Ancient polychromy: study and virtual reconstruction using open source tools

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Digital reconstruction of ancient polychromy is a relatively recent phenomenon in the history of archaeological and architectural heritage documentation. It has emerged as a result of new interest of the experimental archaeology, and of the technological development of Computer Graphic tools. Therefore, this paper presents a project aiming at the scientific reconstruction of the original polychromy and the realistic rendering of an ancient sarcophagus, obtained with the use of some open source tools. In particular, starting from the accurate study of a polychrome Roman sarcophagus (National Roman Museum in Rome, inv. no. 125891), we show how MeshLab tool was used to support the polychrome reconstruction stage, and Blender (or, rather, a combination of MeshLab and Blender) was used to achieve a more sophisticated visual presentation of the current and reconstruction ancient colour. A central role has been given to the rendering of the different and overlapped layers of paint.

1. INTRODUCTION

A renewed interest in the study of the ancient colour of Greek and Roman architecture and artworks emerged in the last decade, originating multidisciplinary studies in the Digital Humanities framework [Siotto 2013]. The usual research activity has been enforced by the development of experimental archaeology approaches, often using digital technologies to propose and assess reconstruction hypotheses. Those hypothetical reconstructions of the original colours and decorations, previously exemplified on physical replicas of objects, are now moving to the digital media. They are usually reproduced on digital three-dimensional models, obtained with the now consolidated scanning technologies [Siotto 2013; Siotto et al. submitted].

The reconstruction of the original polychromy is not a consolidated subject of research, since a lot of work still has to be done to improve our knowledge on the methods and techniques of colour application on Greek and Roman artworks [Østergaard 2010; Siotto 2013].

Digital tools could give us a very powerful context for the experimentation of the different painting techniques and the reproduction and assessment of the many alternative reconstruction hypotheses that could be raised for most of the existing artworks. Taking advantage of the traces of the original decoration, it's now possible to study them and to produce insight on their original appearance.

The advantages of 3D technology w.r.t. the more consolidated photographic medium include: the encoding in a single digital clone both shape and colour data; the possibility to monitor the state of degradation of the colours and of the artwork; the easier handling and dissemination of data.

Given these potentials, one of the goals of this research was to experiment up to what degree a complex project could be implemented with current visual technologies (in order to detect pitfalls and limitations, and possibly suggest future improvements, in development and research), and if this activity could have been deployed with open source or freely distributed systems. This took into account the budget constraints of the majority of the experiences in Digital Humanities. Our overall goal was therefore to demonstrate, hopefully, that we are ready to support scientific studies on the reconstruction of ancient colour with available and low cost digital tools.

The software that was used was: MeshLab (http://meshlab.sourceforge.net), to generate our digital clones, to study and reconstruct the ancient painting on the digital surface and then to visualize and interactively render the results; and Blender (http://www.blender.org/) to render the different layers of paint and display their final effect in a more photorealistic way.

The paper is organized as follows: we review the state of the art in the reconstruction of painted archaeological artworks, both taking into account the archaeological studies and the scientific analyses results, and the more recent computer-aided experiences. Then, we present a specific test case: the reconstruction of the ancient polychromy on the Roman sarcophagus dedicated to Ulpia Domnina (National Roman Museum in Rome, inv. no. 125891), and we describe a methodology for the reconstructing its original colour, with the help of the open source tools. Finally, we show the results obtained and we discuss advantages, limitations and possible future improvements of the approach.

2.   STATE OF THE ART

A new attention about the knowledge of the West ancient polychromy has generated several research projects and important exhibitions, frequently following different investigation approaches [Panzanelli et al. 2008]. Experimental archaeology is experimenting on the reconstructions of polychrome sculptures through digital 3D models and physical replicas.

A more traditional approach, which reconstructs the polychromy directly on physical copies obtained through digital 3D models, was for example adopted for the first exhibition of *Bunte Götter. Die Farbigkeit antiker Skulptur* (2003-2004) and the following editions with different names [Brinkmann et al. 2003; Brinkmann et al. 2010].

A different approach aims to reconstruct the ancient colour directly on the digital 3D model of the artefact. The number of research groups adopting this solution is increasing. A well know example is the *Digital Sculpture Project* directed by Prof. Frisher at the University of Virginia (http://www.digitalsculpture.org/); other interesting case-studies, such as the Caligola [Østergaard 2004] or young Roman portrait [Graham 2012], can be found in the context of the *Tracking Colour Project* of the Ny Carlsberg Glyptotek of Copenhagen (http://www.trackingcolour.com/) [Østergaard 2010]. The application of digital technology as a link between archaeological and scientific information is also the core of a recently completed project by the British Museum. Here the Computer Graphics techniques are used to reproduce the missing parts and the original colour of the frieze, the metopes and the fronton sculptures of the Parthenon. In addition to the 3D scanning of the existing fragments, and the manual modelling of missing portions of geometry, the reconstruction of the original colours is presented as well. (http://www.britishmuseum.org/channel/object_stories/video_parthenon_metope.aspx).

The advantage of using digital technology is that it helps in easy manipulation and editing of the high resolution replicas also at a distance and from researchers with different expertise. Of course, these can also be prepared that will be useful for future researches. Technology is also mature enough to devise new tools able to extend our insight and intervention capabilities and to consolidate procedure for Cultural Heritage research and management [Scopigno 2012].

An extensive bibliography in the Graphics and Computer Vision literature addresses the acquisition of geometry and reflectance from images under controlled and uncontrolled lighting conditions. Two recent overviews are Weyrich et al. [2009], which covers a wide variety of techniques for acquiring and representing BRDFs and SVBRDFs over object surfaces, and Ihrke et al. [2010], which focuses on the acquisition of purely specular and transparent objects.

