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Systematic integration of 2D and 3D sources for the virtual reconstruction of lost heritage artefacts: the equestrian monument of Francesco III d'Este (1774–1796, Modena, Italy)

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Abstract

The role of 3D virtual reconstruction of lost heritage artefacts is acquiring ever-greater importance, as a support for archaeological research and art history studies, as well as a vehicle for the cultural and evocative involvement of the end-user. The main risk of virtual reconstruction is the lack of a faithful restitution but, conversely, very often the artefact conservation state does not allow a complete 3D reconstruction. Therefore, 2D sources, both textual and iconographic, represent a precious integration and completion of the existing 3D sources. This paper proposes an operating systematic workflow to integrate retrieved 2D and 3D sources and assess their compatibility for the virtual reconstruction of lost heritage artefacts using and integrating 3D survey and digital modelling. As a case study, we virtually reconstructed the lost equestrian monument of Duke Francesco III d'Este, 7 m high, built in 1774 in Modena, Italy, by the sculptor Giovanni Antonio Cybei and completely destroyed a little over 20 years later during the revolutionary uprisings. Following the proposed workflow, we integrate data coming from: a still preserved preparatory stucco model, paintings and engravings showing the missing details of the 3D model, a series of urban views returning the proportion and positioning of the monument (statue, pedestal and base), a fragment of the right foot providing the statue size and the appearance of the original white Carrara marble. The final 3D digital model shows a faithful correspondence to the 2D sources and guarantees an effective user's fruition thanks to dedicated virtual applications. Besides the scientific and cultural goal, we highlight the evocative role of this work, which has contributed to the restitution of a monument that is unknown to most citizens and visitors.

Keywords: Virtual reconstruction, Close-range photogrammetry, 3D modelling, Iconography, Equestrian statue

Introduction

In the last decades, the role of 3D techniques in the field of archaeological heritage has assumed, on the one hand, an increasingly importance for the web diffusion of cultural contents, public outreach and education [1–4], also thanks to different mediums of visualization [5] that improves the spread of Cultural Heritage artefacts [6]. On the other hand, 3D technologies have a key role in documenting and supporting archaeologists who deal with continuous work of restoration and their associated studies, generating 3D models for archival purposes, for conservation records [7–9], for 3D visualization [10–14] and reconstructive interpretation of lost artefacts [15–21]. In [22], Lai et al. stressed the importance to use 3D technologies as a tool to improve

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archaeological research and to increase the production of information from archaeological data to 4D analysis and interpretation. Moreover, Bourdier et al. [23] remarked the importance of 3D technologies as a complementary to the other traditional analytical tools in the heritage field.

We can identify two main criteria in the generation of 3D digital models according to Guidi and Russo [24]: firstly, they are faithful representations of the current condition of a monument, thanks to advanced digital survey techniques such as digital photogrammetry and 3D laser scanning, with a following modelling and representation processes based on true geometrical data. Secondly, a 3D digital reconstruction can be conceived starting from historical information and drawings, with a research approach more oriented to the interpretation of lost architecture.

In other words, 3D technologies are tools for discovering new archaeological results stacking on the possibility to “see” what in the past was only possible to be imagined through descriptions, and, according to the UNESCO’s chart [25] to face the disappearance of heritage (as in the Preamble of [25]) as well as guarantee the access to digital heritage (as in Article 2 of [25]). This is in accordance with the meaning of digital heritage as “cultural, educational, scientific and administrative resources, as well as technical, legal, medical and other kinds of information created digitally, or converted into digital form from existing analogue resources” [25]. So virtual reconstructions [26] can be considered a new powerful scientific methodology in addition to the more obvious application for increasing the diffusion of archaeological culture among the non-experts [24], as well as a support for archaeological research and art history studies.

In this paper, we focus on the latter criterion based on the use of historical sources both in form of written text or images, that once properly matched with the 3D acquired geometrical data, may help to recreate digitally a faithful 3D model of the artefact, when they are lost, damaged or simply modified over time.

In particular, a reconstruction process involves various types of sources, with a cross-disciplinary approach [27, 28], and assesses how their explicit or implicit derived knowledge is relevant in the 3D modelling phase [29–32]. Giovannini [4] underlined how the documentation and visualisation of the virtual reconstruction processes is an ongoing debated topic within the scientific community that comprise themes of uncertainty and the possibility to have alternative options for 3D reconstruction.

The integration of geometrical information extracted from 3D survey and historical data, with the main purpose to identify an optimal process of 3D reconstruction of lost buildings, is presented in. Guidi and Russo [24]. In particular, they proposed a block diagram of the reconstruction process based on the integration olf historical data (e.g., historical documentation, 2D reconstructive modelling, 3D reconstructive modelling) with 3D data acquisition and reality-based 3D modelling. Based on their analysis on how a building has changed over years, the result consists of a sequence of 3D models corresponding to different periods, visualized in the same environment, in accordance with historical sources. Forthcoming researches has further developed this model, integrating and harmonizing multiple types of sources [33–35] as ancient maps, drawings, archaeological reports, laws regarding archaeological remains in the city and old photographs, leading to the reconstruction of lost architectures (2D plan and then 3D model) [34, 35] in the current urban context. A similar approach is presented in [22], where Lai et al. proposed a pipeline of the 3D recording for the reality-based 3D modelling and monument analysis, for the reconstruction of a Nuraghe, a Sardinian ancient building. Similarly, in [36], the mapping of the few remaining columns with original elements on top of the Tholos monument in Delphi, Greece, is described and the 3D reconstruction for visualization in educational scenario is presented. Spallone [37] presented different strategies for the preservation of architectures subjected to demolition or transformation, and then focused on a case study in which critical bibliography, archival sources and digital reconstruction are combined. Besides the high number of examples of 3D surveying of architectural heritage, we highlight the contribution of research works [15–19, 38] dealing with the virtual reconstructions of lost buildings or archaeological sites.

Considering smaller sized artefacts, such as statues, architectural ornaments, and similar works of art, Giovannini [4] proposed a practical approach to define the hypothetical virtual reconstruction of architectural elements (namely the ciborium and pergola) from archaeological fragments, which were digitally acquired and allowed to hypothesize the entire sequences of decorations, combining original fragments with their lost parts modelled in a digital environment. This work aimed at creating a system to document the phases of virtual reconstruction using 3D web visualisation. Counts et al. [39] showed how to create 3D digital models from samples and broken sculptural fragments using structured light scanning for making a 3D digital repository an ideal platform for post-excavation study, such as hypothetical reconstructions of fragmentary sculptures based on established typologies, exploring surface treatments (paint, fingerprints, carving marks) and identifying and matching unique joins in order to help reconstitute limestone and terracotta statues. Balletti et al. [40]

reconstructed a digital model of a Venetian galea (galley) starting from the photogrammetric and 3D laser scanning survey of a scaled wooden model of the hull of half of a 25-bench galley of the mid-seventeenth century, which was then integrated by some artefacts present at the Naval History Museum of Venice, surveyed with photogrammetric techniques and 3D laser scanning too. In [41], Fazio and Lo Brutto developed a workflow following three steps: 3D survey and reality-based model production, evaluation of reconstruction hypotheses based on a rigorous selection of reference sources, and 3D modelling and source-based model creation. Their goal is to preserve the original artwork authenticity and the transparency of the reconstruction method. Two fragmentary Roman statues from the "Sanctuary of Isis", inside the Archaeological Park of Lilibeo-Marsala (Italy), were chosen as case study. In [42], Spallone et al. followed a workflow based on photogrammetric survey, 3D modelling and 3D philological reconstruction for the visualization of Japanese statues, which were virtually completed with their weapons and contextualized within the digital model of the temple where they were originally placed.

