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THE STUDY OF DONATELLO'S SCULPTURE OF SAN MARCO IN ORSANMICHELE (FLORENCE), THROUGH A THREE-DIMENSIONAL DIGITAL RECONSTRUCTION IN VISIBLE AND UV LIGHT.

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Abstract

The sculpture of San Marco was made by Donatello for the external tabernacle of Orsanmichele (Florence), at the request of the Arte dei Rigattieri and Linaioli in the early Renaissance. Donatello sculpted it in a block of Carrara marble between 1411 and 1413. Recently, a restoration project admired by the Opificio delle Pietre Dure involved a detailed diagnostic project that was an important help to better understand Donatello's work.
Surrounded by this project, our tasks were to:
- The morphology of the surface was scanned using high-precision laserscanners and a high-resolution photogrammetry, then we made the digital 3D model, and it became the basis on which we entered the data obtained from other diagnostic imaging investigations.
- The 3D UV survey is an innovative investigation methodology for the investigation of three-dimensional works. We carried out a photographic acquisition campaign in visible light and UV fluorescence and UV reflectance, using a very high-resolution camera. From the photogrammetry we created the 3D model in UV fluorescence and reflectance of the sculpture.
- Digital reconstruction and 3D printing of the missing elements of the marble cushion supported the restoration activities in order to integrate the missing parts of the sculpture. Through digital integration technique we have tried to create a probable reconstruction of portions of decorations that can help the public to imagine the sculpture no longer white but with decorations.

Keywords: Sculpture, photogrammetry, UV fluorescence, Donatello, San Marco.

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1 INTRODUCTION

Modern three-dimensional survey technologies have also application in the field of works of art. These include laser scanner technology, structured light lasers and photogrammetry [1,2].

The purpose of the three-dimensional survey operations is mainly aimed at documenting the state of conservation of the work or at the creation of virtual contents for dissemination purposes.

However, these methodologies can also play an essential role for the virtual 3D reconstruction of lost artefacts or with gaps (entire pieces or 2D decorations), as well as become important tools as a support to diagnostic imaging [3,4].

In the first case, the risk is to obtain an inaccurate reconstruction of the missing parts. Furthermore, the operation could be difficult due to the state of conservation of the work and for this reason it is necessary to resort to historical and iconographic sources.

In the second case, the use of photogrammetry applied to diagnostic imaging helps the reconstruction phase and reveals new fields of application to achieve an easier interpretation of diagnostic data.

The proposed case study is represented by the sculpture of San Marco by Donatello located at the Orsammichele museum in Florence.

In 2021-2022 the Opificio delle Pietre Dure in Florence carried out the restoration of the statue and commissioned Studio Micheloni Srl to carry out the diagnostic and survey work here illustrated.

The historical and conservative events of the artwork make it a perfect example for the application of the tested methodology. In fact, over time the statue has undergone operations and losses that have changed its original appearance, but which are documented in photos and historical material. Furthermore, the attempt to save it from the degradation that it would have had by remaining in its original position led to the creation of a copy which preserves part of the lost elements.

Another application of three-dimensional models is their use for seismic vulnerability assessment and static verification [5,6]. The first also in relation to the stability of the supports that house the works of art in Italian museums.

The proposed workflow consists of the following steps:

- Creation of a high-resolution and very precise three-dimensional model by laser scanner and a photogrammetric model with visible light.
- Creation of a UV fluorescence and UV reflectance model.
- Analysis of data and historical iconography to reconstruct the missing parts of the cushion and the gold decorations of the garments.
- Digital reconstruction and 3D printing of the missing elements of the cushion.
- Proposal for a digital reconstruction of the gilding of the Saint's clothes and hair, based on the results of the diagnostic investigations.
- Digital FEM analysis of the structure of the statue.