The above mentioned general issue becomes more difficult in the context of ancient polychromy, because no strong acquirable information about the pigments used is available, and only deteriorated samples are usually found. Previous projects tried to realistically simulate the original colour of the works of art. An interesting example was the one directed by Devebec of the University of Southern California [Stumpfel et al. 2003; Tchou et al. 2004], which returned a three-dimensional model of the Parthenon completed with its decorative apparatus (friezes, metopes and fronton sculptures), (http://gl.ict.usc.edu/Films/Parthenon/film.php).

New technological applications to document the current physical state of conservation of the polychromy were developed by Beale and Earl [2011] at the University of Southampton (UK). They tested a method to study the

physical polychromy preserved in a marble head of an Amazon of the "Sciarra" type (1st century A.D.) found in the Basilica of Herculaneum.

To conclude, a work in rendering visual appearance of a polychrome and gilding medieval sculpture was presented by Dumazet and Callet [2008] at the Ecole Centrale Paris. The methodology followed is called OCRE – Optical Constant for Rendering Evaluation. It used open source multi-spectral physically based ray-tracer software *Virtuelium*, developed at Ecole Centrale Paris to render the visual appearance of material and to be able to do multi-scaled simulations of light interactions (http://sourceforge.net/projects/virtuelium/). Unfortunately, this promising tool seems to be discontinued.

3.   OUR CASE-STUDY: ULPIA DOMNINA'S SARCOPHAGUS

Fig. 1. Sarcophagus of Ulpia Domnina, National Roman Museum in Rome (inv. no. 125891).

The sarcophagus (Figure 1) chosen as a case study was dedicated by four freedmen and their wives to their deceased patroness Ulpia Domnina. The choice of this artwork was the result of a careful evaluation that took care of several requirements, such as the presence of a significant amount of the representative colours, the type of pictorial technique used and the geometrical shape of the relief (despite being a high-relief, the figures are carved in such a way as to facilitate the complete and accurate geometry acquisition and the further digital repainting). Another positive element was that we were able to obtain the permission to proceed with the study in a very fast way and museum curators demonstrated interest and scientific curiosity in the project activities [Siotto 2013].

This sarcophagus is preserved in the Michelangelo's cloister of the National Roman Museum – Bath of Diocletian in Rome, inv. no. 125891. It was built in Proconnesian marble in Rome [Van Keuren et al. 2010] and it was dated in the literature at the late 2nd or early 3rd centuries A.D. [Felletti Maj 1953; Dayan et al. 1981].

The sarcophagus was found in 1953 during the construction of some buildings in Rome. It was not found *in situ*, but within a section of modern wall that was demolished in that context [Felletti Maj 1953].

From the typological point of view, it is part of the serial production of sarcophagi with Victories clipeofore and Cupids of dead [Dayan et al. 1981; Koch and Sichtermann 1982]. The most important feature of this artefact is the peculiar preservation of the original polychromy and of the history of its application [Siotto 2013; Siotto et al. submitted].

4.   METHODOLOGY AND TESTING ACTIVITY

Using an interdisciplinary approach, we studied the nature of the pigments used to paint the Ulpia Domnina's sarcophagus and the different techniques for the application of the colours, which coincide with two different phases (see Subsection 4.1).

Figure 2 shows that our testing activity started after the creation of a high-resolution 3D model using a triangulation laser scanner and the derivation the RGB (Red, Green and Blue) coordinates of these colours from high-resolution calibrated images (see Subsection 4.1). In particular, we decided to use MeshLab (an open source mesh

processing system) for the current colour attribution at the digital copy and to reconstruct an ancient colour hypothesis of the second use of the sarcophagus (that was painted during the middle 3rd century A.D.).

Then, some processing and rendering steps (such as the simplification of high-resolution 3D model, the parameterization and creation of masks) were tested to exchange data between MeshLab and Blender (an open source modelling and rendering software). We imported our technical data from MeshLab to Blender to obtain a realistic rendering of the current and reconstructed colour of the case-study, and to simulate the interaction between the light and the different layers of colour.
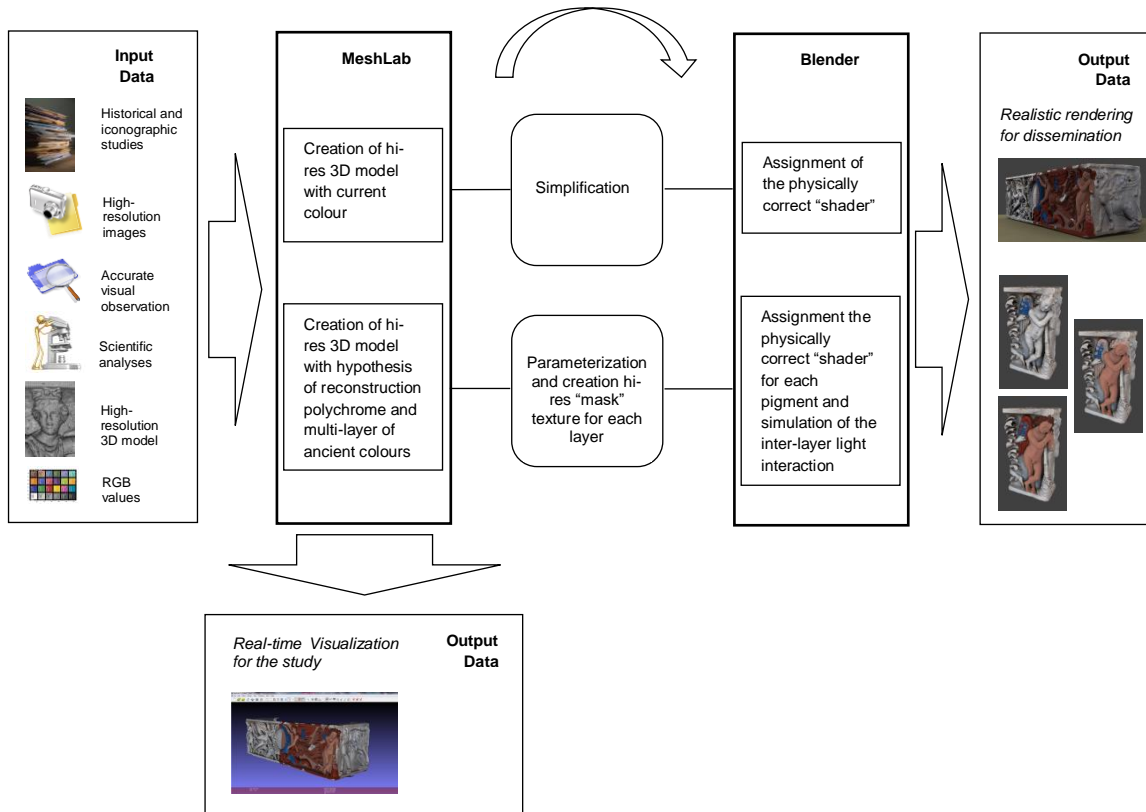

