# Digital Restoration Proposal for Notre Dame statues

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## Abstract

With the impact of digital technology development and the continuous expansion of its application direction, there are a lot of applications be employed in the heritage protection area. It has become a development direction. This article explores the potential of digital technology in heritage protection in the context of increasingly sophisticated digital methods. The primary goal is to design a digital restoration plan for the rooster-shaped statue of Notre Dame damaged in the fire. This plan includes steps of data acquisition and processing, digital modelling and surface repairing, and digital demonstration. In this paper, a large number of successful cases from digital project cases and literature references in recent years was collected. Similarly， there are selected potential cases and technical means to analyze their reference to the virtual restoration of the target sample (Rooster-shaped statue of Notre Dame Cathedral). Through the analysis and comparison of digital technology, the virtual restoration plan most suitable for the restoration of rooster-shaped statues is obtained. The plan is not fixed and has reference significance for the protection and restoration of other statues, buildings, and various cultural heritages. It can provide sustainable and promising concrete methods for protecting cultural heritage.

**Keywords: 3D reconstruction, Digital Technology, Cultural Heritage, Restoration;**

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# Chapter 1

# Introduction

This first chapter is conveyed to describe the context of the research area, what this project consists of, and the importance of this project. Moreover, it will define the scope of this research, the motivations, goals, and the general structure of this paper. It will indicate the important research aim of the cultural heritage protection discipline. Furthermore, it will introduce the fire of Notre Dame, which triggered people to find a more efficient way to restore and protect damaged statues. Through an analytical description of digital technology, a parallel can be produced to bridge both heritage protection and virtual computing fields, exploring a productive plan for the rooster-shaped statue.

## 1.1 Context and project description

### 1.1.1 Necessary information of Notre Dame

At 18:20 CEST, 15 April 2019, a structural fire broke out at Notre Dame Cathedral (see Figure 1). As an essential witness of human civilisation, Notre Dame Cathedral has suffered incalculable losses. The spire and the overwhelming majority of the roof have been damaged, and the upper wall has been gravely destructed as well. Although the vaulted stone ceiling prevented extensive internal damage, withstanding the collapsed burning roof. Fortunately, many artworks and artifacts were transferred to a safe place and survived just a week before the fire. The altar of the cathedral, two organs, and three 13th-century rose windows were hardly noticeably damaged. However, there are still a large number of artworks damaged by strong dust and the high temperature. Especially some external artworks that are severely damaged as well. How to repair and restore cultural relics while protecting them from secondary damage has become the primary goal of Notre Dame. The French government says the cathedral will be restored in 2024. However, the complete restoration and reconstruction of buildings, artifacts, and artworks affected by the fire may take much longer.

*Figure 1 Notre Dame Cathedral fire(15 April, 2019), Fabien Barrau/Getty Images*

This fire reminds people the importance of the protection and restoration of cultural heritage. How to restore and reconstruct it in an efficient way has become the priority.

### 1.1.2 The introduction of the rooster-shaped statue

Due to the collapse of the iconic spire in the fire, the rooster-shaped statue crashed as well. The crowd thought that the statue had disappeared at first, but it was found in the remains of the ruins one day later. This statue has the shape of a rooster which is an unofficial symbol of France. It is considered very important because three relics were stashed inside, including a part of the crown of thorns which was worn by Jesus. Dubbed a 'spiritual lightning rod'[1], the statue and three pieces of cimelia concealed inside in order to protect the faithful of the 850-year-old cathedral and all Parisians. Due to the fall from a 300-foot-tall spire, the statue was sunken on the outside, severely scratched on the surface, and it was impossible to check whether the three relics inside the statue still existed (see Figure 2).

*Figure 2 The damaged rooster- shaped statue, AP Photo/Michel Euler*

### 1.1.3 Digital technologies in heritage protection and restoration

Repairing statues which are damaged by natural ageing or disasters is one of the critical topics in the cultural heritage and protection area. Owing to the continuous development of computer technology currently, the applications of digital technology in cultural heritage protection has been continuously developed. About nine years after the invention and public domain of the World Wide Web project, Tom Levy recorded all field measurements on excavations in Jordan related to the role of ancient metallurgy on social evolution in 1999. That was the start of a rising field of 3D visualisation. It is the first application that referred to as on-site digital archaeology (OSDA) 1.0[2]. Since that time, the employ of computer science and technology to assist in the protection and restoration of cultural relics has become a development direction. At the beginning of heritage protection, researchers used the traditional restoration methods, mainly relying on artisans or artists who has artistic understanding and operation experience. In practice, affected by the subjective aesthetics and ideas of the operator, the restoration of cultural relics lacks rigour and professionalism. The emergence of digital technology can adequately fill this defect. Through precise computerised calculations, the most suitable plan can be obtained, which improves the efficiency and accuracy of cultural relics protection and restoration.

## 1.2 Motivation and Goals

This study has three motivations. The first one is to inspire humanity's attention and passion for the protection of cultural heritage. As Gan Harman said 'It is usually their surroundings as a form of free merchandise, I do not know any way to cherish and spoil (The Fourth Wave, 1984).' People ignore the cultural heritage in everyday life, such as corroded old buildings, damaged statues. Cultural relics which have not been evaluated and restored in time, resulting in the cultural loss. The second is to provide an extension for the restoration of damaged statues. By analysing the feasibility of a digital restoration plan for the rooster-shaped statue damaged in the fire of Notre Dame Cathedral, an effective plan for restoration and protection of statue groups is able to be established. Recently, digital technology has achieved more results in the field of statue restoration and protection. Although a large number of digital technologies can be utilized in the cultural heritage protection area, the specificity and fragility of cultural relics and historic sites do not allow these technologies to be widely used. For example, GPS technology that is suitable for repairing sizeable ancient village buildings is not suitable for repairing broken oriental porcelain. Moreover, using camera flash might damage the valued mural.

In contrast, using Non-Destructive Techniques (NDTs)[3] is the ideal method which can be applied in situ and do not require destructive sampling. The collection and development analysis software recently for its sensors and related data has enhanced its usefulness and is now an essential tool during the cultural heritage protection process. Japanese restorers used laser scanning technology to obtain damaged Buddha image data [4]. Korean researchers used unique cameras to build a high-precision digital measurement system to obtain raw data from the Great Bell of King Sung-Duk[5]. Some Chinese students tried to use Geomagic Studio software to create a more accuracy point cloud model to assist a three-dimensional model of the damaged cultural relic to establish[6]. The Belgian Institute of Archaeological Heritage used virtual reality technology to complete the digital reconstruction of Saint Laurentius Church[7]. Also, Korean researchers used 3D printing technology and digital modelling technology to reconstruct a damaged stone seated Bodhisattva statue [6]. These successful cases provide an excellent factual basis for the digital restoration of the rooster-shaped statue. The third motivation is to provide new ideas for the future development of the Notre Dame, which represented by the cultural heritage in the digital industry. Nowadays, the development of the cultural industry is more and more prosperous. How to develop and use cultural heritage to make it more influential has become a breakthrough point in the cultural competition of various countries. This article will explore the feasibility of digital demonstration and redevelopment technology for the development of modern cultural industries.