2 THE SAN MARCO STATUE

Orsanmichele complex is located in the heart of Florence between the Duomo and Palazzo Vecchio and the building itself has both religious importance since on the ground floor there is the church of Orsanmichele, formerly also known as the church of San Michele in Orto, then civil since on the upper floor the immense rooms where we find the museum today were used as a granary [7]. The perfect coexistence and harmony between the two spheres of civil life in Renaissance Florence find their apex in this building. Outside all around the building there are richly decorated niches with the patron saints who were to protect the various guilds of arts and

crafts which were lay associations born to pursue goals common to all those who practiced the same profession.

The marble statue of San Marco, patron of the Art of Linaioli is one of the works of the young Donatello; it was inserted in the niche assigned to the Guild (of the Linaioli) in the southern façade of the Orsanmichele complex around the year 1413 [8].

The date of birth of Donatello (Donato di Niccolò di Betto Bardi) is uncertain: he was born in Florence between 1386 and1390. In any case, Donatello was an apprentice in Ghiberti's workshop, where he practices both as a goldsmith and as a sculptor in bronze and marble.

Alongside the architect Brunelleschi and the painter Masaccio, Donatello completes the triad of founding fathers of the Italian Renaissance. He contributed fundamentally to the renewal of sculpture, was able to change forever the way of portraying the subject: no longer an immobile icon but a real person portrayed in marble, bronze or wood [9].

2.1 Artistic analysis and Conservative history

The Saint is represented standing on a cushion, holding an open book in his left hand with the cover facing the observer while his right hand is along his side. He wears a robe tied at the waist by a belt with heavy folds, his posture is weighted but the slight twist of the bust makes the overall image of the saint less static. The bearded head is slightly rotated, his face is characterized by a great expressive force, concentrated and severe at the same time.

Originally, at the request of the art of Linaioli, the work was to have gilded ornaments.

Like the other marble statues displayed in the external niches of Orsanmichele, the statue has suffered deterioration from atmospheric agents and certainly at least two bronze-colored patination interventions, one in the seventeenth century and one in the nineteenth century for both conservative and aesthetic reasons.

During an extensive redevelopment of the building in 1986, the statue was removed from the niche and transported to the restoration laboratories of the Opificio delle Pietre Dure in Florence where it underwent a first major restoration operation [10]. To preserve the work from damage due to atmospheric agents, the statue was placed inside the building, on the first floor together with other statues that were previously outside in the niches and which form part of the collection of the Orsanmichele Museum. Outside, inside the niches, faithful copies of the originals conserved inside the building can still be seen today.

Lastly, in 2022 the most recent conservative intervention by the re-storers of the Opificio delle Pietre Dure was completed, on the occasion of this collaboration we were able to deepen the study of the work through the use of non-invasive diagnostic techniques and attempt to reconstruct parts of the gold decorations that are no longer visible today.

3 DIAGNOSTIC TECHNOLOGIES FOR NEW DISCOVERIES

3.1 Models with visible light and laser scanner survey

This first phase is aimed at the reconstruction of a 3D model of the statue with texture created in diffused visible light.

First, the laser scanner survey of the statue was performed. This operation allows to have a certain metric reference for subsequent operations. The laser scanner used is a Trimble X7 which allows for a high acquisition speed, integrated imaging, automatic registration technologies and auto leveling.

The subsequent use of photogrammetry has allowed, starting from the acquisition of high definition images, to arrive at a detailed knowledge of the surfaces of the work of art in order to obtain information for conservation.