Then, the aim of this work is to describe a complete workflow for the virtual reconstruction of lost and damaged artefacts, such as statues and similar 3D works of art, which are described by still existing sources of various nature, such as 2D representations, textual documents, scale models, small fragments and finds, thanks to the integration of 3D technologies such as the 3D acquisition, 3D modelling, texturing and 3D model visualization. This is a challenging research area due to the difficulty to merge multiple and often inconsistent data sources. The expected outcome is a model that is metrical and faithful to the original artefact at the same time.

The workflow has been experimented on a lost equestrian statue, erected in Modena (Italy) in 1774 and made in white Carrara marble, which was completely destroyed around 20 years later, but fortunately fully documented thanks to various and multiple original sources. The paper is structured as follows: The Method and Tools section describes the general workflow and the kinds of tools adopted. The Case Study Background section introduces the equestrian statue and the historical scenario. The Results and Discussion section presents how the workflow is implemented and how the various sources have been used by integrating the related information into the 3D digital model thanks to 3D technologies, and analyses the main goals and limitations of the workflow. Finally, some final remarks close the paper.

Materials and methods

We propose a 3D digital reconstruction workflow based on the integration of historical and iconographic documentation, 3D survey techniques, 3D modelling, measurements and historical analysis. The method originated from similar approaches mainly dealing with lost architectural heritage but, here, the target is set on lost statues and other similar artefacts, and the workflow has been specifically modified and expanded to include the contribution of iconographic sources, which frequently flank physical models or heritage fragments of the artefacts. In [4, 39–45], authors presented several approaches to reconstruct 3D digital model of partially existing artefacts with a smaller size with respect to architectures, and generally with free form shapes, requiring a dedicate approach based on 3D modelling. Due to the multiplicity and complexity of cases, we tried to address the most general problem, dealing with various and heterogeneous retrieved sources—both 2D and 3D, including iterative assessment phases to guarantee consistency with the 2D and 3D data. These last iterative phases, which are fundamental to achieve a reality-based 3D digital model, are rarely formalized in the workflows already available in the literature, thus limiting a revision opportunity to achieve a faithful representation. Therefore, the workflow summarized and generalizes the main operating steps on the one hand and, on the other, guarantees a systematic application to support the multidisciplinary team involved in the virtual reconstruction activity. The workflow is applicable to different kind of 3D lost–partially or totally destroyed- artefacts, e.g., statues, sculptures, craftsmanship objects, monuments, ornaments, and architectural elements. The method is shown in Fig. 1.

The workflow starts with the selection of the artefacts to be virtually modelled (Input phase). The second phase deals with the identification and collection of different types of sources, 2D and 3D as listed in Fig. 1, which are preliminarily analysed.

In the third phase, namely "initial assessment phase", the consistency of the information returned from the sources is evaluated and, in case of conflicting information, the workflow suggest to come back to the previous step in order to search for additional sources. Conversely, the sources are grouped in 2D and 3D ones, each leading to different actions. In case of 3D sources (e.g., remains, fragments, scale models, material, physical copies, etc.) they can be directly processed in the next phase (i.e. 3D survey). In case of 2D sources, they can be classified in "3D shapeable" or not. If a 2D source can be modelled in a 3D shape, as in the case of a pictorial data, the resulting shape will be created as a geometrical feature of the 3D model in the next step within a 3D modelling software. Conversely, if a 2D source returns a quantitative information (e.g., a size, a proportion, a position, etc.) or qualitative (such as a colour or a material) they will be directly integrated as an attribute of the 3D model.

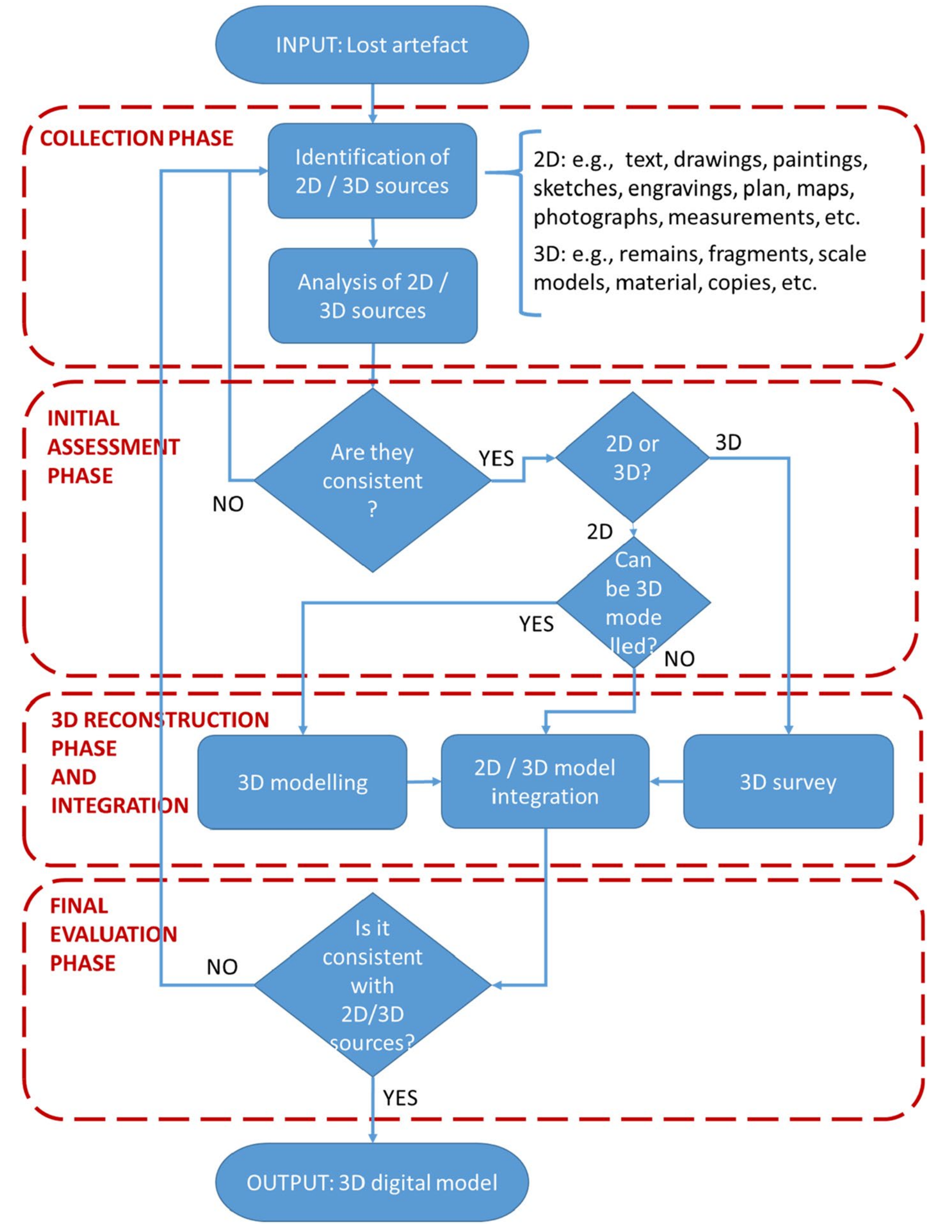

Fig. 1 The operating workflow integrating iconographic and other 2D original sources within the 3D reality-based reconstruction of heritage artefacts using 3D technologies

The next phase is characterized by three different types of software and techniques: tools for the 3D survey of 3D sources, if existing; 3D Computer-Aided Design (CAD) modelling software, for the development of new geometrical elements; sculpting and mesh merging software, for combining mesh elements coming from both 3D survey and CAD software.