### 1.3 Research Question and contribution.

The digital world has evolved exponentially to the point of offering experts digital technologies. What kind of digital technologies can be used in heritage restoration? How does it represent in different cases? What are the advantages and disadvantages of different digital technologies in practical application cases? This article will choose the digital restoration plan of the rooster-shaped statue as the research aim, use case analysis methods to compare and analyse the application of different digital technologies in the restoration of statues area. The feasibility of these technologies will be analysed in their application to the restoration of the rooster-shaped statue. In the end, this paper will offer a sustainable plan to realise the digital restoration of Notre Dame Cathedral. Furthermore, it will provide suggestions for applying digital technology in the cultural industry in the future.

### 1.4 Paper Structure

This paper consists of four sections. The second chapter analyses existing technologies and specifically points out the different protection principles between western and eastern countries. Besides, it describes the development of digital technology from the heritage protection discipline. There is another subsection of this chapter explores the developments of digital technology via generally describe several cases. The third chapter analyses different digital projects in details and making comparisons with these different technologies. It evidences the possibility of digital restoration. Chapter four provides conclusions around those comparisons, and make a reliable restoration plan for Notre Dame Cathedral. This part also analyses the possible use and development direction of digital technology in the future cultural industry.

## Chapter 2

## Background and literature review

### 2.1 Introduction

This chapter introduces the different heritage protection principles between the western and eastern country, explain its concepts and the reason. Moreover, it also defines the 'authenticity' that will be analysed in details. This section offers an overview of the developments in the restoration method from past to now. Besides, the introduction of different digital technologies in this discipline is mentioned in details as well.

## 2.2 Different principles in heritage protection and restoration

Although the principles for protecting and restoring cultural heritage vary from country to country, the protection affair of cultural heritage is very cautious[7]. The developing countries represented by China have adopted a more conservative attitude in protecting and restoring cultural heritage. The legal protection of heritage protection is inadequate, and human intervention by the government has an intense color. However, Western countries such as Europe and the United States are more flexible in protecting and restoring cultural heritage. They are working in more commercial and legal ways. Especially in the restoration of sculptures, due to the difference between Eastern and Western philosophical and aesthetic thoughts, there are considerable differences in the pursuit of sculpture 'authenticity'. Under the influence of Taoism, China paid more attention to 'the moral behind' rather than 'authenticity.' Influenced by religious thoughts and ancient philosophical thoughts, most Western countries pursue objective truth, accuracy and verifiability. It is essential to the pursuit of historical truth, modern archaeological skills based on strict physical and chemical data, and the protection of cultural heritage. In other words, when protecting cultural heritage. Western countries pay more attention to 'preserving the original form', such as the ruins of the Ancient Colosseum and the Parthenon in Athens. The protectors of Western countries do not rebuild it but only maintain its original appearance. However, for some cultural relics damaged under unnatural factors, based on the principle of 'authenticity', the original and undamaged state should be restored as much as possible during the protection process. As a representative cultural heritage of Western countries, the cock-shaped sculpture applies the principle of 'authenticity' to the restoration and reconstruction of it. Therefore, the more 'accurate' digital technology based on computer images is more comfortable to assist in the repair process.

## 2.3 Cultural Heritage protection workflow

A digital restoration project consists of 4 stages: digital data collection, digital data processing, digital surface reconstruction and digital demonstration. First data needs to be collected. If the data is available, then remove all unnecessary data and fix the damaged structure after putting them into a data processing software. Meanwhile, a virtual model will be designed based on the processed point cloud data. The next stage is using an assistant system or algorithm to help the digital surface reconstruction. A realistic texture will be matched to this model. After that, researchers can use VR/AR to test and verify the result of previous stages. If the model is totally correct, there are some other ways to demonstrate the restoration results, which includes printing a real replica by using a 3D printer or establish a digital museum system.

### 2.3.1 Digital data collection

The process of collecting objects data by using digital devices in this paper is named 'digital data collection'. Experts use professional digital measurement devices to get data, such as the Infrared Thermal Imager, 3D laser scanner and other digital equipment. Besides, the digital collection method can save measurement time and improve work efficiency. If the data is stored properly, the obtained data results can be used repeatedly. For example, using digital technology to collect the statue’s data can avoid secondary damage to the repaired object, extract precise information that cannot be noticed by human eyes. It minimises the error of the data collection stage as well as improves the restoration accuracy and efficiency. As a part of digital restoration, it can provide new methods and better solutions for a restoration plan.

The most common digital data collection methods are X-ray imaging, and X-ray computed tomography technology. German physicist Roentgen accidentally discovered the x-ray in November 1895. Because it was not clear what kind of ray it was at that time, it was called 'X-ray'[9]. Also, materials such as calcium tungstate would emit blue-violet fluorescence of the courseware under X-ray irradiation (Discovered by Edison, 1908). He developed a sensitivity screen with X-ray film using this feature, which significantly shortened the X-ray transillumination time and dosage. These two discoveries and inventions have laid the foundation for modern X-ray imaging research. The research of this technology in this field began in the 1920s, and it was only used in paper cultural relics and artworks in the early days. Researchers found that X-rays are high-energy electromagnetic radiation generated by high-speed electrons striking a metal target due to ductile radiation[10]. When X-rays penetrate a substance, the intensity will be weakened due to the absorption and scattering of the substance. The X-ray inspection of bronzes is widely used worldwide. X-ray perspective images are used to detect objects, especially metal artifacts, before repair, to find out the internal cracks, holes, inlays, inscriptions and other rust and hard soils of various objects. The various circumstances under the cover can be used as a reference basis for the symptomatic repair of utensils, as well as the ancient casting process of metal artifacts, especially bronzes. X-ray imaging plays an essential role in the investigation of the preservation status of bronzes such as corrosion analysis, repair analysis, and establishment of bronze fingerprint files before protection and restoration.

Another method for digital data collection is Infrared Thermal Imaging(IRT). With the development and application of infrared thermal detection systems in the first and second world wars, infrared thermal imaging technology continues to develop. However, because this technology was used in the early days to develop infrared communication equipment and infrared search systems to prepare for military warfare, the technology was kept strictly confidential. It was not until the mid-1990s that infrared thermal imaging cameras began to shift from military to civilian[11]. IRT is an established non-destructive and evaluation technique with a wide array of applications ranging from enhancing night vision to detecting defects on architectural surfaces[12]. IRT is a valuable NDT building material and its preservation status for studying the structure, especially in the field of architectural and cultural heritage. It provides the advantage of being able to inspect a wide range without the need for sampling and investigation. There is the basic principle of IRT that all objects emit infrared radiation exceed absolute zero temperature (0 K) so that abnormal changes can be detected and mapped with changes in material's properties, micro-structures, and surface morphology. Thermal variables were measured using an infrared camera in the middle (3-5 μM) and long (7-14 μM) wave infrared bands, responding to the atmosphere with two high-transmittance infrared windows. The investigated scope is displayed as a colourful picture, which corresponding to a temperature scale[13].