Fig. 2. Overview of our test activity using some open source tools (MeshLab and Blender) for the scientific reconstruction of the ancient polychromy and its realistic rendering.

4.1   Input data

From observations with optical instruments and the results of scientific analyses (macro-photography, multispectral and infrared imaging, Raman spectroscopy, polarizing microscope and stereoscope) we found that this sarcophagus was coloured in two different moments of the antiquity. The original colouring was applied in the late 2nd century (160-180 A.D.) when the sarcophagus was made; while the secondary painting probably came from a repainting of the mid-3rd century A.D., when the inscription to Ulpia Domnina was re-carved lowering the original level of the background [Siotto 2013; Siotto et al. in press]. The better preserved colours are the red-hued and the blue-hued ones. They were applied on the relief with a "large area" pictorial technique, with particular care to the polychromy details of the Victories and Cupids face and feathers. In particular, the visual observation and petrographic analysis results showed that the blue colour corresponded to Egyptian blue pigment mixed with bone black. The red ochre of the ledges, flight feathers, cornucopias, crown and ribbon was applied over a fine preparation of gypsum, red *pozzolana* and lime. This was valid also for the different nuances of red used for the chiton of the

Victories and the skin, the hair and the mouths of the Victories and Cupids. Few traces of yellow ochre seemed to be part of the first colouring. Even the interior of the sarcophagus was covered with a mortar of gypsum, red *pozzolana* and lime, even though it was coarser than the mortar used for the relief of sarcophagus. The surface over the mortar was probably coloured with red ochre, although more investigations are needed on this [Siotto 2013; Siotto et al. submitted].

The subsequent step of the work was the acquisition of the geometric data of the sarcophagus by a 3D scanning system based on the *geometric triangulation* principle [Callieri et al. 2011], and the creation of the high-resolution 3D model using MeshLab (http://meshlab.sourceforge.net), an open source mesh processing system developed by Visual Computing Lab ISTI-CNR in Pisa [Cignoni et al. 2008]; for more details on these steps see [Siotto 2013, Siotto et al. submitted].

In parallel, a colorimetric analysis was performed on the sarcophagus to extract the values of the original traces of colours. Unfortunately, the results were not completely satisfying because the spot of the spectrometer was too large for the little traces of colour, which were also non-planar [Berns 2000; Oleari 2008]. Since the accurate colorimetric measurements of those important polychromy traces were not available, we acquired high-resolution, calibrated images of them (see Figure 3) and we derived the RGB (Red, Green and Blue) coordinates of these colours from those images [Oleari 2008].
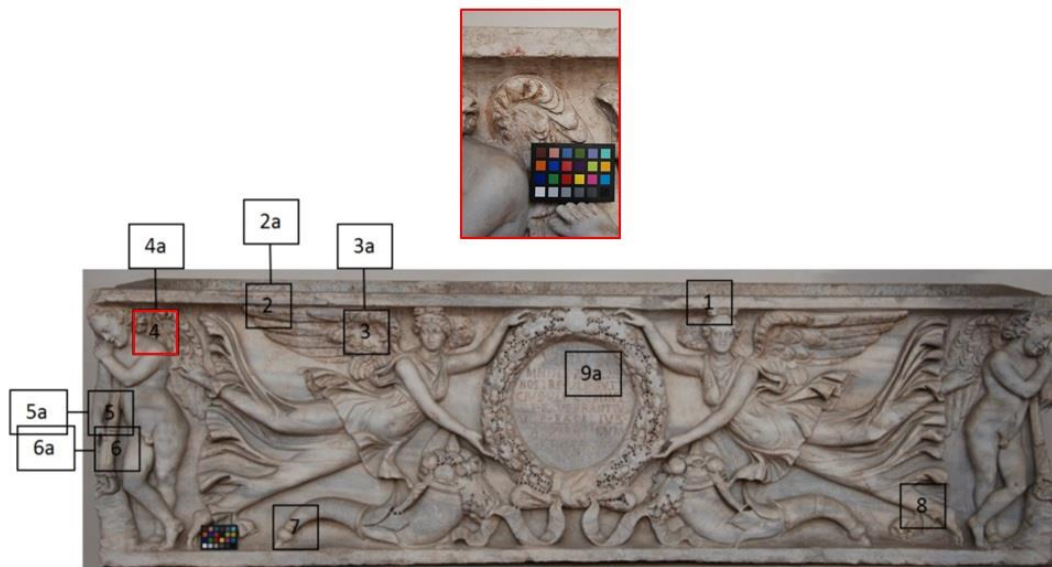

Fig. 3. Point with important traces of red colour where we acquired high-resolution images to derive
(after calibration) the RGB values.