-3D survey techniques are widely used in many application fields with the aim of capturing and collecting all the features (shapes, dimensions, textures, surface treatment) of an artefact or product. This acquisition is typically performed with equipment able to capture the physical specifications and transfer them in a digital form: the most used techniques in this kind of applications are range-based (e.g., 3D scanners) and imaged-based techniques (e.g., Close-Range Photogrammetry (C-RP)). Focusing on the latter, thanks to a Structure-from-Motion (SfM) approach [46, 47], it can extract corresponding image features from a series of overlapping photographs captured by a camera moving around the object. C-RP is able to capture a wide size range of artefacts.

The general process of 3D survey of physical objects is composed of three main phases, plus a final assessment phase: the pre-processing phase, the acquisition phase, the post-processing phase.

With respect of a 3D survey based on C-RP, the following steps are foreseen:

1. Evaluation of the original surface, in order to guarantee homogeneous light conditions around the object, avoiding shiny areas or reflections, or by applying polarising filter, if necessary. Place a scale bar and/or a reference coordinate system, with markers or calibrated control points, in the scene or around the object.
2. Plan the set of photographs around the subject to provide high overlaps of the subject points, capturing the whole geometry. Image acquisition through the camera. Upload and import the photographs in the photogrammetric software. 3D model reconstruction through the software by setting image orientation and alignment, dense surface reconstruction and filtering.
3. Further operations consist of: Cutting the scene surrounding the object (by manually deleting unnecessary points or using automatic masking procedures), except for the reference elements useful to align the models during the comparison phase. Model scaling using reference elements in the scene: the photogrammetric models can be scaled directly in the C-RP software as well as in a further software.

The high dependence of the photogrammetric reconstruction on the quality and number of images, as well as the performance of the camera, requires to carefully plan the set of photographs, capturing the whole geometry of the object (i.e. through images taken all around the object at different heights).

The 3D models coming from both the 3D survey and the 3D modelling software are integrated and combined in a sculpting and mesh merging software, which is able to manage meshed files (e.g., STL files) as the ones resulting from the 3D survey.

In the last phase, namely final evaluation phase, the 3D model is accurately compared with all the available sources to guarantee consistency. If the model reveals features or attributes that are not consistent with some sources, we can come back to the first point and search for additional sources. In case of reconstructions resulting from hypotheses, e.g., due to ambiguity or lack of data, these need to be clearly reported in the artefact restitution.

Case study background

The monumental equestrian statue of Francesco III d'Este, Duke of Modena (Italy) from 1737 to 1780, was sculpted by Giovanni Antonio Cybei [48, 49], sculptor and first chief director of the Carrara Academy of Fine Arts (Italy), between 1772 and 1774. The commission for the statue dates back to the beginning of 1772 and the contract with the sculptor Cybei was stipulated on 14th April of that year [50]. It was commissioned by the citizens of Modena as thanks for the welfare policy of the Duke, who promoted the construction of the "Grande Albergo dei Poveri" (namely "Great Hotel for poor people", currently Palazzo dei Musei, Museums Palace) and the "Spedale di Sant'Agostino" (namely "Hospital of Saint Agostino", currently a cultural centre called AGO–Fabbriche Culturali). These buildings were (and still are) on the opposite sides of Sant'Agostino square, where the statue was originally built [49, 51]. In fact, after evaluating the other squares of Modena, this square was identified as the ideal place for the celebration of the Duke and for the erection of his huge monument. The sculptor undertook to supply the three parts of the statue—one for the rider and two for the horse—by the summer of 1773. From the signed contract, we can learn that the white Carrara marble blocks, which left La Spezia (Italy), reached Modena via Venice in mid-November 1773, after three months of difficult sea navigation. The statue was solemnly inaugurated on 24th April, 1774, with the re-enactment of a parade on the theme of the triumph of the Roman consul Paolo Emilio Lepido, who was considered the founder of the Via Emilia and the promoter of the first library in the ancient Rome. This episode of Roman history was chosen to pay homage to Duke Francesco III d'Este, who promoted the enlargement of the Via Emilia and opened to the public the Estense Library, echoing the noble feats of the Roman consul.

A commemorative volume was edited by Giovanni Battista Vicini (1774), professor of eloquence at the Collegio San Carlo (Modena, Italy) and "Primary Poet of the Court", who involved the greatest eighty-five writers of the Este scene. The importance of the volume is also underlined by the series of illustrations that embellish it, including the large opening panel that analytically reproduces the entire equestrian monument (see Fig. 3, in the next Section) [52]. The equestrian statue resembled the model of the Roman statues and, as a marble colossus more than 7 m high, stood out in the square. The statue, however, representing the symbol of the ancient regime government, was short-lived: severely damaged by the Modenese bookseller Giovanni Battista Fornieri during the revolutionary uprisings of 1796, it was demolished shortly after, when the French army guided by Napoleone Bonaparte entered the city of Modena.

Results

In the following subsections, we implemented the proposed workflow to the lost equestrian monument of Duke Francesco III d'Este, which represents an example of lost artefact due to a voluntary destruction. Each subsection consists in the development of one of the main workflow steps, leading to a partial output that originates the input for the following step in the workflow.

In the first one, namely "Identification and analysis of historic and iconographic 2D sources", we collected and analysed the 2D documents, in both textual and iconographical forms. From the analysis of the detailed descriptions and the graphical elements, we achieved the location, the dimensional data with proportions and the morphology of the monument. The 2D sources returned the design intent of the sculptor Cybei and its evolution over time, from the conception to the realization of the equestrian monument.

In the second subsection, namely "Imaged-based 3D survey of the preparatory stucco model", we performed a 3D reconstruction of the main of the remaining 3D sources, i.e. a preparatory model made by the same sculptor. The 3D survey based on Close-Range Photogrammetry (within the software Agisoft Metashape) returned a 3D digital model, albeit partially incomplete (a few statue details and the entire pedestal and base). This first preparatory model and the other 3D sources—a fragment of the statue and two other preparatory models–allowed to get (and confirm) the statue size, the material and the overall morphology.

In the third subsection, namely "Integration of missing details using 3D modelling", we compared 2D and 3D sources, in particular the 3D models and iconographic sources, and then integrated the first 3D digital model with details using 3D modelling. Two software were used: Autodesk Meshmixer for easily managing the meshed photogrammetric model (in.STL file format) and creating—and then integrating- all the missing details; Dassault Systèmes SolidWorks for directly modelling the monument pedestal and the stepped base, thanks to a parametric approach that simplified the dimensioning and scaling operations with respect to the statue 3D model. A second C-RP survey of a real hand was used to obtain a 3D digital model that was integrated to reconstruct the Duke's left hand.

During the reconstruction process, the comparison of the sources sometimes returned conflicting data. Therefore, following the iterative revision approach (Fig. 1), we come back to a previous step and additional sources were identified, analysed and then integrated.

Identification and analysis of historic and iconographic 2D sources

Valuable information can be obtained from the extensive documentation and the related iconography (such as drawings, paintings, engravings, maps, etc.) recovered and collected from local and national museums and collections.

