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RECORDING MICHELANGELO'S DAVID: ULTRA-HIGH RESOLUTION 3D SCANNING AND MODELING FOR DIGITAL AND PHYSICAL REPRODUCTION

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ABSTRACT:
In the twentieth century, the physical reproduction of a work of art was considered only a business activity and a replica would rarely be on display in a museum. In recent decades, however, as high-resolution digital sampling and fabrication techniques have become popular in all fields, the various ways in which they can be applied to cultural heritage are leading to a more articulated approach to their use. They are no longer considered fakes or imitations, but as artefacts specially designed and built to facilitate the dissemination of heritage or perform simulations without damaging the originals. This case study describes the process of creating the replica of Michelangelo's David that has been displayed in the Italian Pavilion at EXPO 2020 in Dubai. Starting with the planning of the survey, the instruments and facilities used, and the fieldwork process are described. The resulting data have been then processed to produce a model optimised for replication on a large format additive manufacturing printer. Finally, the challenges of processing and managing ultra-high-resolution data are outlined.

1. INTRODUCTION

The realisation of a full-scale physical replica of Michelangelo's David, to be exhibited in the Italian Pavilion at Expo 2020 Dubai (running from October 2021 to March 2022), was an opportunity to test the state of the art in digitising and making physical copies of large sculptures. This experience is also an opportunity to rethink how copies of cultural heritage objects are used.

2. COPYING ART IN THE PAST

Reproductions of works of art, especially physical replicas of sculptures and three-dimensional works of art, are experiencing a new moment of popularity in which the concept of making copies is being updated and has new meanings. This is a significant change of perspective because in some ways the romantic idea still prevails that the material realisation of the work of art is secondary to the creative intuition, so, a fortiori, copies are of no value, if not outright forgeries.

In the Greek and Roman world, the conscious reference to a pre-existing figurative invention was highly valued. Models that were considered exemplary were re-proposed and disseminated in a complex relationship between copies, imitations, variants, and replicas (Calcani, 2010). In medieval and Renaissance workshops, apprentices learned by copying the work and style of their masters, and copying remained the preferred tool of artistic training until the early 20th century.

For centuries, methods and devices were studied to produce ever more faithful copies, and it is no coincidence that the decline of the academic tradition happened with the advent of photography, which made works of art instantly reproducible. Walter Benjamin's famous essay on the "mechanical reproduction" (Benjamin 1935) of works of art referred to cinema and photography and was written long before the possibility of automatic reproduction became concrete.

If reproduction was an element of Pop Art, and Postmodernism used the reworking of the past in an ironic way (Pucci, 2019), in recent years, digital sampling and reproduction techniques have been increasingly used in artistic production as a new creative tool (Labaco, 2013; Coon et al., 2016), both from a more conceptual point of view, reworking works from the past (Crowley, 2022; Sargentis et al., 2022), and reflecting on the relationship between authentic and copy, and the artistic significance of the concept of copyright in light of new technologies (Elias, 2019). The latter is, of course, much debated from a legal point of view (a. o. Dinev, 2020 and Pittman, 2020).

The traditional method of reproduction by casts is considered dangerous for the original works and is generally not recommended; in Italy it is expressly prohibited by law (Codice dei Beni Culturali, 2004). Making a digital model using non-contact methods is therefore the most used technique at present.

3. RECENT EXPERIENCES

The first step in the conservation of cultural heritage is knowledge of it, and many digitisation and physical reproduction projects of sculptures are aimed at this and, in a broader sense, at one of the four phases of the conservation cycle ("Evaluation, Diagnosis, Intervention, Monitoring", see Santana Quintero et al. 2007), to which it is also worth adding "Dissemination".

A new attitude towards making physical copies of sculptures can be felt from several points of view. Replicas are one of the tools used in the context of "heritage interpretation" (ICOMOS, 2008). These initiatives and activities are not aimed at preserving or studying objects or works of art, but at communicating and disseminating the meaning of heritage, often using spectacular reconstructions and multimedia methods. In this context, replicas make it possible to protect the original sculptures while avoiding the threat of transporting the originals for exhibitions (Bitelli et al., 2021) and allowing visitors to touch the works to promote the inclusion of all users. (Merchán et al., 2019).