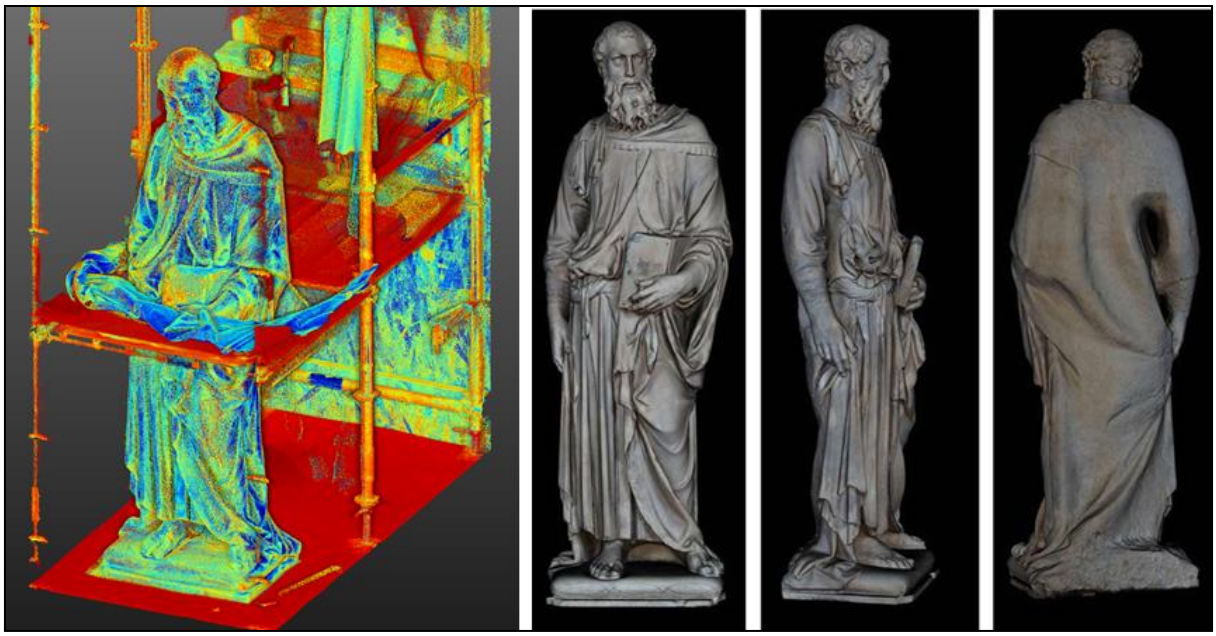

Figure 2: Point cloud from laser scanner and the model with visible light.

The instrumentation used is a Sony Alpha 7 RM4 mirrorless camera, with full frame sensor with 61 megapixels and with high quality lenses. More than 1000 photographic shots were taken, taking care to maintain adequate overlap between different frames and keeping the camera settings unchanged. Small markers have been placed on the statue to facilitate the reconstruction phase.

The photographic shots were carried out by choosing homogeneous light conditions and using a calibration target. This operation made it possible to adjust the acquired color so that it aligns with a known measurable value.

The images were then aligned and processed using photogrammetric software in order to obtain a point cloud and a textured model. The dense point cloud obtained is made up of about 50,000,000 points, which, during meshing, give rise to about 10,000,000 triangular faces. The high density of the point cloud and the definition of the mesh allowed to obtain an extremely detailed model.

3.2 Models with UV fluorescence and UV reflectance imaging

In this phase, the operations of photographic shooting and reconstruction of the textured models were carried out for the realization of the imaging investigations.

The acquisition scheme used for the recording of visible fluorescence induced by ultraviolet radiation includes:

• Two LED lamps with UV light at 365 nm with an emitted power of about 3,000 mW controlled to generate ultraviolet radiation with high spectral purity (emission at 400 nm less than 3 per thousand compared to the emission peak at 365 nm);

• A Sony Alpha 7 RM4 mirrorless camera, with full frame sensor with 61 megapixels, was used for UV fluorescence shooting.

• A modified Sony Alpha mirrorless camera, with sensor APS-C type Exmor® CMOS sensor (23.5 x 15.6 mm) and 24.2 megapixels without the IR/UV cut filter was used for the reflected

UV shooting. Furthermore, for shooting in reflected UV, special lenses without anti-UV treatment were used on which a cut filter was mounted.

The brightness of the room in which the statue is placed and the impossibility of darkening the windows led to the creation of a photographic set using blackout cloths which would allow for the creation of a dark environment. The operation was facilitated by the presence of the construction site which partly covered the statue.

Figure 3: models with UV fluorescence and UV reflectance imaging

The experimentation was conducted by placing the two lamps at a distance of about 0.5/0.8 m from the work and with an angle of radiation of about 30° with respect to the aim of minimizing the interference of the parasitic reflection not perceptible to the naked eye.