A letter to the Duke [53] described the foreseen location of the statue, to which a drawing was also attached (Fig. 2), depicting the site where the statue positioning was proposed: the site, in fact, had to be proportionate "to the vastness of the mass, and in those points of perspective, which adjusted with distances corresponding

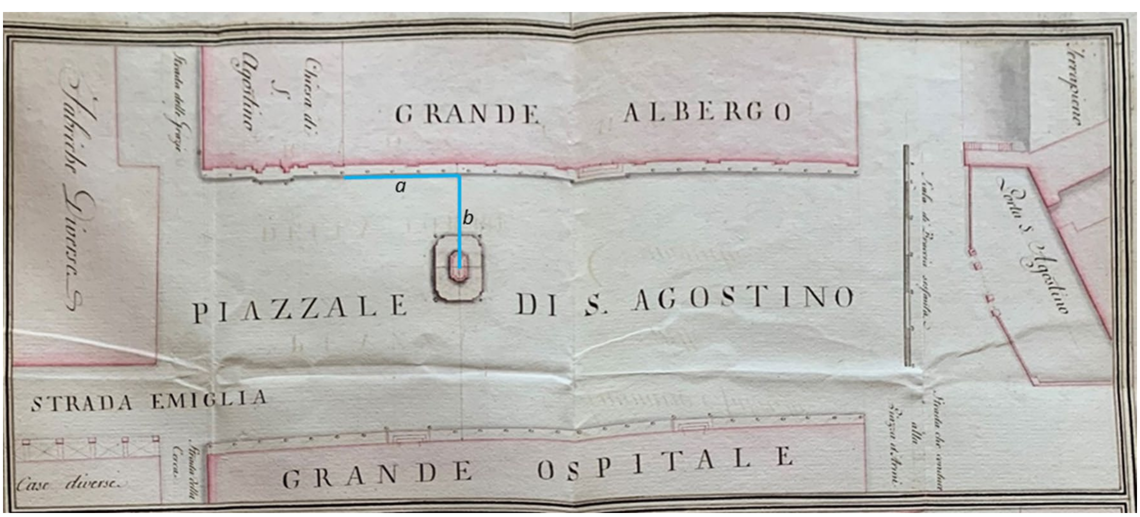

Fig. 2 Plan of Sant'Agostino square in 1774 with the preliminary evaluation on the statue position (Source: [53]). We drew the blue lines (*a* and *b*) to estimate the monument position

to the height of the machine, and to the altitude of the rider, and of the horse". The note reports that the statue "requires a very large space, and for the passage around it to remain free, and because its appearance stands out in various points, but above all in the most essential, which is to look at it obliquely from the right side, from which part the rider and the horse hold the head».

This drawing shows the plan of Sant'Agostino square (still existing in Modena) with the preliminary position of the monument, identified by the blue lines *a* and *b* in Fig. 2, and presents a scale in Modenese arm, an ancient local unit of measurement that corresponds to 0.648 m. Using this scale, we estimated the horizontal distance *a*, from the centre of the monument to the church of Sant'Agostino, in 32.22 Modenese arms, corresponding to 28.87 m. The vertical distance *b*, from the centre of the monument to the wall of the church of Sant'Agostino and the "Grande Albergo dei Poveri", is 26.32 Modenese arms, corresponding to 17.05 m. The distances are summarized in Table 1.

The large opening panel of the commemorative volume edited by Giovanni Battista Vicini (1774) reproduces the entire equestrian monument (Fig. 3). As established in the project, the Duke was depicted as the warrior, bareheaded, with a cloak, equipped with a sceptre and without stirrups, on the model of the Roman statues of Constantine by Gian Lorenzo Bernini and Charlemagne by Agostino Cornacchini; to the latter statue, Cybei had collaborated, as clearly confirmed by the sculptor himself. The horse is represented in the act of trampling on some military trophies, symbolizing the spoils of the vanquished, and stands on a high pedestal that must have been in white marble, decorated with inscriptions provided by Girolamo Tiraboschi and, on the front, by a coat of arms of the house d'Este. The sculpture is placed on a pedestal that rose from a stepped base, surrounded by small columns to support iron chains that the citizens even wanted gilded [54]. This print (Fig. 3) is due to Antonio Baratti (1724–1787) based on the drawing by Michelangelo Borghi da Carpi (1742–1813) [55], included in the commemorative volume edited by Giovanni Battista Vicini and printed on the occasion of the solemn inauguration of the colossus [56].

The overall height of the monument can be estimated using both iconographic and textual sources. The caption of the engraving, at the bottom of Fig. 3, reported the words [52]: "Equestrian statue of white Carrara marble, 40 Roman palm high, elevated to His Majesty Francesco III/by the Modenese citizens on the Via Emilia in the large Sant'Agostino square di that city Work of Mr. Abbot/Giovanni Antonio Cybei of Carrara, Sculptor at the service of His Majesty and of Her Majesty Princess/Hereditary, and Primary Director of that Academy". The caption returned a height of 40 Roman palm, which corresponds to 8.936 m, as 1 (architectural) Roman palm = 0.2234 m (see page 56 of [57]). This overall height of over 8 m was initially foreseen as confirmed by another document, cited by Lidia Righi Guerzoni (page 227) of her essay [54], which reported the overall height of the monument (both statue, pedestal and base) in 33.3 Genoese palms (1 Genoese palm corresponds to 0.2477 m, see page 55 of [57]), so the monument was 8.248 m tall. However, again Righi Guerzoni (page 227, [54]) reported that the same sculptor proposed to reduce the monument size, excessive for the site, in order to make the monument volume consistent with that of the surrounding buildings. Therefore, Cybei recommended reducing the overall height to 29.5 Genoese palms ($0.2477 \times 29.5 = 7.307$ m), as in Table 2.

In addition, a series of urban views show the original appearance of the statue and its position close to the "Grande Albergo dei Poveri". Among these, an engraving by Guglielmo Silvester (Fig. 4) from 1790 and a valuable painting by Giuseppe Maria Soli (Fig. 5), a few years earlier. These sources return the orientation of the monuments, with the Duke and the horse looking at the hospital.

Finally, the contract stipulated on 14th April 1772 [50] between the Duke and the sculptor Cybei reported that the statue was made using three blocks of white Carrara marble.

Table 1 Estimated position of the Equestrian Monument in Sant'Agostino square

Line	Definition	Dimension in modenese arms [0.648 m]	Dimension in [m]
a	Horizontal distance from Sant'Agostino church	32.22	20.87 m
b	Vertical distance from Sant'Agostino church	26.32	17.05 m

Imaged-based 3D survey of the preparatory stucco model

Despite the statue was completely destroyed in 1796, a fragment of the foot ($43 \times 23 \times 50$ cm) remains (Fig. 6) and is kept at the Civic Art Museum of Modena [59]. The fragment of the foot provided additional information on the appearance of the white Carrara marble, which was employed for the identification of the texture to be applied to the final 3D digital model.