The replica can allow new points of view, as in the case study presented here, or immediately convey information that cannot be obtained from watching the original (Scopigno et al., 2017,

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Ashan et al., 2022) and becoming a "digitally augmented replica" (Vaz et al., 2020). The use of replicas also makes it possible to present the result of a study of the presumed original aspect of sculptures without directly affecting the original (Tucci et al., 2017a; Brinkmann and Koch Brinkmann, 2022; Lowe, 2022).

Other experiences involve the use of replicas to replace works of art destroyed by natural disasters, terrorism, and wars (Nagaoka, 2020, Jesus et al., 2022; Gros et al., 2023), or threatened by pollution and climate change (Bonora et al., 2021), or to recompose the original fragments using digitally manufactured components as props (Jo et al., 2020).

By relating the physical characteristics derived from the original objects with the 3D models, it is possible to create real "digital twins" that can be used to carry out studies and simulations for the protection of original works.

The 3D models of sculptures can be processed to obtain FEM models for structural and seismic analyses. Case studies relating to statues made of a homogeneous material of constant density, such as marble, are presented by (Visintini and Spanger, 2014; Wittich et al., 2016; Spanger et al., 2017; Tanganelli, et al. 2021). Alfio et al., (2022) also apply similar criteria to a bronze sculpture supported internally with a steel structure.

In the case of plastic works with intermediate characteristics between sculpture and architecture, such as the pulpit of the church of Sant'Andrea in Pistoia (Bartoli et al., 2020), other information on the static and dynamic behaviour of the digital model can be associated in time real from sensors (Zini et al., 2023).

4. THE META-PROJECT: IT TAKES A SURVEY TO MAKE A SURVEY

4.1 Planning the Fieldwork

Knowing the location, dimensions, geometry, and material of a building or historic artefact is a fundamental part of a heritage conservation project. (Letellier et al., 2007). Then, when a project also involves the physical replication of the artefact, the completeness and quality of the acquired data are essential for a successful outcome. (Manuel et al., 2023; Bonora et al., 2021).

Many considerations guide the choice of a survey method: the size of the object, its complexity, the resolution required, etc., but other factors must be added to these considerations: the characteristics of the property, its accessibility, possible interference, the facilities available, the budget, the relationship with the client or whoever manages the property, etc. It is therefore essential to plan the entire process and in particular the fieldwork phase.

Work in a museum such as the Accademia Gallery in Florence is also subject to strong constraints, both because of the large number of visitors and the need to avoid any risk to the works of art. The fieldwork was therefore influenced by many factors: the size of the area, the opening hours, working when the museum was open to the public, security, and possible interference with other workers and the public. All this required long and demanding planning.

4.2 The Previous Survey

Paradoxically, to plan a survey, it is useful to have a survey. In the case of the David replica, the GeCo laboratory carried out a three-dimensional digital survey of the entire gallery of the Accademia in 2011. The architectural survey was carried out using well-established techniques: topography (GPS and total station), 3D scanning and Structure-from_Motion (SfM) photogrammetry (Tucci et al., 2017b). The 3D models were reliable and reusable, and the digital data were available, well-preserved, structured, and associated with metadata (Wilkinson et al., 2016). Compared to the previous model done by the existing model done by Stanford University (The Digital Michelangelo Project, 1997), the 2011 model included the base and, most importantly, the architectural context.

This allowed the survey to be planned based on reliable and immediate information: the access route, the distance to the other surrounding works, the dimensions of the base and the statue, and the size and distance to the protective fence. At the beginning of the 1990s, a fence 1.60 metre high was built all around the base of the David at approximately 1.90 metres, consisting of metal pillars and armoured glass panels.

The 2011 survey and previous experience also provided information on the building's conformation and structural characteristics. Under the base of the David there is a solid foundation, but the floor around it is empty due to the presence of large air-conditioning systems, the operation of which causes vibrations (Miccinesi et al., 2021). This, together with the constant movement of people, causes the floor around the sculpture to vibrate in a way that is harmless to the artwork and people, but potentially inappropriate for the use of highly sensitive measuring instruments.

The instruments chosen for the measurements, further described below, were a structured light triangulation scanner, which scans small portions of the surface, and a laser tracker system to measure the total volume and compensate for any drift errors of the other instrument.

The acquisition phase with a structured light scanner was simulated using the 3D model from the 2011 survey. The number of acquisitions was planned to follow a circular path around the statue.

