How geometric reverse engineering techniques can conserve our heritage; a case study in Iraq using 3D laser scanning

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Abstract. Laser scanning has become a popular technique for the acquisition of digital models in the field of cultural heritage conservation and restoration nowadays. Many archaeological sites were lost, damaged, or faded, rather than being passed on to future generations due to many natural or human risks. It is still a challenge to accurately produce the digital and physical model of the missing regions or parts of our cultural heritage objects and restore damaged artefacts. The typical manual restoration can become a tedious and error-prone process; also can cause secondary damage to the relics. Therefore, in this paper, the automatic digital application process of 3D laser modelling of artefacts in virtual restoration is presented based on reverse engineering techniques. Two case studies were selected and processed in Iraq to meet the aim of this research and show how reverse engineering approaches can save our culture. The efficiency and safety of the preservation and restoration of cultural relics are improved and visually demonstrated. Different reverse engineering techniques applied to show the geometric potential for such approaches following laser-based 3D data application.

Keywords: Terrestrial laser scanning, Reverse engineering, 3D modelling, Cultural heritage, Restoration.

1. Introduction
Reverse Engineering (RE) is the way towards obtaining the shape and geometry of the object and reproducing its 3D digital model utilizing geometric methodologies. This procedure is conveniently utilized in numerous fields, for example, geometrical assessment, fixing or reproducing worn or harmed parts and so on when the document and computer-aided design are not accessible [1]. The choice of the right digitizing strategy is a significant step as it impacts the time, effort and the final models. Over the last two decades, laser scanning technology has significantly increased due to the wide accessibility of laser techniques and the ability to provide accurate dense point clouds in a short period [2]. Culture relics are ruins of historical heritage made by human knowledge. The thought of protection and renovation of historical legacy has been practiced for a long time because of environmental change, man-made catastrophes, etc. Many archaeological artefacts and settlements are lost, demolished and destroyed in an irreparable way rather than being passed on to the future generation [3]. RE process via 3D laser scanner has expanded the possibilities in the field of culture legacy protection and renovation of harmed or missing parts [4]. The restoration strategy has been depicted as the way towards returning the object to its original condition by fixing it, cleaning it, and
so on. There are two types of renovation: manual and virtual renovation. The manual renovation can turn into a monotonous, troublesome errand and a tedious procedure. It likewise can cause second harm on the relics, particularly for large artefacts. As for the virtual renovation, it has received widespread interest from researchers in recent years. The virtual renovation and computer-assisted domain with different programs of software offer various advantages such as: do not cause extra harm since it is non-contact with the artefacts, ability to control and manipulate effortlessly, the models can be effectively printed by utilizing 3D printing system [5]. Different approaches can be applied to obtain reasonable repairing results. This paper presents the application process of 3D laser modelling of artefacts in virtual restoration based on reverse engineering techniques.

2. Review of previous literature
RE can be described as the way towards getting information about the object’s state (shape, size, dimension, etc.) by inspecting it and reproducing it when needed. RE can be utilized as a gadget which can safeguard information by scanning the original object [3]. There are different types of digitizing techniques. In the past, the manual errand to gain information about the object required a lot of time and could be liable to blunders. Coordinate measuring machines (CMM) were utilized to obtain the surface information, however, the strategy was extremely slow and expensive with complex object [6]. As of late, laser scanning procedure has been broadly used for capturing the data in the field of cultural heritage and utilizing the information for the further purpose for instance; preservation, virtual renovation, advanced documenting, etc. [7] [8]. In the field of virtual renovation of cultural heritage, numerous theories have been tested for optimal results. To repair relics with missing parts, a number of researchers have proposed different and varied procedures to appreciate the geometry of the missing parts, which relies on the symmetry of the relics [9]. Using a symmetric technique to virtually renovate the missing parts for human skeletal ruins then re-producing the missing parts using a 3D-printing technique, shows that the missing parts fit very well with original ruins [10]. In case missing parts do not rely upon the symmetric technique or neighbour information, the restoration can be applied using another procedure. For example, the hand of the bust of Lord Buddha was renovated using anthropometric data. The hand ideally of the person whose anthropometric information matches with the requirement is scanned utilizing the 3D scanner technique, and thus associated with the hand of the statue. This method shows a successful and promising result [11].