Moreover, the statue was preceded by a preparatory stucco model (Fig. 7) by Giovanni Antonio Cybei himself,

Fig. 3 Engraving of the Equestrian statue of Francesco III d'Este, by Antonio Baratti (based on a drawing of Michelangelo Borghi), 1774, (Source: ASMo, mappario Estense, Stampe e disegni, 31/a)

Table 2 Estimated height of the Equestrian Monument

Overall height	Original unit	Overall height [m]	Source	Status
40 Roman palms	1 (architectural) Roman palm (=0.2234 m)	0.2234 × 33.3 = 8.936 m	Engraving of Fig. 3	Preliminary
33.3 Genoese palms	1 Genoese palm (=0.2477 m)	0.2477 × 33.3 = 8.248 m	[54], Page 227	Preliminary
29.5 Genoese palms	1 Genoese palm (=0.2477 m)	0.2477 × 29.5 = 7.307 m	[54], Page 227	Final (real)

Fig. 4 Engraving of the View of Piazza Sant'Agostino with the equestrian monument of Duke Francesco III, by Guglielmo Silvester, 1791 (Source: Modena, Civic Museum of Art)

which is preserved in the Estense Gallery in Modena (inv. 17,815), analysed by Lidia Righi Guerzoni in [60].

The existence of the fragment and the preparatory stucco model has permitted to estimate the height of the statue and therefore of the entire equestrian monument. The length of the fragment of the foot (50 cm) was compared to the size of the foot of the existing preparatory stucco model: this proportion returned the height of the statue in 4.5 m as well as an overall height of the monument in 7.3 m, using the proportion of the engraving of Fig. 3. This presumed overall height confirms that the proposed reduction of the monument height to 29 1/2 Genoese palms (around 7.3 m) by Cybei himself had to be accepted (see previous subsection). Consequently, we estimated that the pedestal of the statue could be inscribed into a 3 m and 1.5 m side rectangle.

The 3D survey of the preparatory stucco model was carried out using C-RP to generate the 3D digital model through digital photographs thanks to a dedicated software. The preparatory stucco model was photographed using a standard compact camera Nikon P310, 16.1MP CMOS Sensor (Sensor size: 1/2.3" (~ 6.16 × 4.62 mm), Max. image resolution: 4608 × 3456, pixel size 1.34 µm, crop factor 5.62, focal length 4.3 ÷ 17.9 mm, 4.2 × optical zoom, maximum aperture f/1.8 ÷ 4.9). The focal length was set to minimal value during the entire shooting session for more stable results, with aperture f/2.8, the exposure value equal to 0, exposure time: 1/40 s, automatic ISO has been set, white balance has been blocked, flash has never been used, and manual focus has been enabled. 871 photographs were taken for a complete description of the stucco model in order to obtain at least three images that framed every detail of the statue from different points of view (Fig. 8a). The drapery of the clothes, the pose of the Duke, the mane and tail of the horse, the volumes of the ornaments that act as a support for the horse's belly determine a high geometric complexity of the model. The top plane of the wooden pedestal of the stucco model was used for scaling and defining the reference coordinate system, and is accurately measured. The reference coordinate system is fixed on the top plane with the plane XY, considered horizontal, and the Z axis vertical. Then, we 3D reconstruct the stucco model within the professional software Agisoft Metashape (Alignment accuracy: highest; Dense point cloud generation quality:

Fig. 5 Painting (oil on canvas) of the View of Piazza Sant'Agostino with the equestrian monument of Duke Francesco III, by Giuseppe Maria Soli, Milan, civic art collections of the Sforzesco Castle, inv. 569 (Source: [58])

high, with mild depth filtering; Meshing quality: high). In Agisoft Metashape, all the 871 images were aligned (with the results of camera calibration and image alignment as in Table 3). The complete process for the generation of the photogrammetric model (Fig. 8) required around 41 h (processor i7-8850H with 2.6 GHz CPU, NVIDIA Quadro 2000, 16 GB RAM).

Fig. 6 Fragment of the equestrian statue of Francesco III d'Este (by Giovanni Antonio Cybei), 1773, marble (Source: Modena, Civic Museum of Art, inv. 466)

This first photogrammetric model originated a faithful 3D digital model (Fig. 8b, c, d).

Integration of missing details using 3D modelling

Despite the excellent general conditions of conservation, the stucco model is incomplete due to the lack of some details, namely, the left foot and the left hand of the Duke, who originally held the baton of command, and the left ear of the horse.

Besides the 2D sources, we identified additional 3D sources that may support the reconstruction of the listed missing details: a terracotta draft model (Fig. 9a) and a second preparatory stucco model, which appears more damaged (Fig. 9b).

The data coming from these additional 3D models were compared with the ones coming from the 2D sources. The resulting details have been achieved as follows:

- Left hand of the Duke, who originally held the baton of command: The terracotta draft model (Fig. 10a) shows the baton wrapped in the clothes drapery, together with the arm. This is partially conflicting with the 2D sources, showing the free positioning of the arm, hand and baton, and therefore more

Fig. 7 A picture from the exhibition on Cybei showing: (in the middle). The preparatory stucco model by Giovanni Antonio Cybei, Estense Gallery, Modena (inv. 17,815); (on the left, middle) The engraving of the Equestrian statue of Francesco III d'Este; (on the left, top). The fragment of the statue foot

compatible with a possible exposure to damage, as was the case of both the preparatory models. Again, the second preparatory stucco model (Fig. 10b) presents the position of the arm closer and more oriented to the Duke's chest with respect to the first preparatory stucco model and the 2D iconographic sources. Therefore, we modelled the arm and the hand following the natural orientation of the arm stump of the 3D digital model, which appears more leaning forward (and less oriented to the Duke's chest).

- Left foot of the Duke: the left foot of the Duke is missing in all the models and is never shown in the iconographic sources (which always show the right side of the monument). Therefore, we modelled the left foot with the same approach of the previous point, following the natural orientation of the leg stump, which descends symmetrically to the right one on the horse's trunk.
- Left ear of the horse: the horse's left ear is missing also in the second preparatory stucco model, while in the terracotta draft model it is outlined in an upright position, compatible with the iconographic sources.

The previously listed missing details, as well as the statue pedestal and the stepped base that raised from the square and lack from the original model, were remodelled with an approach similar to [63, 64]. We firstly used Autodesk Meshmixer, a free design tool for working with triangle meshes (.STL files), re-sculpting sections of the model, scaling and add features to it. Different techniques have been used, in accordance to the previous analysis:

-The Duke's left foot and the horse's left ear were generated by the mirroring the original right details still existing on the right side of the statue (Fig. 10), through the following operations:

1. Copying and isolating the original right details (foot and ear).
2. Cutting and cleaning operations of the surfaces of the right details.
3. Mirroring of the right details.
4. Cutting and cleaning operations of the surface of the rest of the original missing/damaged details.
5. Positioning and merging (integration) of the mirrored details with respect to the damaged details on the 3D model.

Conversely, when the opposite-hand details were not available or if they appeared with a different spatial arrangement, we proceeded with the direct 3D modelling of the missing part, with the eventual support of a 3D model generated using C-RP. This is the case of the Duke's left hand, who originally held the baton of command, which required the following steps:

1. 3D survey of a real hand using C-RP, based on the photographs of a left hand of a person holding a cylindrical object (with the same camera and settings previously described in the 3D survey of the stucco model). The arm had to be kept still while taking pictures. The 3D model of the hand was reconstructed (Fig. 11) within the professional software Agisoft Metashape using 86 photos (Alignment accuracy: highest; Dense point cloud generation quality: high, with mild depth filtering; Meshing quality: high). All the 86 images were aligned, and the reconstruction of the 3D model required 1 hour 45 minutes (processor i7-8850H with 2.6 GHz CPU, NVIDIA Quadro 2000, 16 GB RAM).
2. Scaling the left arm using the same dimensions and proportion of the right one, then cloud cleaning, and smoothing of the 3D acquired hand.
3. Cutting and cleaning operations of the surface of the remains of original missing / damaged detail.
4. Positioning and merging (integration) of the mirrored detail with respect to the damaged part on the 3D model.
5. Direct 3D modelling of the missing details (e.g., the command stick in accordance with the iconographic sources). The result is shown in Fig. 12.