4.3 The Elevation Systems

Considering that the statue is more than 7 metres high in total and that both instruments had to reach the top of the statue, two elevation systems had to be designed to lift the two instruments to the top. They had to be relatively inexpensive, easy to use, easy to transport, require no special qualifications for the operators, be easy to transport and, above all, guarantee maximum safety to be able to work very close to the statue. Two systems were required, each with different characteristics. One system had to allow the operator to climb up to handle the instrument, while the other had to lift the structured light scanner only.

In the first case, a standard mobile scaffold tower (0.90 x 1.90 m) with 4 platforms was used, on which the operator works in a harness with a safety belt. In the other, a gantry with a base of 1.80 x 1.25 m and a maximum height of over 7 metres was purposely designed and built. It consists of a main telescopic column that can be raised or lowered through a manual hydraulic actuator and a bracket for mounting the scanner up to a height of over 7 metres (Mugnai et al., 2021).

Both systems are equipped with stabilizers that increase their footprint. Thanks to the 2011 survey, it was possible to plan how to place and move them and the eventual interference between them. It was therefore also concluded that the protective fence had to be removed.

The need to place sensitive measuring instruments on high stands, the imperfect stability of the floor and the presence, albeit minimal, of people in the working area resulted in sub-optimal conditions for carrying out high-accuracy measurements. However, it is difficult to assess the influence of environmental conditions given the variability of factors at the site. Levoy (2004) also recognises this unresolved critical issue, which is neglected in many other studies.

4.4 Assistance with installation in Dubai

The digitisation and reproduction project began when the construction of the Italian Pavilion at the Dubai Expo was underway and the Theatre of Memory (where the massive reproduction would be displayed) was already under construction. It was therefore necessary to plan the movement of the statue inside the new building. The replica would be transported horizontally, so space had to be provided to lift and place it. It was also checked that there was enough space for an operator to carry out any retouching work in case the marble powder finish was damaged during transport or handling. All these checks were carried out using the 2011 3D model and allowed the replica to be handled and positioned without any problems when it arrived in Dubai.

5. THE INSTRUMENTS AND FIELDWORK

5.1 Custom-made vs. off-the-shelf instruments

The objectives of the project, both to create a digital model for the physical reproduction of the David in an extremely short timeframe and to create a new, high-resolution database to support the knowledge, also presented a major challenge in terms of equipment selection. In 1997, the Digital Michelangelo project took two years to design and build custom laser scanners and mechanical gantries for scanning large statues; in 2021, the challenge was to use state-of-the-art but commercial measuring instruments commonly used in industry.

5.2 The structured light scanner

As already mentioned, the high-resolution survey was performed with a fringe projection scanner, a Hexagon AICON StereoScan Pro R16 (Hexagon, 2023a), hereafter designated StereoScan.

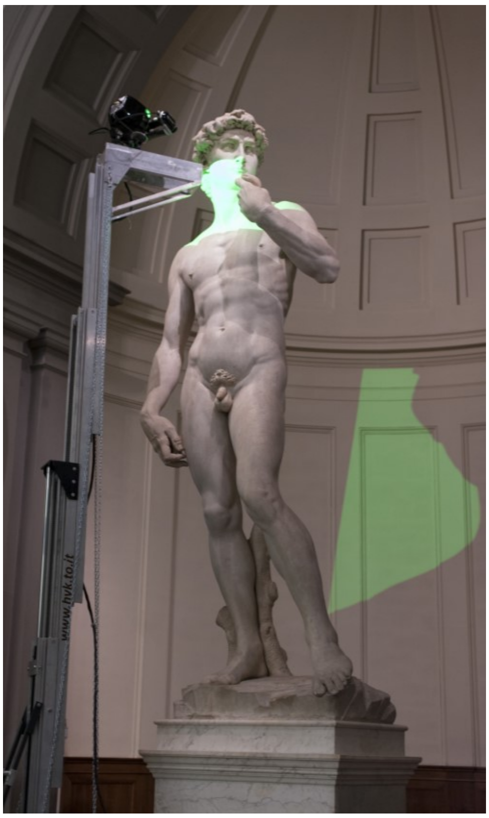

Figure 1. Scanning with StereoScan mounted on the gantry.