With more and more attention and research in the field of 3D, 3D scanning technology was born in the 1960s. Prior scanners used lights, cameras, and projectors to implement this task. Due to the limited abilities of the equipment, it usually took a lot of time to scan the object. After the important time-point 1985, the previous version was replaced by scanners that use white light, lasers and shadows to capture specific surfaces. Especially the advent of 3D laser scanning technology, which allows the capture of 3D digital data. It can be used for a variety of purposes, including 3D recording, non-contact copying and a virtual display. The principle of 3D laser scanning technology[14] is to emit laser pulses and scan the object to be measured through two high-speed and synchronously rotating mirrors so that the pulses can reach the surface of the object being scanned. Through this step, the actual distance from the surface of the object can be calculated. The 3D laser scanner's encoder can calculate the pulse emission angle and calculate the three-dimensional coordinate value of each point cloud. It is thereby obtaining point cloud data collection. Because of its revolutionary technological breakthrough from point to line to surface measurement, this technology has been demanded in the field of digital archaeology and cultural heritage protection since its introduction.

### 2.3.2 Digital data processing

After finishing the data collection stage, all data points stored in the collection equipment with three-dimensional coordinates information which combines to be a point cloud data model. With the data available from the this has to be processed. Digital data processing is a method of processing collected object data through digital algorithms or digital modelling tools. During the processing period, he collected point cloud data (data collection of object surface points, with three-dimensional coordinates X, Y, Z, colour, classification value, intensity value, time, etc.) are inputted into the computer, and then researchers use the engineering software to obtain the three-dimensional shape of the measured object. Plus, they superimposed on the colour and texture. In the end, the three-dimensional digital model is generated. The digital data processing of the measured objects can archive the cultural relics data by storing them in the database, which is conducive to the subsequent repair and protection of the cultural heritage. It is important to use a visualize data model to directly describe the damaged surfaces of the cultural relics and establish a digital model to help preview the repair results.

In recent years, relying on the continuous development of digital modelling software based on computer technology, the Raindrop company has developed the 3D inspection software Geomagic Studio. It is a reverse engineering software that can automatically and quickly generate 3D Models based on the actual 3D point cloud data and polygon network. Thus, the collected data from X-Rays and Infrared Thermal Imager can not be imported into Geomagic Studio. This software is the most powerful software for point cloud processing and 3D surface construction. The time from point cloud processing to 3D surface reconstruction is usually one-third of other software[6]. The main functions[15] of the software include automatic conversion of point cloud data to polygons, rapid reduction of the number of polygons (Decimate), conversion of polygons to NURBS surfaces, surface analysis (tolerance analysis, etc.), output matching CAD / CAM / CAE File format (IGS, STL, DXF, etc.).

Geomagic Studio was used in the product design and parts manufacturing industry in the early days. Because of its powerful modelling capabilities, it has also been used for digital modelling and virtual restoration of cultural relics in recent years.

There is also a similar software Artec Studio which was developed by Artec 3D used for digital data processing. Artec Studio is a powerful and evolving 3D point cloud data software. It must be used with the 3D scanner owned by Artec 3D. Artec Studio can be used for model scanning, data editing, data registration, data synthesis, post-processing, texture mapping, and other technologies to process the acquired point cloud data. As same as Geomagic Studio, the software also has the functions of patching vulnerabilities, data cleaning, data measurement and exporting multi-format files. The software focuses on its portability and real-time and has been favoured by multiple research teams in the heritage protection area. Artec 3D has also been used to generate 3D scans during other historically essential projects. These include the digitalization of numerous artifacts in museums around the world such as the human ancestor Homo Naledi in the Rising Star cave system, President Obama for the creation of his presidential bust, and 1.8 million-year-old fossils found at Turkana Lake, in Kenya, alongside renowned palaeontologist Louise Leakey[16].

Due to the need for a high-tech computing environment, Jack Lit, Cliff Morel and Steve Bangor co-founded MathWorks (1984), which officially brought MATLAB to the market. MATLAB[17] is a commercial mathematics software used for algorithm development, data visualization, data analysis, and numerical calculation. It is a high-level technical computing language and interactive environment, mainly including MATLAB and Simulink. MATLAB can perform matrix operations, draw functions and data, implement algorithms, create user interfaces, and connect programs in other programming languages. It is mainly used in engineering calculation, control design, signal processing and communication, image processing, signal detection, financial modelling design and the analysis and other fields[17]. In the field of heritage protection, this software can assist in the establishment of 3D models of objects for data registration, data processing, etc.

### 2.3.3 Digital surface reconstruction

Now that the data is collected and processed. The next stage is called digital surface reconstruction. Digital surface reconstruction method refers to the process of recovering and reconstructing the texture, color, slight damage and missing surface of the object using digital software or algorithm. Through the data simulation of the existing surface and the digital analysis of the component analysis, more realistic and highly matching results can be obtained. Using this method can accurately describe the details of the original surface of the object and deal with small defects that are easy to ignore.

Due to the use of digital equipment from different manufacturers, different display methods, and different imaging principles in the three-dimensional data collection and processing of objects, the colour data obtained at each stage is deviated or lost. The development of the colour management system can solve this problem. The Eye-One colour management system is employed to generate and modify colour profiles of devices including 3D scanners, monitors, digital cameras, digital projectors and various printers. Followed by the previous step, it applies the colour profile to the application program, driver or Raster Image Processor (RIP) software to achieve the correct colour. Since all most professional imaging and design tools can use colour profiles, it is easy to aid the surface restoration workflow. In the field of digital archaeology and cultural heritage protection domain, a colour system is often used to calibrate and restore the surface colour of cultural relics during reconstruction and restoration. It is an auxiliary method for three-dimensional data processing. For example, colour extraction is performed on the corroded coloured wooden statue surface, repairing the missing colour patches. It was using a standard colour card to assist the digital camera to perform colour correction on the measured object, reducing the adverse effects of environmental factors such as reflection on digital imaging.

In addition to using a colour management system to assist in the restoration of the surface of cultural relics, the use of colour migration technology[18] can also help researchers to obtain more consistent restoration results. Colour migration refers to synthesizing a new image C based on image A and image B. Image C has genetic information such as the colour of A and the shape of B. So image B learns the overall colour tone of image A without changing the shape information. This process is called colour migration synthesis of the image. Image A is called a colour image (source image), and image B is called a shape image (destination image). The most classic colour migration algorithms are Reinhard algorithm (2001) and Welsh algorithm (2002)[18]. The Welsh algorithm expanded the Reinhard algorithm, and it uses a statistical method to calculate the weighted average brightness of the pixel range corresponding to the colour image. It can achieve the automatic colouring of the grey image to match the source image and the destination image. The researchers found that the use of this technology can be used to assist in the repair of decorative colour images of ancient buildings, and can also be used to synthesize the real surface of cultural relics so that the new model has an 'old' surface style.