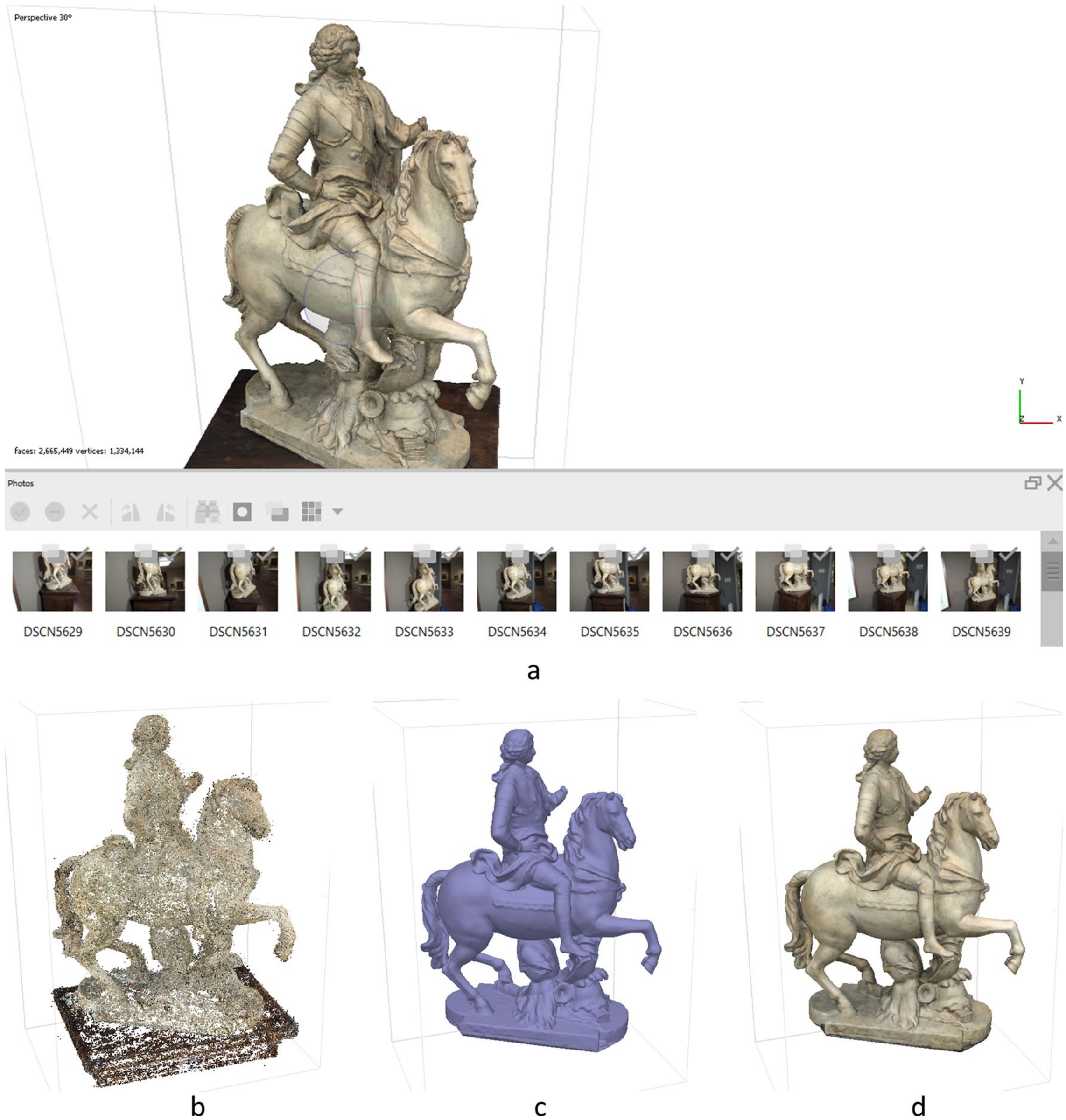

Fig. 8 **a** Photogrammetric reconstruction within the software Agisoft Metashape; **b** point clouds model; **c** wireframe model; **d** textured model of the equestrian statue

Table 3 Results of camera calibration and adjusted alignment in Agisoft Metashape

Root Mean Square (RMS) reprojection error: 0.24 (0.54 pix)	Max. reprojection error: 0.71 (19.75 pix)
Principal point cx: 14.91 pix	Principal point cy: − 32.75 pix
k1: − 0.069748	k2: 0.245727
p1: 0.000241	p2: − 0.002011
b1: 1.4179	b2: − 0.3065

Finally, the 3D digital model integrated with the reconstructed details was re-sized to the height of 4.5 m.-As regards the statue pedestal, the stepped base that raised from the square, the six columns, and the main engraving on the right side of the pedestal, they were directly modelled using a commercial 3D Computer-Aided Design Software (Dassault Systèmes SolidWorks) (Fig. 13). The shape and size of the platform were estimated using the iconographic sources: the stepped base has a rectangular shape, with chamfered corners (as in Fig. 3, 4 and 5)

Fig. 9 **a** Terracotta draft model by Giovanni Antonio Cybei, private collection (Photo credits: courtesy of Accademia di Belle Arti di Carrara [61]); **b** Preparatory stucco model by Giovanni Antonio Cybei, Accademia di Belle Arti di Carrara, Italy (inv. 0,900,254,635) (Source: [62])

or rounded corners (as in the preliminary plan of Fig. 2). Since the paintings are posterior to the plan drawing and the construction of the monument, they represents a sort of witness, so we assume that the rectangle had chamfered corners. The plan (Fig. 2) shows that the ratio of the sides of the rectangular base (w_r and l_r in Fig. 13 a) was 1:1.4. Again, the paintings (especially Fig. 3 and 5) show that the ratio of the length of the statue pedestal and the length (respectively l_p and l_r in Fig. 13 a) of the rectangular base was 1:3. Therefore, since the estimated length of the statue base (l_p) is 3 m, the rectangular base should have the length l_r of about 9.0 m and the width w_r of about 6.4 m. The merging operations of the pedestal and the base with the statue required the use of the software Autodesk Meshmixer.

Finally, the exact positioning of the monument in the current space of the square is calculated through the drawing of the original plan (Fig. 2). According to Table 1, we calculated the distances and were able to place the monument as faithfully as possible near the "Grande Albergo dei Poveri", as well as for the rest confirm the two urban views of Silvester and Soli (respectively Fig. 4 and 5). The position of the monument and the dimensions of its base and pedestal were reported in the current satellite view of the square (Fig. 14). The position of the centre of the base corresponds to Latitude 44.648279° N and Longitude: 10.921311° E.