It is an instrument consisting of a projector and two cameras. The cameras record the distortion of a series of known patterns of structured light projected onto the scene by the projector. Since the position and orientation of the three devices are known, it is possible to scan the scene at a very high density, based on the principle of triangulation. The pattern is projected by 3 LEDs (red + green + blue), the colour and intensity can be adjusted to adapt the fringe projection to the characteristics of the measurement surface. The dimensions of the field of view (FOV), and therefore the accuracy, can be selected using lenses with different focal lengths. The aperture and depth of field are fixed and optimised by the manufacturer for each FOV. The 850 mm FOV was chosen for the entire sculpture and the 500 mm FOV for a detail of the right foot. Table 1 shows the main Stereoscan features.

Camera sensor	Monochrome, CCD progressive scan, full format 1.7
Camera resolution	2 x 15720448 pixels
Sensor dimension	4864 x 3232 pixels
Triangulation angle	30°
Baseline	450 mm
Working distance	840 mm
Overall acquisitions	
Field of view	L-850 mm
Field of view size	710x500 mm
Measuring depth	430 mm
X, Y resolution	0.146 mm
Accuracy (VDI/VDE Guideline 2634 Part 3)	
Sphere Spacing Error	0.030 mm
Length Measuring Error	0.060 mm
Probing Error Size	0.016 mm
Probing Error Form	0.016 mm
Foot detail	
Field of view	L-550 mm
Field of view size	460x310 mm
Measuring depth	280 mm
X, Y resolution	0.094 mm
Accuracy (VDI/VDE Guideline 2634 Part 3)	
Sphere Spacing Error	0.016 mm
Length Measuring Error	0.028 mm
Probing Error Size	0.012 mm
Probing Error Form	0.012 mm

Table 1. StereoScan features and nominal accuracy in the configurations used.

The average distance between the scanner and the surface of the sculpture was therefore approximately 0.8 m. The positioning of the scanner was therefore very challenging due to the need to always ensure the safety of the statue, its three-dimensionality, the size of the scanner and the supporting gantry.

Each scan is pre-aligned on the field with the previous ones. The group of scans (“project”) is subsequently optimised.

The acquisition design originally envisaged a closed-loop system to compensate for errors and verify them on small series of scans. However, this approach would have required the gantry on which the scanner was mounted to be moved for each scan. This would have endangered the statue and greatly increased the time required, so it was decided to take vertical series of scans from each location where the gantry was positioned. In total, 787 scans were made across 14 projects, generating 373 GB of data, as indicated in Table 2.

Parts	Projects	Scans
Base	5	283
Sculpture	9	504
Total	14	787

Table 2. Summary of executed projects and scans.

The scanner has been controlled on the field using Hexagon OptoCat software, which was also used for post-processing. The workflow for each project included:

- Iterative alignment of the scans with an ICP-type algorithm. At this stage, some projects were grouped and then one alignment was performed for the base and 7 for the sculpture.
- Merging of aligned scans, according to the required level of detail. Each project was saved in Preview, Standard Fast and Full modes, used for the different stages of control and final processing.
- Surface optimisation by curvature priority decimation.

The workflow directly processes individual scans and produces meshes merged and optimised according to the required parameters. Single raw point clouds are not available. Table 3 summarises the residuals of the alignments for each project.

Project	Scans	RMS (mm)
Base	283	0.038
Body 1	53	0.028
Body 2	79	0.033
Body 3	94	0.025
Body 4	77	0.033
Body 5	85	0.029
Body 6	64	0.027
Body 7	52	0.029

Table 3. Residuals of the alignments for each project.

The residuals of the alignments of the single projects are satisfactory, but the geometry of the individual scans (acquired in a vertical sequence) and the alignment method used may result in deformations that are not immediately visible and possible alignment problems of individual scans within a project.