The evaluation of the colour coordinates in RGB space showed that most colours were characterized by two chromatic values. Conversely, the layers of preparation, the contour line of the figures and the bottom of the sarcophagus had only a single chromatic value. The results of this investigation showed that the red hue used for the ledges had the same colour values of the one used for the wings, cornucopias, rocks and sculpted letters of the inscription. The blue colour values were the same in all sampled areas of the sarcophagus. The skin colour of Victories and Cupids was the same, although the one used in Cupids seemed slightly darker than Victories. They both had brown hair and red-dark to brownish lips. The eyes of the figures had dark grey pupils and irises (black-blue), and the inner contour was delineated with a red line over a black line (red-black). White substance traces were visible in the inner corner of the eyes. The only red hues which were different from the others (from black to orange instead of black to red) were present on the stick torch. This colour is visible where no remaining of the secondary repainting was found. The observation is similar for the yellow traces visible in other areas of the sarcophagus, like for example

the acorns and hidden areas of the ribbon of the wreath. These colours could be a remnant of the original painting of the late 2nd century A.D. One of the most difficult decisions was to determine the colour of the background of the sarcophagus. The finding traces of fine preparation of gypsum, red *pozzolana* and lime, and the presumed red ochre suggested that it was painted during the second phase of the middle 3rd century [Siotto 2013; Siotto et al. in press; Siotto et al. submitted].

4.2   Using MeshLab to render the current colour and reconstruct the hypothesis of original polychromy

4.2.1. Current colour processing

The acquisition and mapping of the current surface appearance was one of the goals of the project.

An accurate representation of the colour can be useful for several reasons:
- as a support for the analysis and annotation of the colour remains;
- as a starting model and term of comparison for the reconstruction of ancient paint hypotheses;
- as a documentation mean for monitoring the state of the sarcophagus.

Since the acquisition of the material properties of a real object is a very complex issue (see also Section 2), we applied a pipeline where the surface appearance of a real object is transferred from a set of images taken during a dedicated acquisition session.

The colour projection pipeline, which has been recently integrated in MeshLab [Callieri et al. 2011], is essentially composed by two steps: the registration of the images on the 3D model and the projection of colour information from the images to the 3D model. These two steps were performed using Mutual Information [Corsini et al. 2009] and Masked Photo Blending [Callieri et al. 2008] methods respectively. A set of 33 high-resolution images were projected on the 3D model; a snapshot of the coloured model obtained is shown in Figure 4.

When adding colour information to a 3D geometry, it is possible to work directly on the object geometry (mapping colour per-vertex) or by the use of a texture image mapped to the geometry. Both solutions have pros and cons. However, in this case, given the very high resolution of the geometry and the difficulty of creating a sensible parameterization (due to geometric complexity and topological problems typical to models built from 3D scanning), we decided to use per-vertex colour mapping. This is a more compact and straightforward way to store colour information, and it scales well with the geometrical complexity. Additionally, as we will see in the next sections, it is possible to convert from per-vertex to texture and vice-versa.

The current colour model was used both as a starting point for the reconstruction of the ancient polychromy (see Section 4.2.2) and as an input for realistic rendering in Blender (see Section 4.3.1).

Fig. 4. Current colour interactive rendering of a detail of the Ulpia Domnina's sarcophagus created in MeshLab.

4.2.2. Reconstruction and creation of a multi-layer of ancient paint

The polychromy reconstruction was implemented using the painting tool of MeshLab (see Figure 5), on the base of a set of sampled RGB colours, identified in the small colour traces that we have digitally sampled by means of digital macro-photography (see Subsection 4.1). We worked with per-vertex encoding, using MeshLab to apply the colour on the geometry.
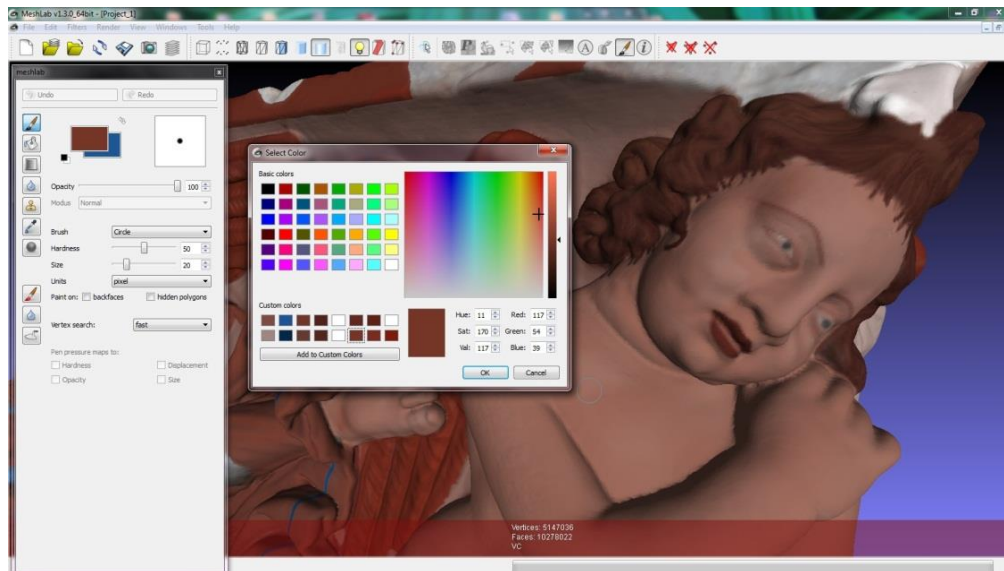

Fig. 5. The interface of MeshLab paint tool.