Discussion

This research work aims to reconstruct the original appearance of a destroyed artefact and develop a historically faithful result, starting from its location up to its colour, size and details. The method originates from similar approaches (e.g., Guidi and Russo [24] and other subsequent works, which deal mainly with lost architectures and sites). In this work, the target is on lost statues and similar monuments, and the workflow has been specifically modified and expanded to include different types of 2D sources, which often flank physical models or fragments of the heritage artefacts (i.e. 3D sources). The literature presents similar works dealing with statues, ornaments, artefacts, objects made by humans, which generally focus on a limited part of the reconstruction process or lack of a detailed and operating description of the whole process or lead to partial results (e.g., 2D plans or sketches rather than fully

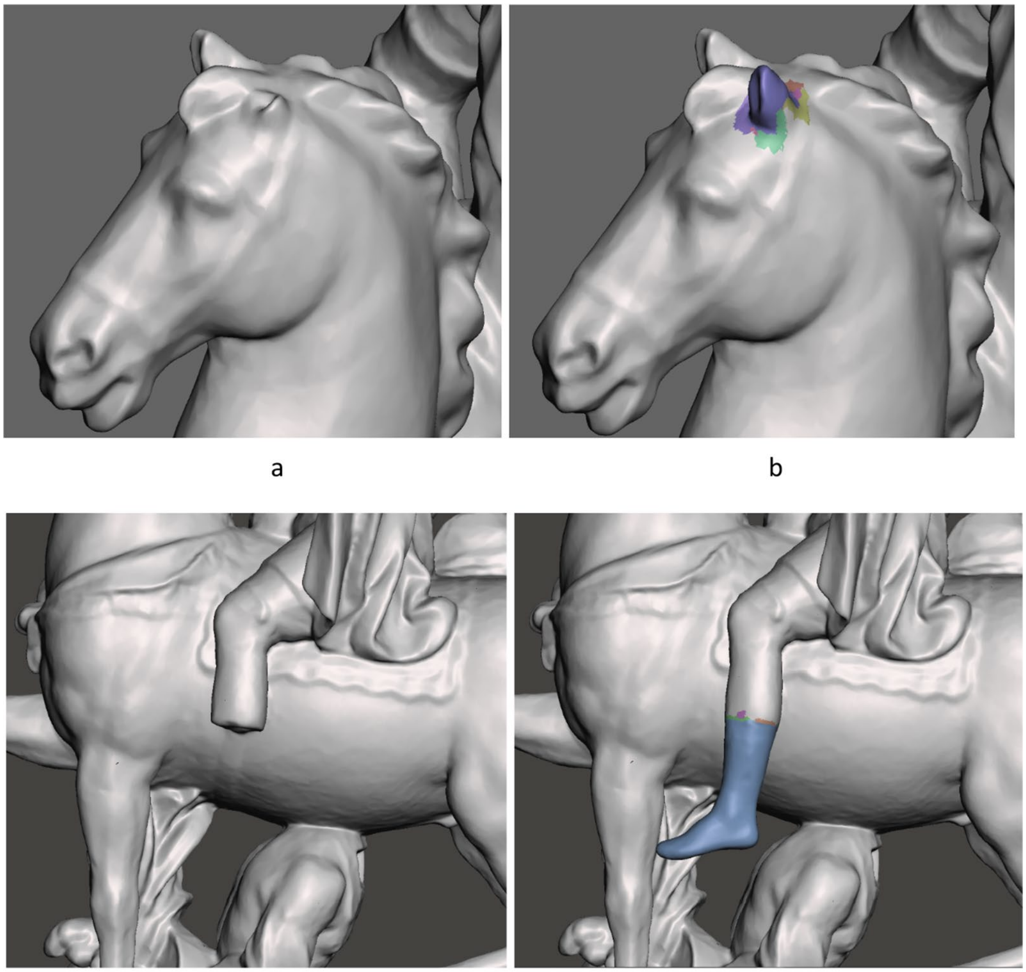

Fig. 10 Mirroring the missing details: the horse's left ear (**a**, **b**) and the Duke's left foot (**c**, **d**) in Autodesk Meshmixer

textured 3D models), even in terms of user's fruition. Therefore, in our workflow we have summarized and generalized the reconstruction process, and accurately detailed the operational steps within the frame of a real case study, to highlight strengths and critical aspects.

As for the case study, we have selected a monument that was completely destroyed more than two centuries ago. The original site where it was originally placed still exists, but there are no remains or evidence. Instead, we retrieved 2D and 3D sources, which reported the existence of this statue, its appearance, dimensions, material and position. Researchers were faced with the need to evaluate different types of sources, sometimes conflicting or in any case not homogeneous, and to make decisions that are not always univocally supported.

The 2D sources do not allow a centimetre precision in the positioning of the statue in the square (the plan of Fig. 2 is an initial project) nor in the sizing of the monument but, as in other cases, 3D physical sources are available. In this case, we have a preliminary stucco model, well preserved and which represented a starting point for the subsequent reconstruction of the statue. The stucco model, in addition to some missing details, is completely devoid of the base and the pedestal with a commemorative engraving of the original monument. As the only statue is not representative of the sumptuousness of the monument and the volume occupied in the space of the square, attention was paid to the reconstruction and integration of these elements from the sources. The material appearance was described only thanks to an original fragment of the statue, the only part of the remaining material, from which the statue dimensions can be assumed, but same cannot be said of the pedestal and stepped base.

The presence of the stucco model, which certainly facilitated a faithful reconstruction, however, also raised

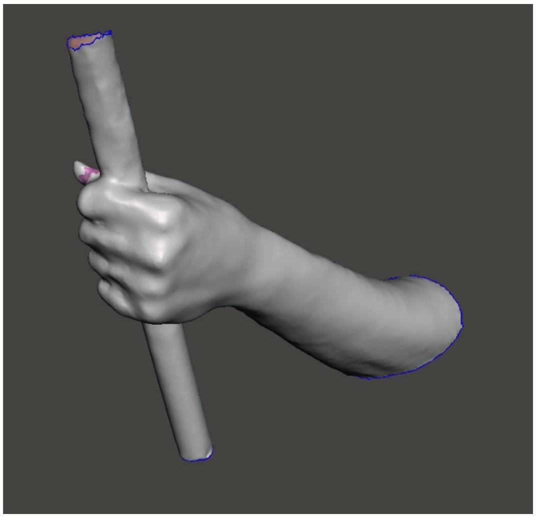

Fig. 11 Postprocessing phase of the photogrammetric model of a real hand holding a baton, in Autodesk Meshmixer

the problem of the fruition of the original sources, and therefore of the evocative nature of the reconstruction carried out. Why should visitors enter a museum to see the ancient look of a square? Why do they have to look at a painting or a scale model instead of seeing a full-scale reconstruction in the original location? So, in addition to the historical intent, we would like to address the evocative role of this type of research, which however, must guarantee a high level of historical fidelity, and therefore the need of systematically leading a multidisciplinary team with different cultural background.

The introduction of subjectivity and personal interpretation is a potential risk of virtual reconstruction, which the workflow nevertheless tries to avoid through iterative evaluations phases for the comparison of the consistency between sources and results. However, assumptions and decisions were made in case of non-homogeneous information from the sources or in case of missing data: when this happened, the hypothetical origin of these elements was reported to the user, in accordance with The London Charter [65, 66]. However, thanks to the support of 3D reconstruction, we systematically used 2D data to compare, integrate and evaluate the consistency of the result. The proposed workflow is the result of the formalization and generalization of the reconstruction process reported in this paper. The 3D digital model represents the resulting connection between sources of different types and scales.

The reconstruction carried out represents an opportunity for restitution that is not only geometrically correct nor contextually correct in the current urban space. The research activity, based on the recovery of the sources located in different museums, collections and archives, together with the 3D reconstruction process, originates a narrative that has aroused as much interest as the 3D digital model resulting from the workflow. This collection and analysis of the sources, as well as the reconstruction of the facts around this lost monument, give rise to an original cultural contribution to the city of Modena, of which none of the citizens is aware.