### 2.3.4 Digital demonstration

In today's era, the most representative digital demonstration technology is AR and VR. Experts collect the digital data from objects, plus data processing to display the digital reconstruction results (e.g. 3D models) virtually to enhance the interaction between people and models.

Virtual reality technology is one of the most popular application forms of multimedia technology. It is a compound product of a variety of disciplines which involves computer software and hardware technology, artificial intelligence sensor technology, robot technology, and behavioural psychology. Nowadays, researchers are more focus on exploration in 3D related technique, such as 3D real-time graphics display, 3D positioning tracking, tactile and olfactory sensing technology and artificial intelligence technology. Besides, computer-acid technology involves high-speed computing and parallel computing technology, and human behaviour research are able to make efforts as well. Along with the development of virtual reality technology, it caused significant changes in the social environment and human life. In 1962, Morton Heilig invented a multi-sensory stereoscopic movie device called Sensorama[19]. The invention of this 'full sensor emulator' implies the ideological theory of virtual reality technology. Afterwards, the father of American computer graphics called Ivan Sutherlan, developed the first computer graphics-driven helmet-mounted display HMD and head position tracking system (1968). It is an important milestone for VR technology. In the following decades, virtual reality technology developed in a high-speed period. Some VR devices were dropped in the market. In 2014, Google released Google CardBoard, Samsung released Gear VR, and in 2016 Apple released a VR headset called View-Master. After that, Vive (HTC) and PlayStation VR (Sony) also followed appear. At this stage, researchers not only pay attention to theoretical research but also devote VR technology to practicals. It was widely used in scientific research, aviation, medicine, military and other related fields. As a new technique, it was utilized to cultural heritage protection, and suitable for applications in different sectors. For example, some artists used VR technology to rebuild artworks or cultural relics, reproduced historical scenes or damaged items. It is also used for public display of restoration projects. There is a research project announced from Trinity College, the University of Dublin with ADAPT (SFI Research Centre for Digital Media Technology in Ireland) in 2018. Researchers use VR technology to produce the digitally copied building of the Public Record Office of Ireland, which was destroyed by fire during the Irish Civil War broke out. Historians and computer scientists at Trinity College are using VR technology to reconstruct damaged buildings. Moreover, they pile up surviving documents and missing records on shelves to revive the Irish Public Records Office. In addition, a project website (http://www.beyond2022.ie) was launched, which demonstrates the scope of the project and technology involved[20].

In addition to VR technology, AR technology also played a role in the digital demonstration. AR is a technology-supported medium in which digital information is overwritten and registered in the real world. It can build a real-time interaction relationship between users and machine. This technology can dynamically, organically, and in real-time integrate the information in the computer into the actual environment of the user after special processing. When users move in the environment, the enhanced information will also change accordingly, to achieve a high degree of unification between the actual environment and the enhanced information. In 1992, Tom Caudell and David Mizell used the word 'Augmented Reality' [21] for the first time in the paper 'Augmented reality: an application of heads-up display technology to manual manufacturing processes', which was used to describe the coverage of the elements presented by the computer. Caudell and Mizell discussed the advantages of augmented reality over virtual reality. For example, there are relatively few elements that need to be presented by a computer. The processing power requirements are also low. At the same time, they also know that in order better to integrate the virtual world with the real world, the requirements for augmented reality positioning technology are continually increasing. In the following development process, the application range of AR technology has been continuously expanded, and it has also been applied to the restoration of cultural relics and monuments and the protection of digital cultural heritage. For example, the research group in Belgium used AR technology in the process of reconsecrating the Saint Laurentius Church in Ename[7]. The Pure Land: Augmented Reality Edition (Pure Land AR) installation premiered at the HK Art Fair 2012 also used mobile media technology to create a complementary 'augmented reality' rendition of the same data from Cave 220 (a cave full of Dunhuang murals, China)[22].

In addition, 3D printing technology is also used to inspect and display three-dimensional models. 3D printing is a type of rapid prototyping technology. It is based on digital model files, using powdered metal or plastic and other adhesive materials to construct objects by layer-by-layer printing[7]. As a new expression of digital technology, 3D printing technology provides the help of digital display for the protection of cultural heritage. Different from VR and AR technologies, 3D printing technology is able to transform the virtual display of objects into physical and displays. The first 3D printer in the world was launched in the United States in 1986. It was initially employed in mould manufacturing and industrial design fields. It was not until recently that it was used to assist the digital display of cultural relics. For example, using 3D printing technology to repair missing stone statues of Buddha[6]. Researchers use it to check the repair results of three-dimensional software for cultural relic models or use it to print copies of cultural relics for alternative exhibitions.

Digital museum (virtual museum) is a project built by a variety of digital technologies involving virtual reality technology, three-dimensional graphics and image technology, computer network technology, three-dimensional display system, interactive entertainment technology, and special visual effects technology. It ultimately presents the real physical museums on the Internet in a virtual way. The entire museum environment can be thought of as a 3D model. Visitors freely explore the virtual museum, watch the three-dimensional simulation display of various collections in the museum as well as learn relevant information about items. In fact, digital museums have been established before the Internet has become a prevalent factor for daily use. In 1992, Apple released an offline virtual museum in the form of a CD-ROM[23], which is an interactive electronic museum that allows users to walk between rooms to view exhibits. In the following years, offline and online virtual museum projects developed rapidly, such as Vatican Museums (Rome), British Museum (London), and the Digital Forbidden City Museum (China). These cases show the role of the digital museum concept in the field of cultural heritage protection.

# Chapter 3

# Case studies: Digital technologies in heritage protection

## 3.1 The Workflow and best practices for cultural heritage protection

Due to the fact with combining relevant facts and literature and facing two urgent restoration and restoration needs, the best way is to use digital technology to virtually repair and reconstruct statues. The workflow in this field is to use digital scanning technology to collect objects data in the early stage, then rely on digital algorithms or modelling software for data processing. The next stage is using a colour management system and image algorithms to restore the statue's surface. Finally, use VR or AR technologies for digital presentations and redevelopment. For further options, artists can apply the digital virtual reconstruction results to the physical restoration of real cultural relics, or use it to digital archiving and other digital industries.

## 3.2 Digital data collection

### 3.2.1 X-ray imaging and XRF computed tomography technology

In the baroque statue inspection case of the Pieta wooden sculpture[10], the technical team used the Twinned Orthogonal Adjustable Tomograph (TORATOM) equipment to collect data on the statue. The sculpture is 600mm high, coloured wood, and the colour has been renovated many times. Because utilizing XRF CT technology requires a large number of XRF images, and there is a limitation on the size of the sample. It takes too long to take a single image from the sculpture. The team placed the Pieta sculpture on the operating table, and only collected the upper half data from it (see Figure 3). They mapped the XRF image to the surface of the object and reconstructed it by the tomographic image to assist data processing. During the project, XRF data was recorded at a rate of 13 frames per second. The exposure time of a single frame was five milliseconds, including a readout time of 2.64 milliseconds. An XRF image took 19 minutes. The image acquisition and processing of the entire statue requires more than one image, so the entire process takes a long time. In addition, the ability to use this technology to obtain deep concave parts of statues works not very well, and there are great defects in detecting some objects with large surface fluctuations and elaborate details.