5.3 The Tracker Scanner

The other instrument used is a Hexagon Leica Absolut Tracker AT960 with Leica Absolute Scanner LAS (Hexagon, 2023b), hereafter designated Tracker. This is a handheld triangulation scanner that uses a laser line (Wavelength 690 nm) whose distortion on the measurand is acquired by a 2D imaging sensor. The scanning angle can be selected between 8°/20°/40°. LAS sensor has a working range (measuring depth) of about ±40 mm. The average working distance between the device and the centre of the working range is about 180 mm. At this distance, the maximum usable scanning width is about 220 mm. To facilitate the positioning of the scanner, the sensor also emits an auxiliary laser pointer. When the instrument is at the optimal distance from the surface to be scanned, the laser pointer intersects the measuring laser at the centre of the working range. The position and attitude of the scanner are tracked by the tracker.
Six measurement parameters are needed to describe the position and orientation of the scanner:

- Three position parameters (horizontal angle – Hz, vertical angle – V, distance – D)
- Three orientation parameters (rotation around the X-axis - ω, rotation around the Y-axis - φ, rotation around the Z-axis - κ)

The scanner is equipped with reflectors on each face and a set of infrared (IR) LED targets. The tracker determines the position parameters using a laser interferometer coupled to a distance meter that detects the position of the reflectors, and the rotation parameters by means of an IR camera that detects the position of the IR LEDs. Table 4 shows the nominal measure uncertainty (MU) of the Tracker AT960 + Scanner system LAS.

Spatial length UL (2σ)	
UL < 8.5 m	± 0.060 mm
UL > 8.5 m	± 0.026 mm + 0.004 mm/m
Sphere radius UR (2σ)	
UR < 8.5 m	± 0.050 mm
UR > 8.5 m	± 0.016 mm + 0.004 mm/m
Sphere surface UR (2σ)	
US	± 0.085 mm + 0.015 mm/m
Sphere surface UP (2σ)	
UP	± 0.080 mm + 0.030 mm/m

Table 4. Deviation of measured values from nominal ones or from a best-fit surface (according to ASME B89.4.19-2006 standard – Maximum Permissible Error).

To maintain a direct line of sight between the scanner and the tracker, the latter was positioned at four station points. The laser tracker was repositioned using a network of 8 points distributed around the measurement volume, consisting of automatically recognised spherical reflectors.
The position of the tracker is determined by inverse intersection with a redundant number of reflectors and is estimated to be of the order of 50 microns. Given the imperfect stability of the floor, due to the presence of voids in the subsoil mentioned above, the survey was not carried out in optimal conditions. It is therefore considered that the uncertainty of the measurements made on the statue is greater than the nominal values.
After the alignment and optimisation of the four projects, a cloud of about 43 million points was obtained.
The acquisitions were carried out in 13 days. Table 5 summarises the days of acquisition.

Day	Date	Device	Parts
1	2020/12/09	StereoScan	Base
2	2020/12/10	StereoScan	Base
3	2020/12/11	StereoScan	Feet
4	2020/12/14	StereoScan	Right side
5	2020/12/15	StereoScan	Back
6	2020/12/16	StereoScan	Front
7	2020/12/17	StereoScan	Front
8	2020/12/18	Tracker+LAS	Full body
9	2020/12/21	Tracker+LAS	Full body
10	2020/12/22	Tracker+LAS	Full body
11	2020/12/23	Tracker+LAS	Full body
12	2021/01/07	StereoScan	Front
13	2021/01/08	Both	Details

Table 5. Summary of the fieldwork days.

5.4 Preparing the 3D model

The first phase of data processing was aimed at the objective of preparing the surface model suitable for the production of the physical replica for the EXPO Pavilion.
Both measurement systems are triangulator scanners, i.e. with a baseline between the source of the laser beam or light pattern and the sensor (or two sensors, as in the case of StereoScan). Measuring a point with such instruments is only possible if the instrument can be positioned so that the point is in the line of sight of all the instruments at the same time. The scans of

David, acquired with StereoScan, show many gaps in areas with accentuated concavities, because it is difficult to maintain the specified condition, also considering the unwieldiness of a large instrument mounted on a bulky gantry.
These holes, especially where they are more extensive, such as between the fingers of the right hand, the locks of the hair, the armpits, and the groin were integrated using the points measured with the laser scanner, even though it is a less dense point cloud. The tracker scanner, which was manually operated by the operator on the scaffold, is smaller and has a shorter working range, so it was easier to orient it to scan parts not visible with the other instrument (Davis et al., 2002).

