Ravenna’s Archaeological Heritage

Integration of techniques for accurate documentation through 3D digital models

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Abstract: Since 1996 several monuments of Ravenna’s historical centre have been registered as UNESCO sites due to the outstanding value of their mosaic art pieces, as well as the peculiar architectural features in baptisteries, churches, mausoleums: they provide crucial evidence showing the transition from Ancient Roman typologies to Late Antiquity buildings.

By testing the interaction between the 3d mapping technologies and the applications the entertainment, this paper will explain the results of an interdisciplinary research project and its future potential, by illustrating the methodology used to obtain reliable and multipurpose 3D models. The creation of a mapping database is the central purpose of the operations carried out on captured data and such material is suitable for both the interactive exploration using 3D devices such as Oculus VR as well as for an accurate documentation of the state of conservation of relevant ancient buildings in Ravenna.

More specific technical points deal with fully exploiting image-based modelling tools based on Structure from Motion (SfM) algorithms and render-to-texture solutions (*baking* in CG applications). In this context, the typical automatic solutions implemented in the latest generation of photogrammetric software play a very important role since they avoid time-consuming manual parameterization within the entertainment applications. On the other hand, other problems concerning the full employment of 3D data from active and passive sensors will be shown: the field of this methodology is called BRDF, and in particular splitting apparent colour textures (from passive sensors) into a set of images providing the render engine with more accurate and specific information to achieve higher photo-realism.

Keywords: Ravenna, Byzantine Architecture, Oculus VR, BRDF, shadow removal

Research overview and expected outcomes

Recent tragic events caused by the earthquake in Emilia Romagna (May 2012) have strongly raised the awareness as to how fragile our built heritage is, and with it, its superficial decoration (mosaics, frescoes, etc.).

When the plan to document some relevant buildings of Ravenna’s historic centre came to be, an integrated research project was set up: surveys were carried out in order to document the Arian Baptistery, Theodoric’s Mausoleum, some Urban Gates of the ancient town and other of mosaics inside the Domes. These examples of Ravenna’s “urban archaeology” will be converted into multipurpose 3D models, obtained throughout an integrated procedure, thought out in order to build “light” and reliable 3D models suitable for more outputs: web sharing, documentation, architectural/archaeological investigation and preservation practices. The outcomes achieved through a series of case studies will provide all parties in the field of

conservation and valorisation of Cultural Heritage with a dynamic and robust procedure, based on common applications. Once the digital data is obtained, the second step deals with its usage into real-time applications and new devices.
The final goal of optimized 3D models is to allow a fully interactive experience and an exact documentation of the current state of conservation of monuments using an immersive gaming interface: Oculus VR allows a realistic perception of both mosaic surfaces and masonry walls of domes, and this is thanks to the 3D vision with 110° viewing field and the movement-tracking system of the observer's head.
A fundamental aspect of this research has to do with the realisation of smart photo-realistic 3D models which then are then used as "vectors" of metric-morphological data, rather than poor low resolution models with an applied texture, which in many cases offer an accessory and schematic representation of digitally acquired objects, as they can't properly interact with render engines (in real time or not).
Another aspect we want to emphasize is the interaction between 3d models and render engines: in terms of computational "weight", as well as light-matter simulation; the following steps summarise the main issues dealt with by our procedure:

- Colour pre-processing of frames intended for image based modelling
- Improvement of automatic parameterisation tools within SfM applications
- Appearance preservation of low detail models (low-poly)
- Conversion of apparent colour textures into diffuse colour textures through a shadow removal technique
- Segmentation of apparent colour texture into a set of images aimed at a more reliable simulation of mosaics.

Colour processing and photographic survey

The methodology adopted starts with topographic and/or laser scanner survey of monuments, followed by a photographic campaign. In the case of the Arian Baptistery and the Urban Gates, both scale and orientation of the models were provided by a general topographic survey. In the case of the Mausoleum of Theoderic, a complete 3D laser scanner survey of both the interior and the surrounding areas was carried out using the phase shift device Z+F IMAGER 5010C[1].
RAD Coded targets supplied a set of homologous points meant to provide the necessary information to SfM applications hence creating a proper integration between photogrammetric models and active sensors.

[1] The Survey was made possible thanks to the scientific Collaboration with MicroGeo S.r.l (Calenzano, Florence). Ph.D. Sergio Di Tondo and Degree Student Marco Neri carried out the measurement campaign.