The acquisition of the images involved moving the set around the statue in order to film it from multiple angles.

The acquisition methods and tools were used only for the reflected UV captures which, on the other hand, do not require a totally dark environment.

The reconstruction phase using photogrammetric software was not easy due to the lack of light and contrast that the images presented. However, the presence of the markers already used in the visible and the references on the statue have allowed a correct reconstruction of the texture. The meshes, on the other hand, required subsequent processing.

3.3 Mesh processing and correction

The survey using photogrammetric techniques and laser scanners made it possible to obtain an accurate and precise 3D model of the work. The result obtained is a mesh formed by a surface divided into triangles.

The processes of reconstructing surfaces from point clouds are quite complex: point sampling is often non-uniform while positions and normals are usually noisy due to errors.

Using such a mesh for 3D printing or deformation operations becomes more difficult. Therefore, a series of operations must be performed to sample and reduce noise such as plugging holes or topological correction.

Once the raw mesh was obtained from the photogrammetric processing software it was exported in a compliant format to preserve its textures and UVs, such as *.obj.

Using a mesh processing software, we proceeded to a first cleaning and repair of the highpoly mesh, repairing most of the imperfections (non-manifold edges, coincident or overlapping vertices and edges, zero-faces, normals, concave parts) and deleting the parts of the mesh due to the noise and the parts adjacent to the base of the statue.

The model was then aligned to the vertical axis, finished in the lower edges and suitably scaled through matching operations with a mesh obtained from a laser scanner.

The mesh is then processed in order to eliminate the mesh tunnels originating from the photogrammetric calculation, to close the holes present and to repair the parts that escaped in the first iteration. Mesh islands and mesh tunnel bugs are fixed.

The base of the model is also closed by a single flat face, which is then correctly subdivided to respect the triangular topology of the mesh.

Therefore, once a watertight model has been obtained, with a correct topology, free of errors and with correct UVs, a model with the different textures (photogrammetric model from UV shooting) is superimposed, making sure that they coincide perfectly.

In order to have a unique mesh that can accommodate the various textures, the RGB data is reprojected. The new texture thus created is conveniently saved in a special channel and saved as an external file (*.bmp).

Two versions of the mesh are then created, one with a greater number of polygons (Highpoly) and one decimated by more than 50% (Lowpoly), in order to have a model with a suitable number of faces and therefore of detail depending on the use.

3.4 Static analysis

In this phase, an initial static analysis of the statue was carried out to highlight the critical issues due to its shape and material.

Starting from the digital surveys described, the model was processed in finite element analysis software (FEM) and used for structural analysis. For this purpose, the LowPoly model was used which had a low polygon count and was transformed from a surface model to a volume model.

The structural analysis was performed on the FEM model consisting of 582,606 isoperimetric tetrahedral elements with four nodes. Being made of marble, the following parameters were used: Elastic Modulus of 50,000 MPa, Poisson's coefficient of 0.2 and a density of 2,700 kg/m^3.

In this first phase, only a static analysis has been performed considering the weight of the work to evaluate the deformations and any crisis zones due to the geometric shape.

Furthermore, the static analysis of the geometry of the masses of the work has also made it possible to evaluate the stability of the statue.

The value of the stresses both in the Z direction and in the main ones have values below 1 MPa both in the case of traction and in the case of compression. Therefore the values obtained from the previous analysis result to be below the presumed limit of the material.

The results show that the stress levels are concentrated in the ankle area due to the position of the center of gravity with respect to the footprint and this highlights its propensity to project forward.