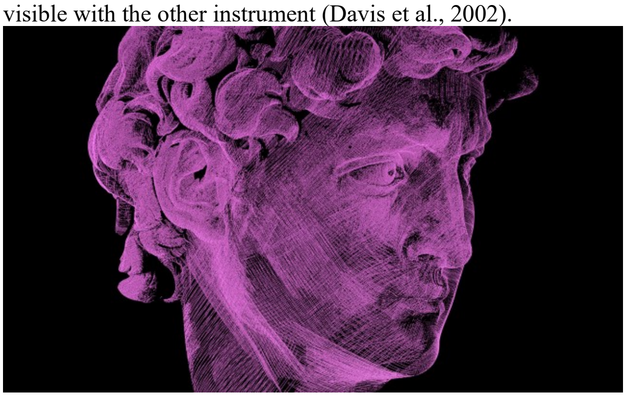

Figure 2 – A detail of the point cloud

This dataset was used to fill in the gaps in the StereoScan dataset and the two models were merged to obtain a first printable model, i.e. free of topological defects, watertight and 2-manifold, consisting of over 43 million faces. This model was then further optimised in accordance with the technical characteristics of the printer in question and the subsequent processing steps to be carried out.

Figure 3 – High-resolution digital model

5.5 The 3d Printing

For the realisation of the physical model, the selected printer was a Massivit 1800 (Massivit, 2023).
It is a printer capable of printing a maximum print volume of 145 x 111 x 180 cm, placing it in the Large Format Additive Manufacturing (LFAM) class, which includes printers capable of printing volumes greater than 1 m^3.
The printer uses a proprietary material (Dimengel 100) an acrylic photopolymer gel and a technology called Gel Dispensed Printing (GDP). This can be considered a combination of two distinct additive manufacturing technologies. The material is deposited by a nozzle as in the Fused Filament Deposition (FFD) technology and is immediately cured while printing by a UV light as in the Stereolithography (SLA) technique.
This technology combines a large print volume with high operating speeds of up to 30 cm per second in the XY plane and up to 35 cm per hour in the Z axis.
The planned layer thickness was around 1 mm, so a model was created with the appropriate resolution. This was divided into 14 parts, which were printed in 160 hours. The rough parts were assembled and finished as described in (Tucci et al., 2023). Before being transported to Dubai, the copy of the David was digitized with a terrestrial scanner.

Figure 4 – The placement of David's replica in the Italian pavilion for Expo 2020 Dubai (photo by Massimo Sestini).

6. CONCLUSIONS AND PERSPECTIVES

The creation of digital models of large statues for the production of physical replicas is an increasingly common practice. Capturing Michelangelo's David in high resolution to make a physical replica was a challenge.
The various stages of the workflow have enabled the state-of-the-art technology and processes used to be verified. The equipment used, which is used in an industrial context, allows very accurate digitisation even of large sculptures. On the other hand, the experience highlighted certain critical points that can be important in this type of survey.
The environmental and working conditions were important: to study a very tall and articulated statue in the most effective way, with necessarily bulky equipment and always with the safety of the work of art in mind, would require a very long time, incompatible with the daily life of a large museum. The model obtained in this way has some misalignments, which are completely negligible for the production of the physical model,

but which we have nevertheless tried to eliminate in the high-resolution model for the study.
After the realization of the physical model, the research is continuing to obtain the best possible model for the documentation of the current state of Michelangelo's David. During the work, some rigidities of the Hexagon Optocat management software were highlighted.
The workflow provides that only meshes that have undergone some form of resampling and decimation can be exported.
These are useful functions in the industrial and production field, but for research purposes, it would be preferable to be able to access and export the raw data for possible processing in third-party software and for archival purposes.
Furthermore, even using a high-performance PC, it is not possible to produce a single model with all the data acquired at maximum resolution (Levoy et al., 2000).

Figure 5 – Detail of the foot of the high-resolution model with texture

Instead, models of correctly aligned individual portions were produced which represent the most detailed surface documentation available.
Even though the scans produced by the StereoScan scanner are textured, the colour quality of the texture is poor. It is possible to manually edit the photos of the single scans, but the corrected scans cannot be used to make new alignments.
Comparisons are also underway between the various models and versions available to gauge their differences. In addition to the models produced during the current project with different qualitative parameters, comparisons are also underway with the available models of the Digital Michelangelo Project, with the one obtained from the survey of the Accademia Gallery in 2011, and also with the model obtained from the scan of the finished copy before being transported to Dubai.

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