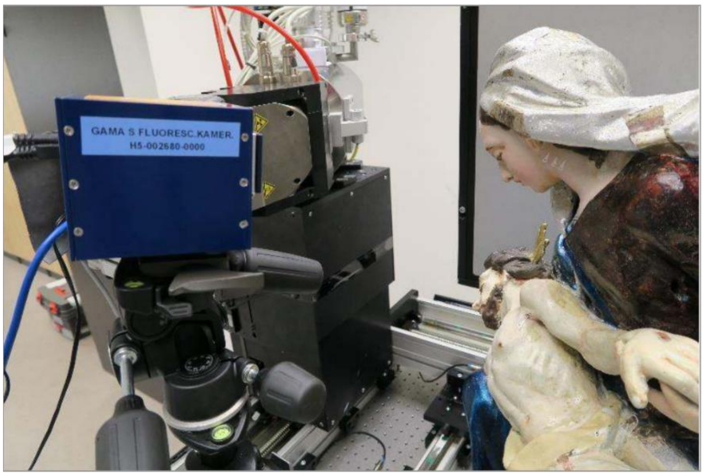


*Figure 3 The Pieta wooden baroque sculpture on the operating table[10]*

Although using X-ray imaging and CT imaging technology for statue detection and data collection has the advantage of low cost and non-contact. It has strong practicality. However, its work efficiency is not good enough. It needs to use other sophisticated tools for data analysis and processing, which increases the workload. Furthermore, for some unique materials, whether the radiation will damage the sample is still needs to be proved with further discussion and experiment. However, during the data collection process of the rooster-shaped statue, this technique can be used to initially check whether there are 'three legendary relics' inside the statue. It can be utilized to confirm the internal damage of the statue through obtaining a perspective image.

### 3.2.2 Infrared Thermal Imaging (IRT)

The basis of heritage protection is testing, including test their internal structure, defects and surface damage. Due to the high energy power, the application technology in ordinary X-ray imaging requires sufficient protection conditions and may cause extra damage to objects. However, infrared thermal imaging technology is a new type of non-destructive internal imaging method that identifies defects based on small thermal changes from typical locations. Since its low energy and high quality, it is ideal for testing cultural relics because of its rapid, non-contact and in-situ testing. Infrared thermal imaging technology has been applied to the non-destructive testing category of internal structures of cultural relics which made of different materials, such as the employ of the cast-iron Buddha head of the Song Dynasty in the National Palace Museum of China[24].

Due to the exhibition and display needs of the museum's statue, the staff from the National Palace Museum of China chose to use this technology to understand the overall structural strength and thickness of the statue in order to design a fixed arrangement plan. Because the interior of the sample is a cavity structure, the experts used a continuous thermal excitation transmission method for detection. The sample is made of cast iron, which is one of the usual metal materials. The thermal conductivity coefficient K is relatively high, about 30-50, so the thermal diffusion coefficient is much larger than the Non-metallic material. That means the capacity of metal store heat is relatively weak, resulting in very fast heat conduction inside. The metal Buddha head has a hollow structure, and the thickest point reached 3cm, which allows the continuous thermal excitation transmission method to be carried out conditionally. Researchers used a heating rod to carry out continuous thermal excitation in the sample cavity, collect thermal signal data outside, and obtain infrared thermal imaging results about the sample after processing(see Figure 4 and 5).

 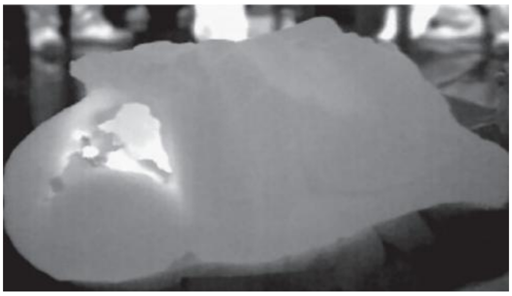

*Figure 4 Left, the cast-iron Buddha head (Normal)[24]*

*Figure 5 Right, the cast-iron Buddha head (Thermography)[24]*

The normal photo of the sample shows that there is corrosion on the head of the statue. However, the damaged area looks more diminutive from the surface, as shown by the red line in the figure. However, the results of thermal imaging show that the area of internal corrosion and flaking is much larger than the surface looks.

Therefore, it can be concluded that infrared thermal imaging technology can be used to the detection of heritage relics made by metal materials, especially for the internal detection of an object with cavity structure. Moreover, it can efficiently detect and acquire cultural relics in a non-contact and steady-state. It can provide data on the internal structure, defects of objects in order to assist the heritage protection. The damaged rooster-shaped statue is made of copper and has a hollow internal structure similar to the cast-iron Buddha head. Thus, infrared thermal imaging technology can be used to assess the degree of damage to the inner surface of the statue, as well as to detect structural damage that can be seen by the eye. It is a perfect method to diagnose mental damage, the internal expansion and ageing after scorching at high temperature.

Nevertheless, we must also pay attention to controlling the temperature of the heating rod during the operation. High temperature may cause secondary damage to the statue. It must be calculated accurately, and real-time monitored.

### 3.2.3 3D laser scanning

In the process of digital restoration of a Japanese coloured wooden Buddha statue[25], P. Stephen Fowles and his team used the ModelMaker H scanner system to collect statue data. This system has a flexible six-axis arm that can record the surface of objects as more extended as possible. With the support of a stable base, this scanner can gain the data information of the measured object under safe and stable conditions. The research team used eight hours to record the full statue data and provided the (x, y, z) data set, with the coordinate spacing between 0.2-0.4 mm. After converting the data into a polygon mesh model, they got a 3D model of the Buddha statue (see Figure 6).

*Figure 6 The Buddha sculpture model developed from the laser scanned data[25]*

Generally, the rate of 3D scanning is more than several hours each square meter to succeed sub-millimetre resolution. Besides, the complexity of the object's surface may exceedingly affect the scanning time. Compared with the X-ray imaging method, it can reduce the radiation. It has no restrictions on the material and complexity of the measured object. In the process of digital data collection, it has been used widest, and the prospects are even more worth waiting. However, it also has shortcomings. The current case is only applicable to the data collection of the appearance of the object. The cultural relics detection results for the internal structure have not been confirmed. Therefore, it is worth to explore the application of detecting the internal structure of the cultural relics. Generally, the price of 3D laser scanning equipment is pretty high, and the scanning cost is high as well. In the process of repairing the rooster-shaped statue, 3D scanning technology can be taken in obtaining the three-dimensional data of the statue without direct contact. It can generate the highest-precision point cloud data model, which avoids the damage caused by the model marking and improves the efficiency of obtaining data.