Colour processing (Apollonio et al. 2013) is a fundamental step to achieve good results in terms of morphological and chromatic reliability of the output files, as the goal is the modelling of a high quality 3D representation of the mosaic decoration, residual frescoes, etc.
Before every set of photos was shot, a first acquisition of a ColorChecker Classic (formed by 24 coloured patches) was added to the set of images, in order to balance radiometric aspects of those photos with uniform ambient illumination. For every set characterized by the same illumination, a first image is necessary in order to provide grey 18% adjustment and then to create specific CameraRaw Settings (.XMP file). These files will then be loaded into each homogeneous set of images and applied to them in order to to supply a uniform colour temperature to each part of the Baptistery's interior. Since internal niches are generally very dark, the ISO factor for those specific architectural elements was set to 400, thus resulting in brighter images (fig. 1).

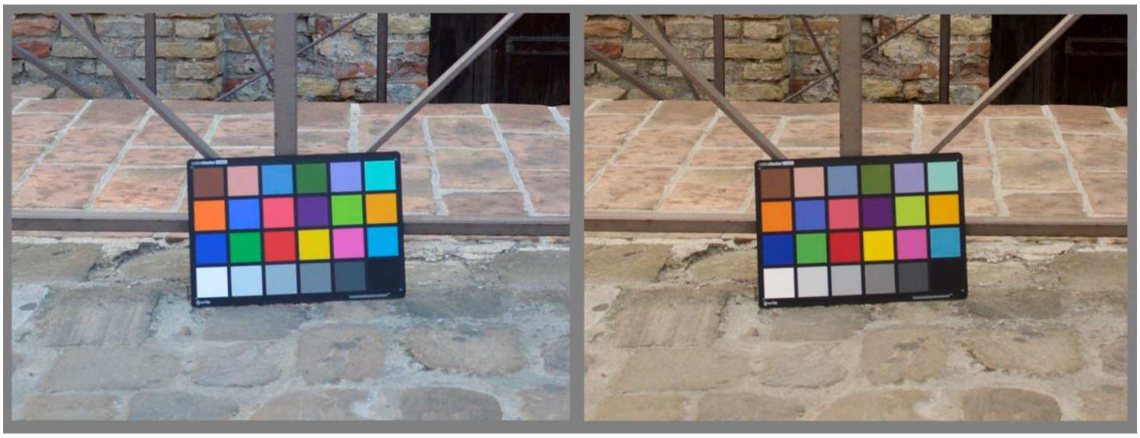

Fig. 1 – White balance of the digital image through a X-Rite ColorChecker® Classic target (24 coloured squares).

The research unit carried out different photographic campaigns of the two main monuments discussed in this paper. For the Arian Baptistery, in order to obtain a complete documentation of the interiors, the survey was split into five sets of photos: the interior elevation structure (comprehensive of walls, niches and dome), the floor and other three smaller sets of photos, documenting the main door, the baptismal font and an additional patch needed to improve the model texture quality.
The resulting noise effect on the images was reduced using an Adobe Photoshop plugin (Imagenomic Noiseware), able to remove the distinctive spurious and extraneous information on these higher ISO shots (fig. 2).

Fig. 2 – Noise reduction through Adobe Photoshop plugin Imagenomic Noiseware.

The set of resulting ".Tiff" file format images were then imported into Agisoft Photoscan for the orientation phase. The crucial step of this modelling process is based on a severe network planning: in SfM slang the word "network" means the position of cameras with respect to the surveyed object. Of course, restrictions to being able to move all around the object, badly affects the final quality and reliability of the 3D model. The main parameters to be taken into consideration when planning a network are the following: the distance from the object (that affects the geometric resolution of the final mesh); the distance between two consecutive cameras (vertically and horizontally); the speed and duration of the photographic campaign, as the varying sunlight on the object surface may affect the final quality of the model and its texture; and, last but not least, the appropriate quantity of photos to include in SfM application before running the process (fig. 3).

Fig. 3 – Images set for the photo modelling of the whole interior of the Arian Baptistery.