3. Case studies
Two case studies were selected to run this research. The first case study was the statue of a lady (Abu Bint Dimeon), a wife of the king Sinutruk I, and famously known as the Lady of Hatra. It is one of the famous discovered statues found in the ancient city of Hatra, to the north of Iraq. Found in the large temple with other statues of her family in the city of Hatra, dated to the Hellenistic period (31-139 BC.) as shown in the Figure 1. However, a second case study was selected to check the methodology adopted and the scenario applied in this research. A second heritage artefact was chosen due to its unique value, which was the famous Lamassu head. Lamassu refers to a protective deity from Mesopotamian culture. The winged bull-headed human creature guarding the gates of the palace, dated to the Assyrian period (883–859 B.C.), as shown in figure 1.
4. Methodology

4.1. Scanning session
Stonex X300 terrestrial laser scanner produced by Stonex Company was used for the survey. The Stonex X300 rapidly determines high-resolution measurement results within a very short time. Before starting the actual scanning, the site needs to be planned carefully to determine the optimal scanning positions and the optimal targeting locations. Artificial targets were distributed over the statue and its surroundings in order to facilitate the alignment of the point clouds acquired from different stations. In the first case study, the point clouds acquired from nine scan positions with a distance to the sculpture of about 3m. The field of view (FOV) angle was 30˚ to cover the statue and part of the background with fine scanning mode. Point clouds of about 4,733,538 points were generated and used later to create the 3D model. In the second case study, the data has been delivered from previous work [8]. The point clouds were acquired from five scan positions. Point clouds of about 1,861,195 points were delivered then and used to create the 3D model in this project.

4.2. Data post-processing
JRC 3D-Reconstroctor (Stonex Native Software) was used to process data in this research including filtering, registration, 3D modeling and texturing. The pre-processing phase was performed for two main purposes: (1) noise removal filter for raw data and (2) to add extra information to raw data for further processing steps (i.e. registration, meshing, etc.). Registration is the process of aligning data from various positions in a single and common coordinate system. Most of today’s laser processing software performs the registration following Coarse-to-Fine strategy by getting a rough match among the data using common features (targets) and using an automatic Iterative Closest Point (ICP) algorithm to refine the registration. There are two types of automatic registration available on JRC 3D-Reconstroctor: pair-wise registration (ICP registration) and global registration (LM-ICP with Bundle Adjustment). LM-ICP with Bundle Adjustment was used to refine the alignment as it allows to register all the scans and evenly distributes the registration error. Table (1) and (2) show the registration reports in both case studies. Stonex X300 efficiently provides huge point clouds with high density and resolution. However, when moving upward to the meshing phase, it has resulted in highly noised and low detailed mesh for close range acquisition. Therefore, we took the benefit of integrating an external DSLR camera with the scanner to reserve more details on Lady of Hatra. It was beneficial.

| Table 1. Registration report for Lady of Hatra. |
|-----------------------------------------------|
| Pre-registration | LM-ICP with Bundle Adjustment |
| Reference scan | Moving scan | Mean error (mm) | No.of iteration | Mean error (mm) |

Figure 1. Research case studies: Lady of Hatra (Left); Lamassu Head (Right).
4.3. 3D modeling
As the 3D data acquired by the scanner are discrete 3D points without any neighbourhood relationship, meshes can be made from point clouds by connecting neighboring points to polygons. The mesh can represent the object very well, which is much easier for renovation procedure than the point clouds model. Following the meshing process, the files are exported in the form of (PLY) format for the restoration process. Figure 2 shows the final 3D-models of individual statues.

Table 2. Registration report for Lamassu Head.

| Reference scan | Moving scan | Mean error (mm) | No. of iteration | Mean error (mm) |
|----------------|-------------|-----------------|------------------|-----------------|
| 1              | 5           | 7.6             |                  |                 |
| 5              | 4           | 6               | 23               | 7.5             |
| 4              | 3           | 2.5             |                  |                 |
| 4              | 2           | 4               |                  |                 |

4.4. Virtual restoration
Virtual restoration is a very important process to protect and conserve the original damaged statues. The repaired digital model adds a further level of concepts to the virtual museums, and guarantees virtual preservation, which helps to pass the heritage to the future generation. For various kinds of missing and damaged parts, the virtual renovation can be classified into three categories: (1) the missing parts can be found. In this case, the mission is to scan the body and the missing parts, then reassemble the parts after restoration. (2) The missing parts are not found but can be concluded from the existing parts. In this case, the restoration for missing and damaged parts can be applied based on the neighbourhood information. (3) When the missing parts are huge, the restoration can be applied
based on the evidence such as photos, document, and historical information [12]. Following these facts, the proposed pipeline for virtual restoration applied in this research is illustrated in Figure 3.

![Figure 3](image)

**Figure 3.** The proposed virtual restoration pipeline.

Detection process. The first step in virtual restoration is detecting the missing and damaged parts. Table 3 and Figure 4 show the types of defected parts of Lady of Hatra case study. However, Table 4 and Figure 5 show the types of defected parts in Lamassu Head case study.