## 3.3 Digital data processing

### 3.3.1 Geomagic Studio

In the case of repairing the broken statue Sissi[6], the technical team used a 3D scanner to obtain the point cloud data of the sample. They imported the data into Geomagic Studio software for data processing and optimisation. Including data reduction, noise removal and noise processing. This case not only shows how to repair the curved folds of the edge of the model but also shows good strength in dealing with the depressions left after the impact of the statue. The researchers selected and deleted the defect area, filled the depression with Geomagic Studio's fill function, and completed the repair. Moreover, the team also used the 'clear' and 'eliminate nail' functions to repair the rough surface and small hole defects. After error detection, it was confirmed that the average value of the error was about 0.006, and a model of the Sissi statue was obtained (see Figure 7).

*Figure 7 The final rendering of Sissi statue[6]*

In this case, Geomagic Studio software demonstrated the efficiency and accuracy of its point cloud data processing. In particular, it has advantages in handling the surface shape and precise details of the model, which meets the desires of users for high-quality models. As an automated reverse engineering software, Geomagic Studio has the following advantages. First, Geomagic Studio provides a variety of modelling formats, including the current mainstream 3D format data, points, polygons and non-uniform rational B-spline surface models. Second, productivity is ten times higher than traditional CAD software when it is processing freeform graphics and some other complex shapes. The automated features and simplified workflow can shorten training time, save users from performing tedious and avoid to take labour-intensive tasks. Third, the complete data attributes and accuracy ensure that high-quality models can be generated. Fourth, it can be used with most mainstream 3D scanners, computer-aided design software, conventional drawing software, and rapid equipment manufacturing systems. It has strong compatibility and can effectively reduce the budget. Fifth, it can be used as an independent reference program for rapid manufacturing, or as a complement to CAD software. Applying this technology to the point cloud data of the rooster-shaped statue can effectively reduce the impurity information contained in the model, repair the depressions and cracks caused by the collision. Moreover, it can smooth the rough surface caused by the friction between the statue and the ground. It can also be employed to fill small holes and deal with the edge of the curved surface that is extruded and twisted. Thus, a three-dimensional model that best matches the expected result is generated.

### 3.3.2 Artec Studio

In the case of three-dimensional reconstruction of Kungang pottery artifacts[26], the researchers used the Artec 3D system to 3D scan and model the pottery. When using the matching scanner for data collection, the three-dimensional data of the sample appears on the display interface of Artec Studio 9 software in real-time. It is convenient for the operator to preview the scanning status and reduce errors during the scanning process. After completing the data collection, Artec Studio 9 provides different data conversion modes (two-dimensional selection, three-dimensional selection, rectangular frame selection and Cutoff plane selection) to facilitate the change of the use of various forms of data. When researchers used Artec Studio 9 to register the pottery automatically, it was found that the 3D model of the sample has data loss and data registration is incomplete, which needs to be optimised by other software.

Therefore, in this case, it can be seen that the advantage of Artec Studio 9 is timeliness. Users can get the point cloud data in time, and the diversification of conversion modes is also suitable for processing different digital projects. However, the software also has disadvantages. The first one is compatibility issues. This software cannot access other different types of input devices and binds to the scanners of Artec 3D. Nevertheless, the ability to process point cloud data is not strong enough, lacking accuracy in registering data. And most of the time it requires external algorithms and software for secondary optimisation. Fortunately, the recent version Artec Studio 14 has completed many technological advancements. It can use the advanced PBR (Physical Rendering) algorithm to generate the reflective removal function of the same colour surface, and the bridge function, which can use the existing scanning area to fill the holes and bridge the gaps. Compared with the high compatibility and accuracy of Geomagic Studio, this technology is not feasible for processing rooster-shaped statue point cloud data, and the expected results are not good.

### 3.3.3 MATLAB software

In the mentioned Kungang pottery repair case, due to the limited ability of Artec Studio 9 software in data preprocessing, the researchers used MATLAB software to assist. In MATLAB software, the bounding box and iterated complete path (ICP) algorithm[27] are used to optimise the registration of point cloud data. The ICP algorithm is a heuristic search procedure for finding the best path through a weighted trellis. It is intended for problems in which the cost of computing the edge weights, and dominated the cost of finding the path given the weights. After reading the initial point cloud data, researchers remove the excess point cloud data by adding a bounding box to intercept the required point cloud data. Next, they use the pcregrigid function to optimise the point cloud registration of the ICP algorithm, and then take out the point cloud coordinate data and merge the point cloud data to generate the optimised model (see Figure 8).

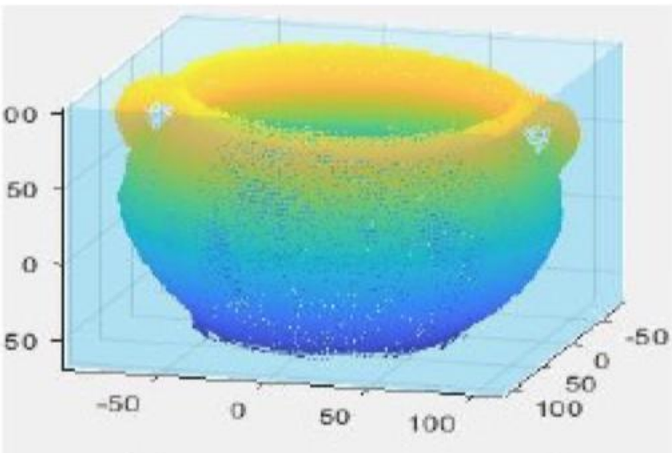


*Figure 8 The optimised model of the Kungang pottery[26]*

The use of optimised ICP algorithm in MATLAB software for registration of point cloud data has not only good accuracy but also the matching speed is relatively satisfactory. At the same time, the researchers compared the speed of registering data using the original ICP algorithm and the optimised ICP algorithm in MATLAB. They concluded that when the amount of point cloud data is more massive, the MATLAB software optimisation using the ICP algorithm has an advantage in registration speed. Therefore, the software can be used in conjunction with Geomagic Studio to register point cloud data for rooster-shaped statues. The data model after preliminary processing in Geomagic Studio can be imported into MATLAB, and the optimised ICP algorithm can be used to perform the secondary data registration processing. Then, all obtained data can be exported to Geomagic Studio for detail repair and model generation.

## 3.4 Digital surface restoration

### 3.4.1 Eye-One colour management system

Researcher Cheng Huwei from China used the Eye-One colour management system provided by X-Rite to correct the colour of the bronze surface during the restoration of the Shang Dynasty bronze[28]. In the process of texture data collection, a three-point light source with more uniform light was deployed, and auxiliary equipment such as reflectors are used as auxiliary to reduce reflection. Researchers also made the lighting more uniform, which causes the light and dark transitions are naturally soft. At the same time, the X-rite white balance card is used to define the camera's white balance, and the camera's photo file generation format is set to RAW to ensure the quality of the texture photo. In order to obtain more realistic texture photos, the researchers recorded the colour temperature of the lights and used X-rite 24 colour cards to shoot. When performing post-colour correction, use this colour data as a reference to control the amount of colour shift to manage colour.

