dissemination and promotion of digital 3D reconstructions, researchers are also developing VR, AR, and XR environments. The researchers Liritzis I. et al. have proposed the development of an educational application that combines science, history, and archeology to enhance learning regarding the Sanctuary of Delphi [16]. The pilot study was aimed to introduce cultural heritage and archaeology to university syllabuses to support e-learning studies.

As presented by Gomes L. et al., both innovation in data acquisition sensors and an increase in computational power have made digital reconstructions based on 3D scanned models an ongoing research field [17] with many existing challenges regarding current 3D reconstruction frameworks, such as:

- The accuracy and trueness of the proposed digital reconstruction [18];
- 3D modeling problems (self-intersections and non-manifold geometry) [19];
- 3D model topology (triangles or quads) [20];
- File format interoperability towards VR, AR, XR, and CAM [21];
- Aspects related to open and reusable digital cultural heritage 3D models [22];
- Empowering linked Cultural Heritage data [23].

2. 3D Reconstruction Cultural Heritage Projects and Frameworks

The development and wide adoption of 3D scanning technologies have enabled 3D digitization and reconstruction projects to emerge around the world. The pioneer projects, as well as the most complex 3D reconstruction projects, are discussed here.

The most prominent pioneer project focusing on the digitization of cultural heritage is the "*The Digital Michelangelo Project*" by Levoy et al. [24], which integrates the 3D scanning of 10 statues created by Michelangelo. The authors have adopted a wide variety of scanning solutions, including triangulation laser scanners, time-of-flight laser scanners, and digital cameras. As was presented on the project website during their academic year abroad in Italy of a large team including 30 faculty, staff, and students from Stanford University and the University of Washington, the authors have been involved in several side projects such as the Digitizing of the Forma Urbis Romae. The team has scanned the 1163 fragments of the impressive Marble Plan, which is the key source document of ancient Roman topography, measuring 60 feet across, 45 feet high, and 2–4 inches thick.

The authors have developed computer algorithms to aid in the reconstruction of the Marble Plan, and they have created a public database that includes all of the 3D scanned fragments intended to be used as a public tool for study and research. The authors have managed to approximate only 10% of the original monument, based on the features and fitting between fragments. The results have been presented and published in the Proceedings of the Third Williams Symposium on Classical Architecture, Journal of Roman Archaeology, in 2005.

In this case, the accurate 3D reconstruction of the Forma Urbis Romae represents an impossible task, as the existing fragments represent only about 15% of the original marble map, and with the disintegration of the Roman Empire in the fifth century A.D., the Forma Urbis suffered the same fate as the rest of the city; for several hundred years, marble slabs were systematically stripped from the map and used to construct new buildings, or simply burnt in kilns to make lime for cement [25].

As presented by Adán et al., the process of defining the automatic reconstruction of archaeological pieces through the integration of a set of unknown segments is a highly complex problem, and when only a few segments of the original pieces are available, the solutions, exclusively based on computation algorithms, aim to create credible whole restorations. The authors have proposed the use of hybrid human/computer strategies to tackle incomplete 3D puzzles. The method has been applied successful on the fractured pieces belonging to the remains of Roman sculptures at the well-known Mérida site in Spain [26].

Most of the 3D reconstructions of cultural heritage projects are focused on archaeological pottery. Ceramic studies have played a central role in the development of archaeology, as ceramics represent by far the largest class of artefacts recovered during the excavations of historical sites. A method intended to assist in the tedious task of reconstructing ceramic vessels shards using 3D computer vision has been presented by Cohen and Ezgi [27]; their proposed method aligns the shards based on a set of 3D weighted curve moments; the main advantage of the proposed method is that it can be extendable to surface markings.

For physically reconstructed cultural heritage objects such as ceramics, it is important to capture the photorealistic 3D model. A post-reconstruction of photorealistic 3D models of ceramic artefacts intended for use in interactive virtual exhibitions is presented by Chow and Chan [28].

A recently published review paper by Angelo et al. presents the computer-based methods for the classification and reconstruction of 3D high-density scanned archaeology pottery [29]. It aims to provide a complete and critical analysis of the state-of-the-art until the end of 2021 of the most important published methods on pottery analysis, classification, and 3D reconstruction.

In case of complex cultural heritage objects, 3D laser scanning is combined with 3D modeling techniques to define 3D reconstructions. A case study that combines cultural heritage and ship design is presented by the authors Arapakopoulos et al., for a traditional Greek Boat with Trechadiri hull type named after “*Aghia Varvara*”; the boat is characterized as a modern cultural heritage monument by the Greek Ministry of Culture [30].

The use of 3D laser scanning and additive technologies for the reconstruction of damaged and destroyed cultural heritage objects is presented by the authors Parfenov et al.; they have been successfully used for outdoor sculptures in St. Petersburg that have been destroyed during WWII [6].

Other researchers have proposed a reconstruction and analysis method for a bronze battle axe, and have compared the inflicted damage injuries using neutron tomography, manufacturing modeling, and X-ray microtomography data [31].

As presented by other researchers, the main risk of a virtual reconstruction is the lack of a faithful reconstruction. Their work proposed a systematic workflow that integrates 2D and 3D sources [32]. Another recently published state-of-the-art approach that has the advantage of making the reconstruction activities easier and less arbitrary is to integrate iconographic 3D comparison elements within the reconstruction process [33].

Implementing 3D reconstruction within digital interactive applications represents an important tool in safeguarding cultural heritage and making it available to future generations, and supporting immersive learning opportunities [34].

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