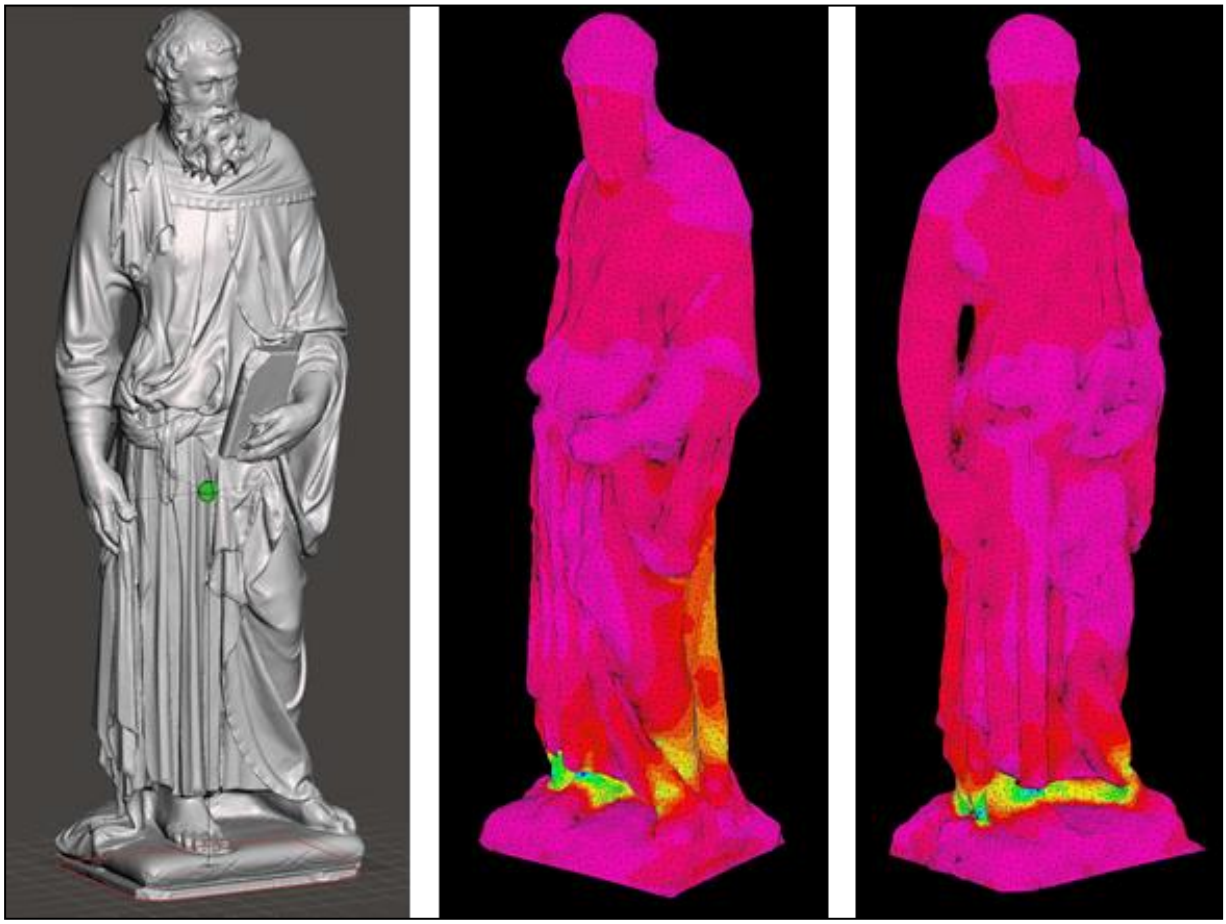

Figure 4: Structural model and result of the analysis.

Although in this phase in-depth seismic verification studies of the work have not been conducted, a point of vulnerability can be identified in the ankle area also with respect to the horizontal actions due to a seismic event.

Making an initial assessment according to simplified approaches for assessing the vulnerability of artistic artefacts [12], the statue of San Marco belongs to a typological category T3 (statues, sculptures in general and large vases), in particular A2 (object placed on a flat surface, pedestal). The dynamic response mechanism is of type A, specifically R4, or oscillatory response mode with rollover as associated damage mechanism.

Further studies will include the study of the non-linear behavior of the materials considering the non-linearity effect produced by the contact surface of the pedestal statue under dynamic actions.

On the basis of the results determined, it is possible to highlight how the structure of the statue has a point of weakness at the level of the ankles, respect to static vertical loads and respect to horizontal seismic actions. Furthermore, the geometry of the statue highlights a danger of overturning in case of seismic event and for this reason it will be necessary to provide appropriate devices of restraint and seismic isolation at the level of the support base.