Geometric Processing for texture improvement and general optimization

Large amounts of data obtained from both active and passive sensors need to be treated through a set of software ranging from mesh processing to entertainment applications to fully achieve an optimized 3d database, since our final purpose is to have smart, low-weight interactive models to be broadcasted.
To convert heavy meshes into digital bases fit for Unity 3D, a number of applications was adopted. In fact, when dealing with applications developed in the field of interaction, a critical aspect is the number of polygons that game engines, graphic cards and – more generally, hardware - have the possibility to manage without any loss in the animation linear flow. A low frame rate will lead to an unnatural and unrealistic experience. In the Arian Baptistery case study the "weight" of the model was even more critical, as Oculus

VR was used for the final visualization. This kind of device needs to render two different interactive images at the same time: one for each eye. Therefore, polygons must be drastically reduced.
A common strategy in these cases is that of applying coarse decimation tools, which are often included both in SfM software or smarter solutions implemented on mesh processing applications (3D Systems Geomagic, Innovmetric Polyworks, MeshLab, etc.). Even when a decimation tool is applied carefully, the resulting model doesn't always meet the true requirements of real-time visualization. As a matter of fact, the main problems are the "constructive materials" of digital models. In fact, among the many issues affecting a 3D model, there is one fundamental point to be understood in this specific case: is it made of triangles of quadrilaterals polygons? SfM models are heavy meshes built with millions of triangles, but generally, 3D geometric applications for entertainment rather use "quads" or four sided polygons. The latter interact more efficiently with light and material simulations inside render engines, since bands of polygons can easily follow the natural curving of architectural and natural/organic shapes[2]. Another aspect to be considered: quad models are easier to be parameterized. Parameterization is a very common operation in computer graphics as it involves the creation of a 2D version of the digital model, used to project texture images more efficiently rather than using common (and now obsolete) planar, spherical or cylindrical projections, etc. In conclusion, highly detailed models made of triangles cannot be used in game engines even if their photo-realistic appearance can provide a high degree of visual reliability for an interactive experience. The strategy adopted by the research team in order to solve this problem comes two folded (CIPRIANI et al. 2014): on the one hand the newer technique called "retopology" (fig. 4) is adopted when the final purpose is true interaction in real-time applications (low-poly models); on the other hand - when the model is oriented towards actual documentation of the shape - a global re-meshing is run eliminating topological and geometrical defects on high-poly models (fig. 5).

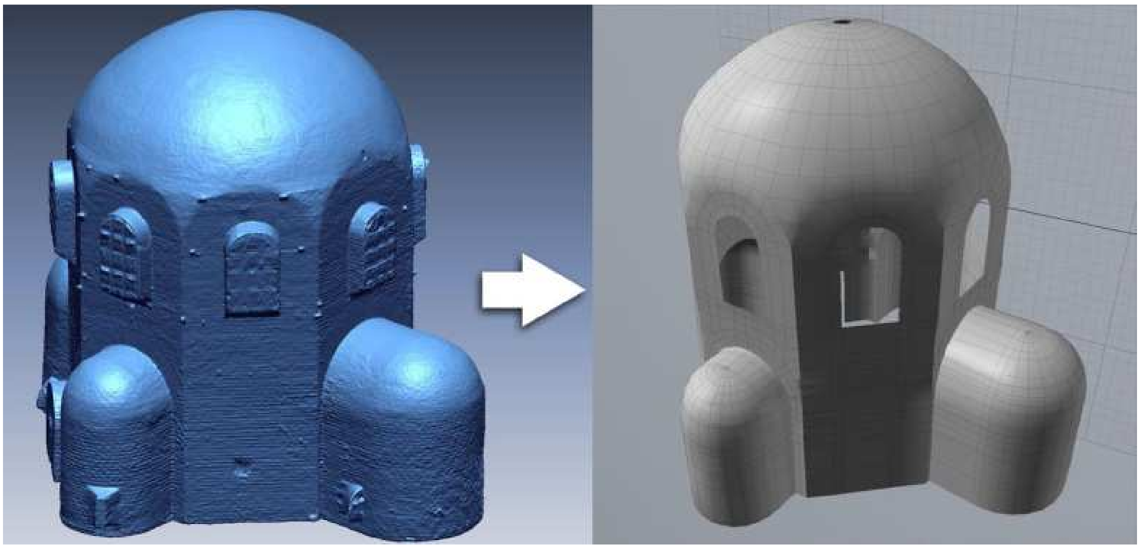

Fig. 4 – Model of the interior of the Baptistery before (left) and after (right) the retopology process.

[2] On the general aspects of quad dominant meshes, see: LAI et al. (2010). A more recent survey on the topic is presented in BOMMES et al. (2013).