In order to achieve high-quality results for the re-painting phase, we needed to paint directly on the high-resolution 3D model. This required a longer working time, because this model needed more hardware resources for the visualization and manipulation. In our case, it was not possible to directly paint on the 19 million triangles final model, so the mesh was split in several sub-portions (see Figure 6). Each piece (from 2 to 4 million of triangles) was

painted separately and then all of them were reassembled together (see Figure 7). After recombination of the portions, in a few cases it was necessary to harmonize the colour along the edges of the joined pieces, but this was just a minor overhead.
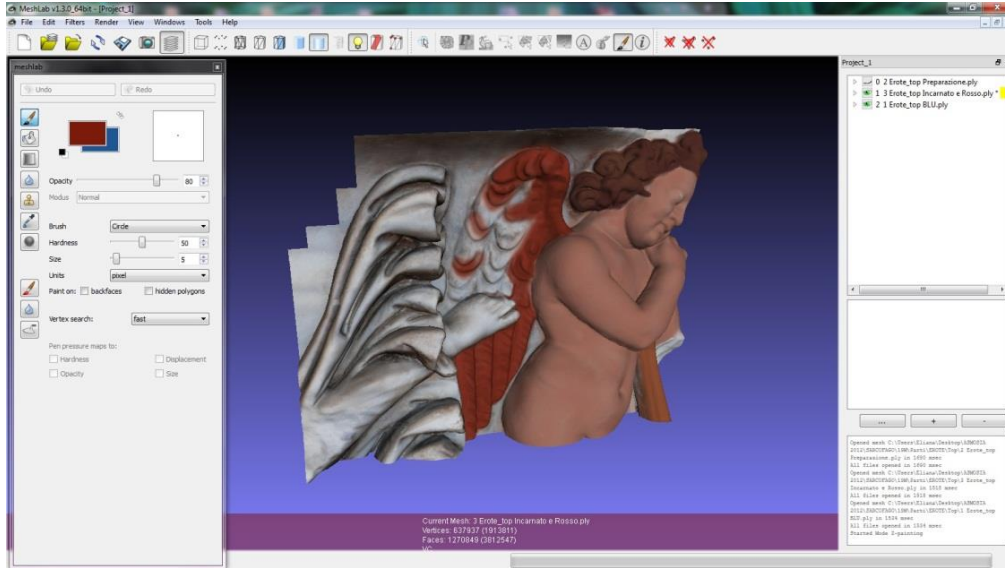

Fig. 6. One of the portions of the high-resolution 3D model which were painted separately.

MeshLab offers a basic but flexible paint interface; colours can be defined as RGB or HSV (Hue, Saturation and Value) coordinates, and chosen colours can be stored in a personal palette. The simple brush-based painting takes advantage of the usual parameters of brush size, hardness and transparency; two colours are available for painting at any time (as in the majority of tools). As more advanced tools, MeshLab offers a clone brush (which works similarly to the Photoshop one) and a "noise brush", used to paint colour with subtle variations. An undo function is also available. Additionally, MeshLab does support input from graphic tablets, mapping the pressure on different painting parameters, like brush size, opacity and hardness (see Figure 6).

The only missing feature in the current release is the direct support of layers, as generally found in all 2D (and in some 3D) painting tools. Currently, MeshLab only has a single colour layer, and each painting action changes this colour information. This is not a problem if we want obtain a complete hypothesis of polychromy reconstruction as shown in Figure 7. However, this limitation required working on each layer independently.

Fig. 7. Virtual reconstruction of secondary painting (middle 3rd century A.D.) of Ulpia Domnina's sarcophagus.

The Ulpia Domnina's sarcophagus is characterized by overlapping of several layers of colours because it was painted in the late 2nd century and repainted during the middle 3rd century A.D. Also, in some cases the colour layer was applied over a layer of preparation or over the others colour layers.

To make a colour appearance test of the multi-layer paint that defined our case-study (see Subsection 4.3.2), we coloured each sub-portion with a single layer of paint. For example, we started to paint the portion with the Cupid with RGB values of preparation layer (made with gypsum, red *pozzolana* and lime). Then we painted the same part only with a RGB values blue colour (Egyptian blue pigment mixed with bone black layer). The same method was adopted for each layer of colour found in the sarcophagus thanks to archaeological and scientific integrated study (Siotto 2013; Siotto et al. submitted).

The determination the original painting of late 2nd century was complicated by the distribution of the secondary one (middle 3rd century), which was applied in a rather crude manner over the fine preparation layer with gypsum, red *pozzolana* and lime. The test activity with the MeshLab painting tool on the high-resolution 3D model was a good test for helping us to better face this problem. The final result – a hypothesis of virtual reconstruction of the secondary painting – came from the integration of the results of scientific analysis and visual observations of the polychromy traces on the sarcophagus and on its digital model. Obviously this proposed restitution is partially based on arbitrary choices, as most of the virtual restoration hypotheses. Nevertheless, it is a valid base to have a better and systematic idea of the polychromy of the Roman sarcophagi (see Figure 7).