4 THE RECONSTRUCTION OF THE MISSING PARTS AND THE GILDING

As previously described, the statue of San Marco has suffered over time the loss of the parts that were more breakble and subject to injury more easily. The most "famous" lost parts are

represented by the tassels of the cushion, one of which (the right) is still present in the copy displayed on the facade of Orsammichele. We currently only have photographic documentation of the left one.

A different story should be made for the gold decorations of the dresses which have been lost over time and probably during the restyling operations carried out over the centuries.

This chapter will describe the methods of digital reconstruction of the lost parts which find its conclusion in 3D printing and in the creation of an application designed for the use of the results also for a wider audience.

4.1 The cushion decorations

The reconstruction of the sculptural parts of the cushion started from existing data that could help recreate these objects.

For the right tassel in particular, the existence of the copy exposed outdoors made it possible to apply photogrammetry for its reconstruction.

Starting from the HighPoly model of the base only of the copy of the statue, with the left tassel still present, it was cropped, corrected and made watertight and exported in a separate file. The mesh of the whole statue and the missing part have been superimposed through operations of orientation and three-dimensional alignment and matching. When both meshes were perfectly superimposed in the common part, we proceeded with a boolean operation of subtraction, thus obtaining the mesh of the right tassel, perfectly shaped to adhere to the mesh surface of the entire original statue.

The left tassel required more complex operations. The starting point was the historical photographic documentation of the object taken from multiple angles.

Starting from a separate mesh from the statue, which reproduces its specular volume with respect to the other tassel, a basic volume was created for the left tassel through the connection and fitting on the entire mesh.

The tassel and statue mesh were imported into a 3d sculpting software, where the tassel mesh was subdivided to a suitable number of polygons and, using the statue mesh as a base, the contact zones with the pillow and with stand.

Taking the historical photo superimposed on the model as a reference, the dimensions, the position of the tassel and the orientation of the object were corrected through camera-matching operations.

The sketched mesh of the tassel and that of the corner of the cushion and the base are joined and again, using Boolean subtraction, the intersection portion is subtracted, so as to create the perfect coincidence and graft with the mesh of the complete statue.

On the tassel mesh thus obtained and suitably divided, by means of camera-matching and superimposition of a high-resolution zoom of historical photos, parts of the photo were projected using it as an alpha channel in grayscale, in order to reproduce the details based on to the intensity of the grays (Black for the concavities, white for the convexities).

Before exporting, retopology operations were carried out, in order to uniform the distribution of the polygons in the various parts. Some decimation iterations have also been made, in order to make the mesh at an adequate subdivision level.

To make the texture-free tassels aesthetically uniform to the rest of the statue, textures have been created based on a neutral color to which an Ambient Occlusion map is superimposed.

Figure 5: the cushion decorations reconstruction and 3D print.

Once the 3 parts of the statue were obtained, models of the individual parts were created and one made up of a single mesh, obtained via a Boolean union.

Versions in HighPoly and LowPoly of the models have been exported, in order to be able to use the model in various uses and to be able to import it into various software including interactive visualization, for 3D printing or for archiving.

The models obtained were lightened, where necessary, and exported in (*.obj) format, so that they could be used in the most common 3D printing slicing software.

For the realization of the two tassels, FDM printing was chosen with a hybrid technical filament, composed of PLA and plaster extruded with a high percentage of infill, a high shell thickness and chosen a layer height of 0.1 mm, with a low extruder movement speed, in order to guarantee the best possible quality on a professional CoreXY type printer (Ultimaker3 Extendend).

The print result requires little finishing and sanding, in addition to the removal of the necessary supports and skirts in contact with the bed.

Printing tests of the overall model of the statue in 1:8 scale were also conducted with excellent results, even with classic PLA filaments, verifying and confirming the accuracy and precision of the three-dimensional model obtained.