- Finally, this research focuses on the development of a 3D digital model, which is a result itself and therefore

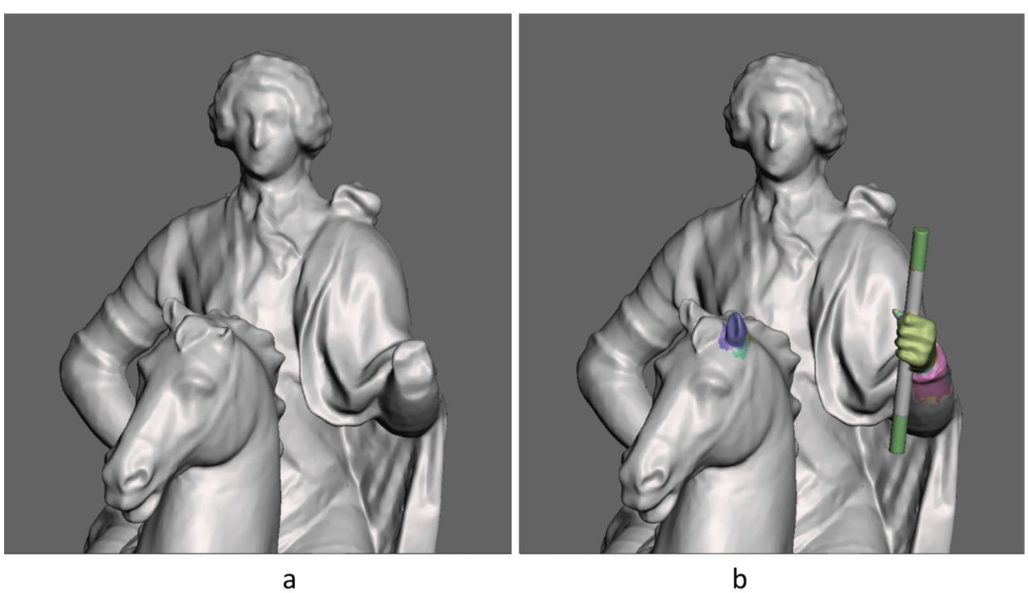

Fig. 12 Integration of the photogrammetric hand into the model of the statue and the baton of command, in Autodesk Meshmixer

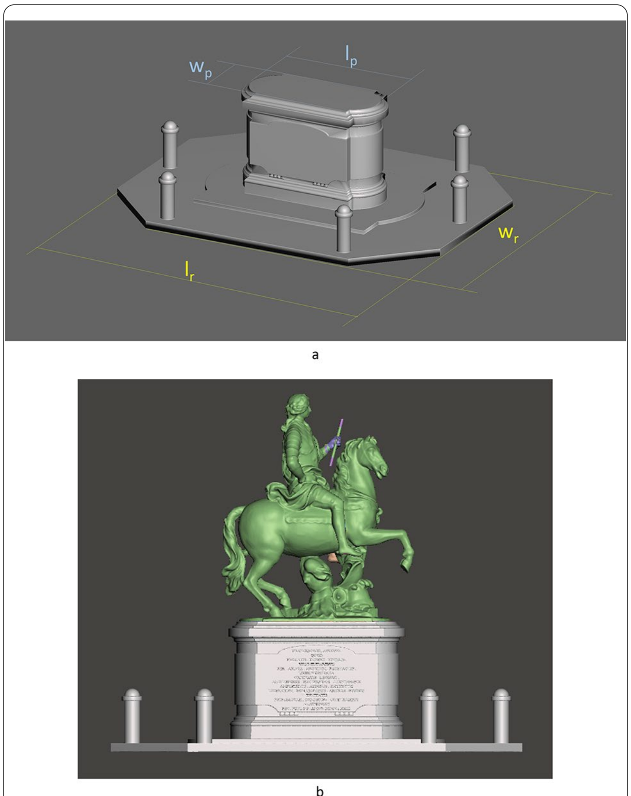

Fig. 13 **a** Stepped base and pedestal of the statue; **b** final reconstruction, with the main engraving on the right side of the pedestal, in Autodesk Meshmixer

directly usable by the users. In particular, as regards the user's fruition, two main applications have been developed. Thanks to its digital format, the 3D model can be communicated via the web, disseminated, analysed, archived, shared, etc., representing a positive example of digital fruition of cultural heritage [25]. As a demonstration, we reported two examples of how the 3D model was used in recent public events.

The first one was to reproduce the original appearance of the square into a virtually augmented scene where the 3D model is overposed the real scene (i.e. Sant'Agostino square). To this aim, the 3D model of the equestrian monument was integrated into an augmented reality application that the visitors can independently download and install on a common personal device (e.g., a smartphone or a tablet). Thanks to a Global Positioning System (GPS) localization, this virtual reconstruction operation brought the statue back to its original size and location within the square (Fig. 15), in September 2020 during the national Philosophy Festival, held in Modena every year.

Again, the 3D model is more accessible and sharable than the physical one. As a further example, the 3D virtual model of the equestrian statue was then exhibited during the exhibition "Giovanni Antonio Cybei and His Time: An eminent sculptor at the European courts and Chief Director of the Carrara Academy of Fine Arts" (Carrara, Italy; 9th July–10th October 2021) [61] besides other original models and statues by Cybei. The preparatory stucco model, in fact, cannot be moved from Modena due to its fragility and the consequent risk of damage, so the current Director of the Carrara Academy of Fine Arts asked to substitute it with the virtual 3D model realized by us. The exhibition included also some of the previously presented iconographic sources and the original foot. The 3D model was made interactively available to the visitors thanks to a touch screen and, differently from

Fig. 14 Aerial photo of Sant'Agostino square, Modena (Photo credits: Imagery©2022 Google, Imagery©2022 Maxar Technologies, Map data©2022). The yellow and red lines identified respectively the position of the base and its size

Fig. 15 Screenshot of the augmented reality application showing the 3D textured model in Sant'Agostino square (Modena, Italy)

a physical model, the 3D virtual model could be rotated, explored in its hidden.

Conclusion

In this work, we propose an operating systematic workflow to integrate iconographic and other 2D original sources (e.g., texts, letters, etc.) with 3D sources for the 3D reconstruction of lost heritage artefacts combining 3D technologies, such as 3D survey and 3D modelling.

The workflow was tested and implemented on a case study, the lost equestrian monument of Duke Francesco III d'Este (Modena, Italy), which was completely destroyed in 1796. However, the accurate identification and analysis of 2D and 3D sources provided data and witnesses from the past of its original appearance. The constant assessment of the partial reconstruction with different kind of original retrieved sources, 2D and 3D, iconographical and textual, original remains and preparatory models, were achieved thanks to iterative evaluation phases in the workflow. The result shows a faithful correspondence to the 2D sources, which guided the reconstruct of 3D missing details that were surveyed or modelled, and then integrated within a 3D digital model.

This 3D model was positively implemented into dedicated virtual applications, guaranteeing an effective user's fruition in public events.

In conclusion, the workflow demonstrated to be able to support the fully development of the final 3D model, by integrating all the retrieved 2D and 3D sources and assessing their compatibility.

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Photo credits
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Author contributions
Conceptualization, FG and SS; methodology, FG and SS; data curation, SS; 3D modelling and 3D reconstruction, FG; validation, FG; writing—original draft preparation, FG and SS; writing—review and editing, FG; visualization, FG; supervision, FG. All authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no competing interests.

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