4.3   Using Blender for realistic rendering

We described how MeshLab was used to support the modelling and painting stage (3D attribution of the current colour and polychromy reconstruction). MeshLab supports interactive visualization; however, this real-time exploration, useful as it may be, cannot provide a photo-realistic visualization of the model. By design, MeshLab is a mesh processing system and not a full-feature rendering tool. Effects like soft shadows cast, sub-surface scattering (important for the marble surface) and a configurable lighting management are not available. For this reasons, we adopted another open source tool, Blender (or, rather, a combination of MeshLab and Blender) to achieve a more sophisticated visual presentation of the colour reconstruction.

Blender (http://www.blender.org/) is an open source modelling and rendering tool, one of the most used open tools in the Computer Graphics field. Supported by a huge community and ever growing as a project, it offers feature on par (or better) with respect to commercial tools. Thanks to its features and open nature, it is lately quite used also in the research world, from biology to cultural heritage.

Our goal was to use Blender to obtain photorealistic rendering of the two coloured datasets (global and layered painting). To this aim, we had to set-up materials (to simulate marble and paint), lighting (to illuminate the object) and rendering/compositing.

4.3.1. Rendering of current and ancient colour

Blender does natively support per-vertex colour encoding; thanks to this feature, we could directly import our coloured 3D models and render them. However, the amount of polygons that a rendering tool like Blender can handle is much lower than the one handled by MeshLab; while able to manage, as far as we tested it, 6 million triangles in a single rendering scene, this solution does not scale well and it is not what the rendering engine is optimized for. For this reason, we used the geometric simplification feature in MeshLab to generate lower-resolution models for the rendering (2 million triangles each).

Our idea was to show the marble part of the sarcophagus with a marble material, and the re-painted part with more opaque shading. Since we had the model for the complete sarcophagus with the actual colour and the model containing just the repainted right side, we created a scene by placing both models in the same position and assigning the correct material to each one. At rendering time, we produced two images, one with the actual colour (see Figure 8) and one with the re-painted surface: combining the two, we obtained the half-and-half look (see Figure 9) we wanted to obtain.

The material for the marble part is a sub-surface scattering material with a limited specular component, with parameters chosen in order to obtain an optical response similar to marble, and diffuse colour coming from the photographic mapping. The material for the re-painted surface is a more diffuse material, with main colour coming from the painted per-vertex data, plus some procedural grain/surface roughness.

Even if the result is satisfying, it is still limited, since the rendering does not take in account the different materials used in the colouring; to simulate this distinction, we had to start from the painted layers dataset.

Fig. 8. Realistic rendering of current colour of the marble Roman sarcophagus
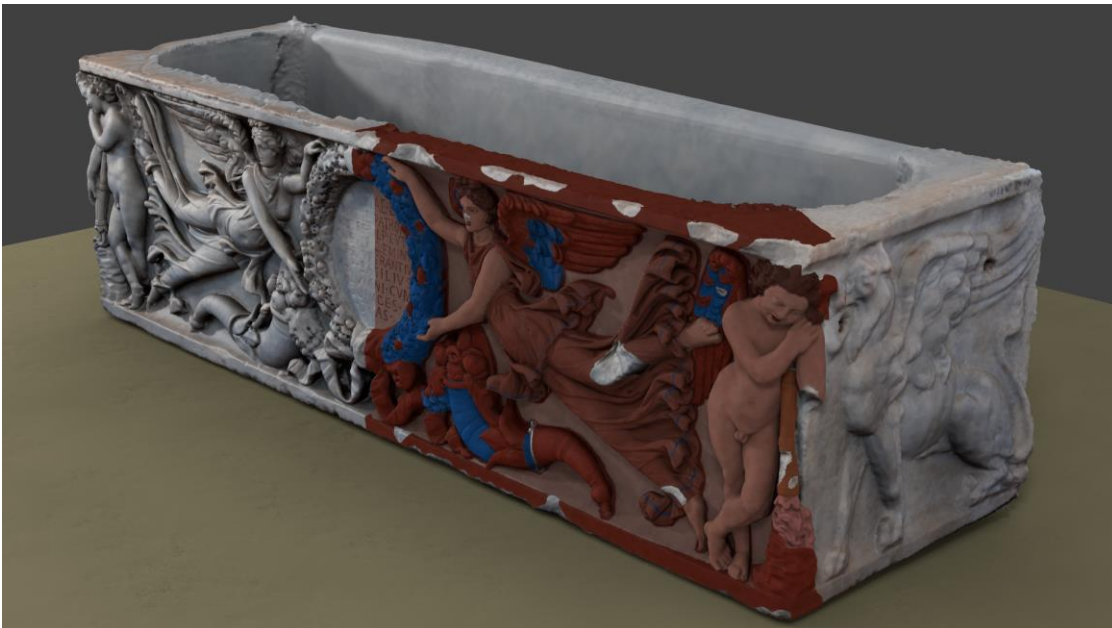

Fig. 9. Realistic rendering of the ancient polychromy reconstruction.

4.3.2. Rendering of the multi-layer painting data

In order to render the multi-layer dataset, we had to use a multi-layer material. However, Blender does not support a native multi-layer material. On the other hand, it is possible to build one by combining shading nodes. Blender uses a way to represent the material of an entity using "nodes": this representation is extremely powerful, because it lets the user create a material by combining multiple shaders using an intuitive visual graph.

The idea was to represent the various paint layers with specific shaders (one shader for each pigment). The layer for each paint was represented by a "mask" texture (detailing where a pigment was present), and the layering structure was obtained with a cascade of shading nodes (to simulate the superimposition of layers).