The colour management system can generate colour characteristic description files for the scanner, which is suitable as an auxiliary tool for 3D scanning technology. It is easy to use, and researchers can use the USB cable to connect to the scanning device. Besides, it is excellent in displaying shadow details, and colour transition smoothness has a wide colour gamut and is not easily affected by external factors such as light illumination. Therefore, it has a positive effect on the surface restoration of the cock-shaped statue. When sampling the statue, the Eye-One colour management system was used to generate a colour profile and embed the file into the 3D laser scanner, Geomagic Studio, MATLAB software, and subsequent output devices. Thus, natural and accurate colour data is obtained, and the influence of environmental factors such as light on the bronze statue is avoided.

### 3.4.2 Color migration algorithm

In the research project on the rendering of painted terracotta warriors[18], the researchers used Welsh algorithm to carry out colour migration experiments on the statue surface. They used the remaining colour information from the surface of the statue as the source image obtained a new image of 'ageing'. The new image and the grayscale image of the texture of the statue were subjected to another colour migration. Finally, the restored, painted texture pattern was obtained.

The texture pattern obtained by the colour migration algorithm has full colour. It is more realised with the natural ageing objects, which is helpful for the subsequent import of modelling software for 3D mapping. However, the shortcomings of Welsh algorithm are also apparent. When using this algorithm, the computer needs much time to calculate the best matching point, thereby reducing the efficiency of the algorithm. Also, the Welsh algorithm works by matching the brightness of a pixel and the standard deviation of the brightness of its neighbourhood, which requires high consistency between the brightness and colour correspondence. That also increases the limitations of using the algorithm. Also, it increases the limitations of using the algorithm. Colour migration technology can play an essential role in the process of restoring the rooster-shaped statue. In this stage, researchers need to obtain the archived digital image (statue photos before the fire) at first. They should take the damaged statue photos as well, extracting the remaining colour information on the surface. Next, They can use the Welsh algorithm to calculate the best matching point, generate new texture pictures and grayscale images. After finishing the secondary colour migration, the restored texture patterns can be compared with the archived statue photos.

## 3.5 Digital demonstration

### 3.5.1 Virtual Reality

In the field of heritage protection, virtual reality is suitable for applications in different sectors. For example, using VR technology to rebuild artworks or cultural relics at that time, reproduce historical scenes or damaged items, or as a basis for repairing damaged or lost cultural relics. It is also used for the public demonstration of restoration projects. As a new application case of virtual reality, the virtual reconstruction project of Yuanmingyuan Park was proposed and carried out by Professor Guo Daiheng[29], a researcher at Tsinghua University at the beginning of the 21st century. It has been instrumental so far, and there is a good deal of 3D models of artifacts damaged by fire and war have been established. As a demonstration of the digital restoration project of Yuanmingyuan Park, the public can use VR interactive devices to access and visit the project. Professor Guo's research team has developed the virtual reality-based Yuanmingyuan Park mobile navigation system. This system collects massive data which includes positioning, navigation, location recognition, and audio explanation. These data are equal to achieve a high-definition immersive experience for visitors. Through the virtual park system, the precious cultural relics that had disappeared for more than a century are reproduced, and the historical scenes are re-exposed to the public. At the 2017 'Approaching the Future of Yuanmingyuan Park' technology experience exhibition in Hong Kong[30], the creative team also combined the remains of Yuanmingyuan Park with VR interactive devices. The 'Twelve Beast Heads (famous twelve bronze statues in China)' lost in the war, and the destroyed fountain pool was rebuilt and displayed.

Therefore, combined with related examples, it can be seen that the utility of virtual reality technology is able to urge more excellent progress to the digital demonstration in the cultural heritage protection area. Modelling cultural relics and historical sites through 3D modelling technology can display them in a comprehensive and picturesque way as well as offer users a more intuitive visiting experience. Thus, it can enable cultural relics to share resources in real-time without being restricted by regions as well as adequately protecting cultural relics from excessive tourists. The impact of the tour can also be used as an essential way to test the digital restoration project to assist the protection of cultural heritage. By importing the processed 3D model data of the statue into the VR device, the researcher can touch, modify, and check the statue model through the immersive experience effect. It can also let the visitors see the restoration results within the interactive device.

### 3.5.2 Augmented Reality

In the restoration process of the monument to the Saint Laurentius Church in Ename[7], researchers used AR technology to demonstrate the progress of the restoration project. In order to explain this huge restoration project to the public, a multimedia application was developed. A website named TimeScope1 was launched on 2 September 1997. TimeScope1 superimposed a 3D model of an early medieval monastery church onto a live video through a touchscreen installed in a large on-site kiosk. It allowed visitors to see the ordered structure in their original state. There was also an accompanying multimedia presentation provides other functions, including the display of the economic life and social activities of the medieval inhabitants of the region (see Figure 9).

*Figure 9 TimeScope1 provides Augmented Reality[7]*

There is also a case at the University of Illinois in the United States shows the application of AR technology in the digital demonstration area. After using a 3D scanner to get the data, researchers used Geomagic software to removing excrescent data, filled holes, and overall 3D mesh clean-up to improve the appearance of the model. The AR technology was used when established the 3D model in Autodesk (a modelling tool). Students can see the Alma Mater statue[31] that has been dismantled and repaired through the camera equipment and take a photo with it (See Figure 10).

*Figure 10 Students use camera equipment to take photos with the Alma Mater statue[31]*

Viewers can use AR technology to view and visit cultural heritage as well as combine virtual objects with reality. So that restorers can use it to assist repairing buildings, statues and other cultural heritage, showing the expected results of restoration or achieve other commercial goals. Compared with VR technology, it is free from the multiple types of hardware devices, and it does not completely isolate the experiencer from the virtual environment. Instead of entirely virtual activities, it assists experiencers to interact with both virtual and real environment. The information from the real world is not totally discarded but is appropriately used. There is a considerable benefit of AR technology in daily application scenarios. It can be employed to reproduce the scene virtually where the rooster-shaped statue atop on the spire of the cathedral. Visitors can see the real scene before the fire through the cameras of electronic devices such as mobile phones and tablets. It can also be applied to show the restoration process of Notre Dame to the public, using digital means to virtually demonstrate the process of 3D data collection, digital modelling and surface restoration to satisfy the curiosity of the public. Moreover, it can also invite the public to supervise the progress of the project.