### Table 3. The type of defects in Lady of Hatra

| Defect index | Type of defects                           |
|--------------|------------------------------------------|
| 1            | Missing bracelet in right hand           |
| 2            | Broken right bust                        |
| 3            | Defect in the veil due to the stone behind the right hand |
| 4            | Broken right hand                        |

![Figure 4](image)

**Figure 4.** The damaged parts in Lady of Hatra.

### Table 4. The type of defects in Lamassu Head

| Defect index | Type of defects |
|--------------|-----------------|
| 1            | Missing right beard |
| 2            | Missing part in the crown area |

![Figure 5](image)

**Figure 5.** The damaged parts in Lamassu Head.
4.4.1 Restoration processing. 3D-Reshaper software and 3D-Coat software were used for the restoration process. 3D-Reshaper software developed by TECHNODIGIT (part of HEXAGON) characterized by its: easy to use, flexibility window, allows to receive point clouds from all digitization equipment in different formats and treat them in a very short time. It offers necessary tools needed for reconstructing the missing and damaged parts (symmetry, registration for a surface to surface, scaling, etc.). 3D-Coat (gaming engine) software developed by PILGWAY offers different tools to enhance the mesh such as sculpt, modify, cleaning, smoothing, etc.

4.4.2 Reconstruction of the missing parts.

4.4.2.1 Lady of Hatra case study

1. Reconstruction of the missing bracelet. In this case, the missing bracelet was not found, but the restoration could be applied based on the neighborhood information as the half of the bracelet was in good condition. First, half of the bracelet was selected, then a central plane was created. Giving the central plane as a plane of reference for the mirroring command, the missing bracelet was reconstructed. After the reconstruction, the Boolean operation was used to connect the missing bracelet to the original one and merge it with the statue as shown in Figure 6.

![Figure 6. Virtual restoration of the Lady of Hatra bracelet.](image)

2. Reconstruction of the right bust and veil. The missing right bust was reconstructed based on neighborhood information. Because the left bust was in good condition, the process was based on mirroring parts. The method used to reconstruct the damaged bust was as follows: the first step was cropping the chest area from the statue and analyzing it for the symmetrical process for this particular part. The symmetrical chest area was registered with the original statue using a surface to surface registration method (Best align N points) with mean registration error of about 1.8 cm. Deleting unnecessary triangles from the chest area and keeping only the right bust area. The geometrical result for the right bust needed enhancement and artistic touch. Gaming engine software (3D-Coat) was used to merge and sculpt the bust with the original mesh and to modify the folds of her dress as shown in the Figure 7. In addition, due to the stone formed behind the right hand, the lady’s veil had a defect. The first step was removing the stone and then filling the area of the hole. The area was smoothed and modified using 3D-Coat software and as shown in Figure 8 below.
As highlighted in ‘figure 4’, one more damaged part of the Lady of Hatra statue needed to be restored and recovered which was the lady’s right hand. However, this part of restoration tended to be more complicated at glance and needed further RE algorithms to be solved. Therefore, the hand restoration process was postponed to the next phase of this research and is not included within this piece of paper.

4.4.2.2 Lamassu head case study
In this case study, the restoration process was applied to Lamassu Head beard and crown. The missing parts in this case were reconstructed based on the existing neighborhood information. The reconstruction was carried out using symmetry with respect to the mid-sagittal plane. The first step was to identify the plane passing through the head landmark. Giving the central plane as a plane of reference for the mirroring command, the missing parts were reconstructed. The mirror imaging technique allowed obtaining the contral-lateral region used as a starting point to only design the missing area needed. After deleting unnecessary triangles, free form deformation (FFD) was applied by moving the control point of missing parts dislocated to the original head for better matching. The Boolean operation was used to join and merge the missing parts with the original head as shown in ‘figure 9’.
5. Conclusion

Reverse Engineering process and the advanced technology have opened a new avenue in the field of cultural heritage conservation and restoration which represent the nation’s treasures. This paper is showing in a streamlined way the automatic procedure of producing missing parts of cultural relics in digital forms, which reduce the repetitive and tedious manual restoration work that might cause additional damage on the relics during handling. Stonex X300 laser scanner device was used to capture the data from different positions for two case studies. After pre-processing, the global registration (LM-ICP with Bundle Adjustment) was applied to align all the scans in a single and common coordinate system and later check the quality of registration, then surface reconstruction was performed. However, due to the fact that Stonex X300 laser scanner device introduce high noise and low details in the minimum range missions, in case of the Lady of Hatra, the data was integrated with an external DSLR camera to improve the quality details to deliver watertight and smooth mesh with fine details. Virtual restoration algorithms which include symmetrical, co-registration and enhancement by professional software was applied to reconstruct the missing parts in both case studies. The proposed methodology to reconstruct the missing parts proved to be fast, reliable and effective. The visual analysis show successful and promising performance results, however, statistical analysis is necessary to validate the applied methodology which will be postponed to future processing stage of this project.

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