We selected an area of the Ulpia Domnina's sarcophagus that presented an interesting layering of colours for this experimentation: the Cupid on the left end of the front of the sarcophagus.

While for the previous dataset (the whole sarcophagus) we used per-vertex encoding, for masking we needed a texture-based representation; for this reason, we decided to convert our basic high-resolution model into a low-resolution mesh (around 500K triangles) with texture parameterization. To obtain a parameterization for our model: we tested both the internal Blender parameterization tool and the MeshLab parameterization, with similar results.

We then created, for each layer, the "mask" texture, describing where the pigment was present and where not; this is basically a black-and-white image. To create these textures, we started from the painted high-resolution geometries of each layer (see Figure 10). Starting from these painted meshes, we "baked" the colour information onto textures maps. Creating the mask directly inside Blender, using the texture paint functionality, is also an option (possibly, an even faster one); however, we imported the mask from the MeshLab painted dataset to show how it was possible to combine the high-resolution interactive painting and visualization with a realistic rendering. This was because painting on the higher-resolution mesh enables to line-up small details with their geometric counterpart, although it is harder due to the slower rendering.

Fig. 10. Creation of masks to overlap different layers of colour:
original colour (left); preparation of mask (centre); blue colour mask (right).

The setup of the material for the object, then, was done starting from a base shader to simulate marble; on top of this shader, we built a cascade of mixing nodes. The final material node graph, visible in Figure 11, is simply a sequence of mixing nodes, each one driven by the mask texture. The result was that, for each part of the object, the correct shader to use was decided according to the presence of a certain pigment (the value of the mask texture) and the layering of preparation and colours (the order in the sequence of mixing nodes).
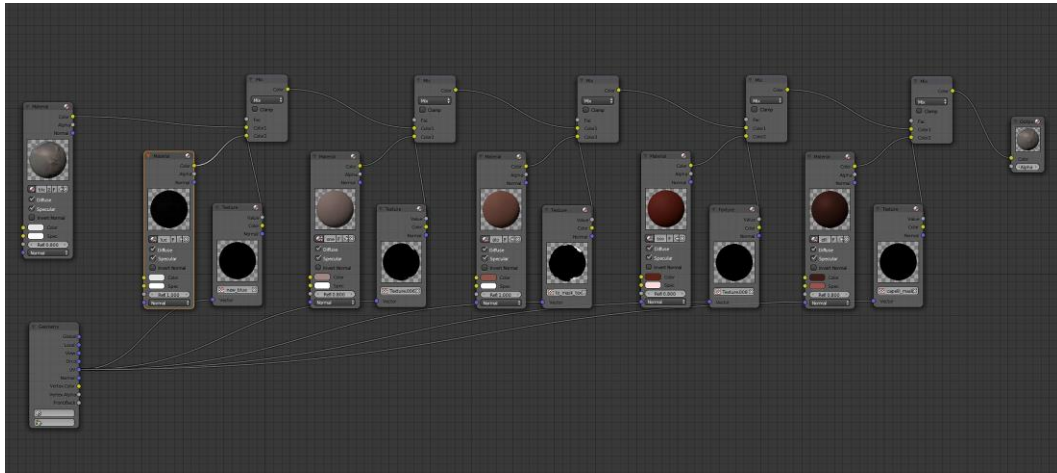
Fig. 11. The material node graph, that assigned a shader to each different pigment or layer in the sarcophagus portion.

The experiment was successful, in the sense that it was possible, using this setup, to render a series of photorealistic images where each different material has its own shading (and not the simple Lambertian rendering used in most of the real-time tools). It is also possible to animate the layers in a video (make each layer appear one after another), to better present the layering structure. Figure 12 shows the different renderings that could be created using the material node graph.

The limitation, however, resided in creating the correct shader for each ancient colour/pigment; in order to do so, in a physically correct way, we should have started from BRDF measurement for each colour. Since this data is not available, we just manually created plausible material for each colour (starting from the measured RGB colours and the grain/roughness visible in the microphotography).
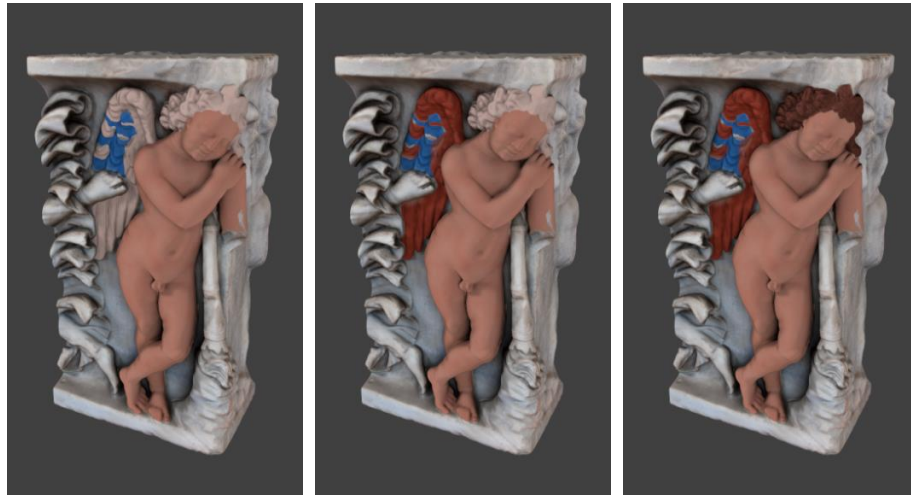
Fig. 12 . Test to create overlapping of different coloured layers.