### 3.5.3 3D printing

During the reconstruction and restoration of the damaged sitting Buddha statue[32], a research team used 3D printing technology to make a physical, virtual recovery model verify the measurement accuracy. And it was utilized to check the aesthetic performance of the modelling results. The replica model was also used to display the final restoration result. The team used a 3D printer in material extrusion type and polylactic-acid filament. They printed it four times, using opaque plastic hardened by ultraviolet. The completed 3D printing output was used for the restoration of the bodhisattva. Moreover, the antique colouring was performed separately to reduce the sense of aesthetic difference and prevent discolouring since the variational lighting environment (see Figure 11).


*Figure 11 Completion of Buddha statue restoration[32]*

In this case, 3D printing technology demonstrated the role of its digital expression. Compared with VR and AR technology, printing the physical model can more intuitively and accurately check the accuracy of the repair process. It can check the completeness of 3D data collection and the accuracy of 3D modelling. It is easy to control the progress and results of the entire repair process. The 3D printing technology can also actually output the restored result model for display or other industrial and commercial purposes. However, the defect of the 3D printing technology is the complexity and rarity of the printed materials. Except for the rare ingredients, it costs much money to buy printing devices as well. The budget requirements for the restoration project are relatively high. However, using a 3D printer to print a physical model of the rooster-shaped statue can detect missing information during the 3D data collection process, check the repair results of the damage and preview the final repair results. The printed replica model can also be used for other purposes such as exhibition and preservation.

### 3.5.4 Digital museum

As a means of the redevelopment of cultural heritage protection, the Digital Museum project came into being. In September 2018, a fire broke out in the Brazilian National Museum, which has a history of more than 200 years, and almost 20 million artifacts in the museum were almost destroyed. However, before the fire, as early as 2016, Google's art and culture team collaborated with the Brazilian National Museum to digitise the museum's collection[33]. They used the 3D scanning, high-resolution photography, AR, VR, and other technologies to present the 360-degree original appearance of the museum on the Google Street View platform. Google has now opened an online virtual Brazilian museum. Although it is a virtual form using street view images and digital exhibitions, it is still significant. Now, users can enjoy the collections of the National Museum of Brazil in Google Street View (see Figure 12). It is reported that in the virtual museum, Google combines information such as museum floor plans and walking tours. Thus, visitors can change the location to enjoy different exhibits with the click of a mouse. Meanwhile, visitors also can enter the website, select the cultural relics they want to know to start the virtual tour and appreciate these cultural relics that have been destroyed in the fire from a distance.

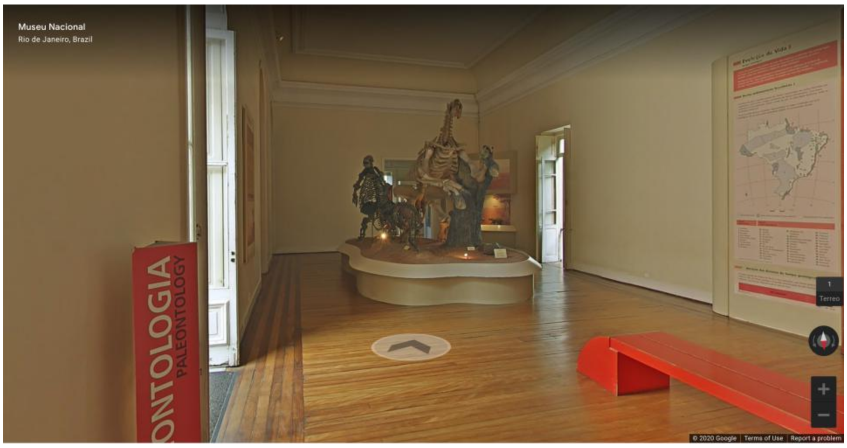


*Figure 12 National Museum of Brazil in Google Street View*

The digital museum project has advantages in the digital redevelopment of cultural heritage. Especially in the application of virtual tourism, it provides users with a convenient opportunity to visit places without leaving the house. The virtual restoration and reconstruction of cultural relics are brought back to the audience again in an immersive and attractive way. Using this new form to develop cultural heritage not only about respect but also provides new methods for creating the commercial value of cultural heritage. The digital museum project can make progress for the development of the tourism industry. It transforms the artistic and cultural connotation of cultural heritage into commercial value in order to achieve economic development. For Notre Dame, applying 3D scanning, VR, AR technology to build an online virtual museum is an excellent choice. The project should support tourists to visit Notre Dame Cathedral remotely, visit this ancient building and enjoy the fascinating culture and art. It should provide an immersive way to view cultural relics. This project can help the Notre Dame Cathedral play its economic and cultural value during the maintenance period, reduce the negative impact of fire, and promote the spread of culture and economic development.

## Results/Conclusion

### 4.1 The best solution to reconstruct the rooster-shaped statue

There are many options for the digital restoration of the rooster-shaped statue. However, all plans have to go through three processes of three-dimensional data collection, data processing and digital modelling, digital surface restoration. This article analyses the various stages of the statue restoration project. The application of digital technology has resulted in a plan to repair the damaged statue of Notre Dame Cathedral.

In general, in the process of digitally repairing the rooster-shaped statue, a variety of three-dimensional data collection methods can be used to collect the original data. First, researchers can choose to use X-ray or CT technology to confirm whether the legendary 'three relics' inside the statue and how damaged they suffered. Afterwards, they can employ thermal imaging technology to check internal damage. They are able to use 3D laser scanning technology to collect data on the external surface of the statue in the following stage. When they obtain the 3D data of the rooster-shaped statue, they can import the data into Geomagic Studio software to generate a point cloud. Meanwhile, researchers can simplify the point cloud data as well as clean up the unnecessary data in this software. In the following stage, they can get a preliminary three-dimensional model after finishing data processing. Researchers can amend the surface of the model in the Geomagic Studio as well. For instance, repair cracks, reconstruct concave surface, smooth scratches and fill small holes. Finally, a colour management system can be used to generate a colour feature description file. They can use the colour migration algorithm to obtain natural statue textures and colour information. Moreover, the texture file is imported into Geomagic Studio software for matching the target object and synthesis, thereby obtaining a virtually restored statue model. After this, a 3D printer can be used to print the real three-dimensional model and perform the result detection and data verification. At the same time, the generated real model created by 3D printing technology can be unitized for digital demonstration. For further options, the three-dimensional virtual model of the statue can also be stored in the cultural heritage database for permanent preservation.

## 4.2 Future development

The development of digital technology in the field of cultural heritage protection is up-and-coming. Especially in restoration and virtual reconstruction of damaged cultural relics area. It is not only suitable for repairing statues, but also for repairing large buildings, rebuilding landscapes and reproducing historical phenomena. Therefore, applying diversified digital technologies to the restoration of Notre Dame Cathedral has research significance firmly. It can improve its restoration efficiency and make the restoration results more satisfactory. Moreover, for different repair subjects, the repair scheme proposed in this paper cannot be copied entirely. In the process of digital restoration of heritage relics, different restoration principles and restoration goals must be considered. Restoration plans should be formulated according to factors such as sample material, size, damage degree, and project budget to achieve the most sustainable plan for cultural heritage protection.

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