4.2 The gold decorations of the dresses and hair

During the restoration intervention, the work of art is studied, analysed and finally restored; it often happens that during the work new details are discovered, new information about the work itself. Sometimes thanks to chemical analyses or thanks to diagnostic imaging investigations, insiders, restorers, art historians, etc... can understand characteristics of the work that are not visible. Thanks to increasingly precise digital survey techniques, the restorer can use a digital simulation (3D survey) or a photogrammetric image that faithfully represents the morphology and dimensions of the work being analysed.

On the digital image it is possible to simulate virtual interventions that modify only the digital image of the object thus allowing designers, control bodies and companies to make evaluations on the project proposal.

In our case, the digital image of the work has been modified in order to make visible what laboratory analysis and photographic imaging diagnostic investigations have brought to light, so that all people, not just experts, can "see" the missing decorative elements that completed the work.

After the first investigations and analysis on the work, we had seen that there were traces of gold on the hair and beard of the saint, and in some points of the robe, traces that looked like decorations could be seen in UV fl. At these points, photographs were taken in visible light, in

UVfl light and in IR. First, cross-digital analysis were carried out by superimposing images of the same point in the three fields of the electromagnetic spectrum. In a second step, in agreement with the working group, we decided to propose a reconstruction by integrating the no longer visible golden decorations.

On the beard and hair of the Saint, traces of gilding were visible, in certain points even to the eye, or with the help of a portable microscope; the high-resolution photographs in the visible light have highlighted many traces which suggest that both the beard and the hair must have been gilded. To get an idea of what the work could have looked like in the visible light mesh of the work, we inserted the gilding using photo-editing programs. The mesh with the golden parts was superimposed on the 3D model thus obtaining a 3D digital image of the work with a golden beard and hair.

Figure 6: a view of the golden beard and hair computer simulation

The analysis work carried out in correspondence with the traces of decorations present on the garments was instead more complicated; In its history, the statue has undergone at least two bronze-coloured patination interventions, and other interventions which then removed these patination's, and which also almost completely removed the traces of the older decorations. As a first step, we identified the area of the drapery where the signs were most visible, we carried out photogrammetric surveys of the area in the various fields of the electromagnetic spectrum, visible light, UVfl and IR. Afterwards, thanks to photo editing programs (Photoshop), we superimposed the three surveys that were analysed; we carried out the relief of the traces that were visible in UVfl and IR light and then we superimposed them on the relief in visible light at the end we inserted some gilding in place of the traces. From the image that has been created some decorative elements are recognizable, others not entirely but the important thing is that the images thus obtained help us to understand that the statue was not white as we see it today but had golden decorations that enriched it.

4.3 The interactive desktop application

The final part of this work concerned the creation of an interactive software to allow virtual interaction with the work and the visualization of data provided by surveys and diagnostics.

The developed application can be used on any computer without the need for other software and without installation. It allows viewing and navigation of the 3D model of the statue in visible light and in UV light.

Figure 7: A view from the desktop application.

Through the interface it is also possible to activate the visualization of the virtual reconstruction of the stone gaps or the gold decorations of clothes and hair.

This application has been designed to allow the use of the model by a wider public and for use in exhibitions and museums for educational purposes.

5 CONCLUSIONS

The paper presents the results of an experiment that involved the use of modern methodologies for the study of a masterpiece such as Donatello's San Marco.

The photogrammetry was used to investigate matter in the field of visible light and UV. The analysis of the images and models allowed to confirm the hypotheses of the existence of gold decorations on some parts of the statue.

Furthermore, using the photogrammetry and the modelling and manipulation of three-dimensional meshes, the missing parts of the base of the statue were reconstructed in accordance with the historical documentation.

In this case, the virtual reintegration of now lost decorative elements made it possible to optimize the readability of the work, without resorting to interventions on the original. Even if the results obtained deserve to be further studied, the images of the statue with the golden areas allow us to better understand the historical testimony of the civilization from which the work belonged.

The results obtained have shown that such an approach to the diagnostics and study of works of art is a valid support to restoration operators and opens new perspectives in the field of investigations on sculptures and their representation.

Furthermore, the digital models represent a documentation that can be used as multimedia material available to scientific scholars and to the museum visitors.

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