5.   EXPERIMENTAL RESULTS AND DISCUSSION

The main results of the proposed approach are:
-   a high-resolution 3D model with half current colour and the half per-vertex ancient colour reconstruction, and a series of high-resolution models of specific areas of the sarcophagus, each one depicting a single layer of the original painting process and directly rendered and visualized in real-time using MeshLab (see Figure 13);
-   a sophisticated rendering of the low-resolution 3D model with half current colour and half the ancient colour reconstruction (see Figure 14), and an animation video of the different colour layers with plausible material created for each colour (see Subsection 4.3.2).

The first output data, directly rendered and visualized in real-time using MeshLab, provide an immediate and powerful instrument for the study of the ancient polychromy. Using the moveable light and different real-time shaders, it is possible to closely inspect the painted geometry giving to the researcher or user a much deeper level of understanding of the relationship between colour and geometry. The second output data from Blender simulate the marble and a series of different colours to produce a more sophisticated and realistic rendering for the dissemination of our results. This was possible using a more complex light effect, such as a sub-surface scattering between layers, a light colour shift/diffraction and, finally, a light bouncing between layers needs to be simulated.

Fig. 13. Rendering results of left part of sarcophagus with ancient polychromy reconstruction produced by MeshLab.
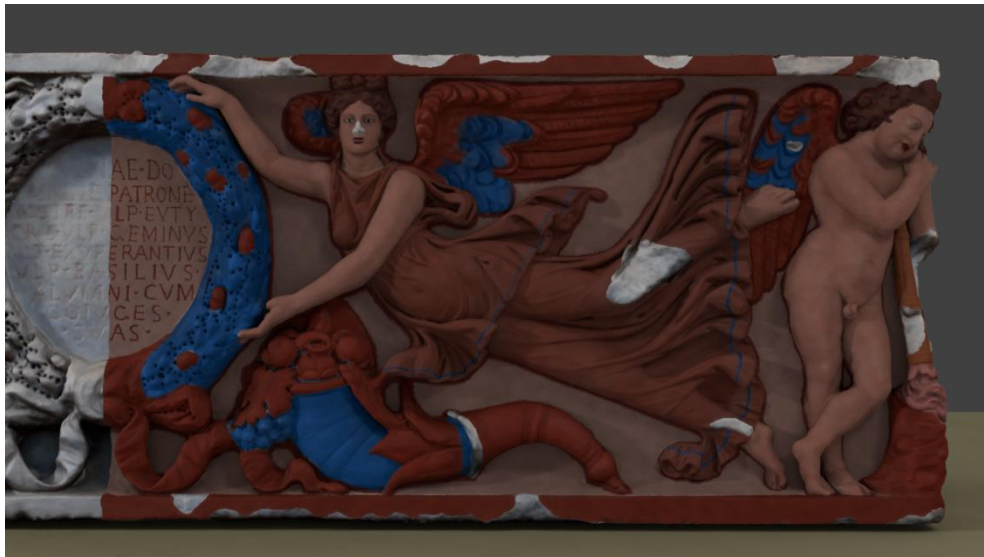

Fig. 14. Sophisticated rendering engine provided by Blender the same part of sarcophagus shown in Figure 13.

In particular, we experimented that while the MeshLab painting tool proved to be easy to use and quite flexible, it demonstrated also not to be structured enough to represent the layered structure of the original polychromy. This process, even if able to produce a satisfying result, encountered some limits that are intrinsic to the tool:

- The rendering in MeshLab is a simple Lambertian model, quite limited in representing complex materials. While it is possible to change the shader MeshLab is using, it is still limited to a single shader for the entire object, while it was necessary to simulate marble and a series of different paints.
- MeshLab does not support a layer-based structure for the colour information. This means that it was not possible to store and visualize the different layers of paint in a single model. The reconstructed layers were stored as a series of meshes, each one depicting a single layer.

Also in Blender there are two important points that need to be addressed:

- The design of a physically shader for each pigment. At the moment, the shaders for the various paints were manually created using the basic colour (coming from the calibrated photos) and some general consideration on the nature of pigments (granularity, shininess, transparency) coming from multidisciplinary studies (archaeological and scientific analyses). In order to have a correct simulation, it would be necessary to measure the BRDF of the paint (recreated using an experimental archaeology approach), and to represent the measured BRDF with a shader.
- An improved simulation of the inter-layer light interaction. At the moment, each layer just overrides the underlying one. Even if it is possible, in the current setup, to have semi-translucent layers (partially showing the underlying one), this is not enough to reproduce all the possible ways in which the light interacts with the layers of paint. More complex light effects like sub-surface scattering between layers, light colour shift/diffraction, and light bouncing between layers need to be simulated.

CONCLUSIONS

In this paper we presented some of the results of a project regarding the virtual reconstruction of the secondary polychromy (middle 3rd century A.D.) of Ulpia Domnina's sarcophagus. The goal of the work was to study a possibly define an integrated methodology where the massive amount of material which is acquired and combined when studying the artwork could be used to obtain a rigorous and realistic restitution of the ancient polychromy.

In order to obtain a digital model of a plausible hypothesis, two open source tools (MeshLab and Blender) were combined to colour and render the model obtained via 3D scanning. The combination of the tools was necessary to overcome some of their intrinsic limitations, and it proved to be able to produce realistic results.

We aim at further improving the procedure, in order to reduce the user intervention to prepare and convert the data between the tools. This means that the MeshLab features should be improved to be able to prepare and export the different "masks" (or alternative solutions). On the Blender side, a more structured script should be able to read the output from MeshLab, and produce different renderings in a semi-automatic way. This possible extension would be the best solution to take advantage of the potentials of these tools, and enhance their integration for future uses.

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