Automatic parameterization inside SfM applications is made easier and improved in both cases (low-poly made of “quads” and high-poly made of isotropic triangles), but in order to add an additional support to this delicate phase another expedient can be adopted. A difficult aspect to manage, once the parameterization of a complex shape is required, is the segmentation of the model; in fact an uncontrolled number of islands - in which a 3D boundary representation is split in the parameter space - can lead to incorrect results. A second clue to automatic parameterization tools is to provide the mesh with a series of cuts along a connected tree of edges (PIPONI, BORSHUKOV 2000): basically, it means breaking the connectivity between edges along an ordered sequence of borders. These edges should be carefully selected in order to convert non-simply connected shapes into a set of opened surfaces corresponding each one to a single island of the UV parameter space. In order to get a neat parameterization it turns out to be convenient to split the boundary representation into different sets, coexisting inside just one mesh; it is then possible to re-import it inside Agisoft Photoscan and run the texturing command. This pre-segmentation of the model is called Semantic Partition and can be carried out easily within different applications, ranging from entertainment to mesh processing. The result is parameterization, whose features make it more similar to the results obtained using unwrapping techniques (fig. 6), such as angle preserving parameterization, stretch minimization and angle based flattening, etc. (SHEFFER et al. 2006).

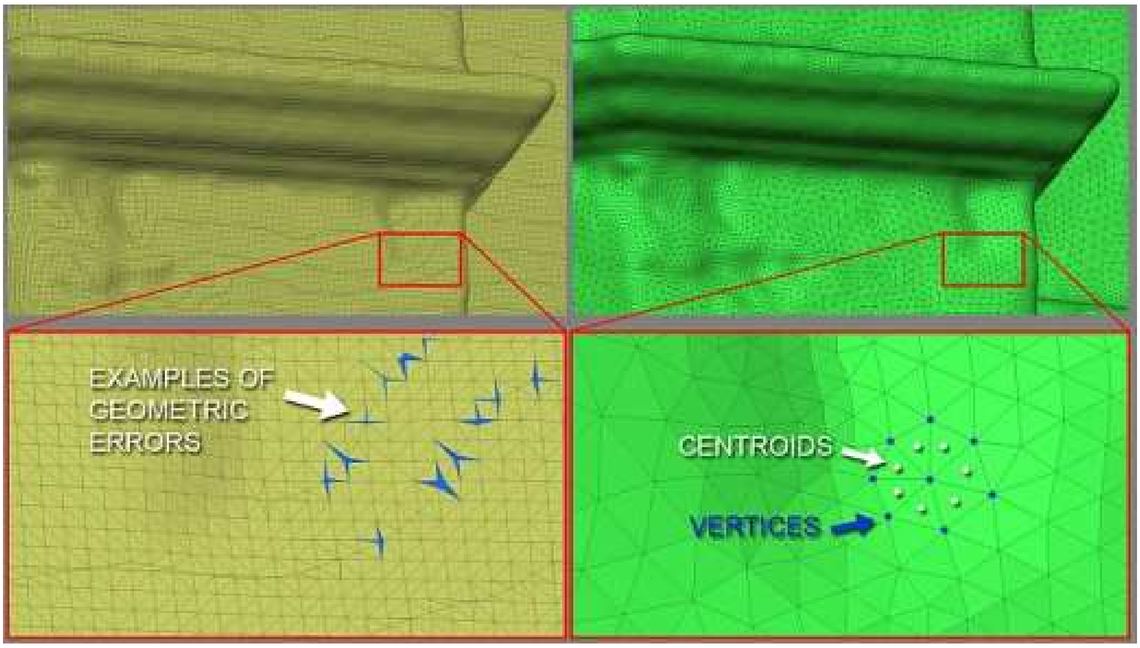

Fig. 5 – Geometrical errors from SfM application: boundary lines among structured meshes are formed by small sets of triangles (underlined in blue) whose presence causes a poor parameterization result (uncontrolled number of islands, waste of parameter space, etc.). Once undergone a global remeshing, the model is formed by an isotropic net of triangles – who are able to facilitate automatic parameterization inside SfM applications.

Fig. 6 – The semantic partition of a mesh (healed from topological and geometrical defects) simplifies the achievement of regular - and consequently - editable texture.

The mesh, once parameterized in an automatic manner, yet avoiding classic and frequent defects produced by SfM applications (in particular high-quantity of sparse islands), can now be optimized. In case of low-poly models for real-time exploration it is important to re-establish all the fine details included into the original high-poly representation. The essential way to reclaim the detail into coarse meshes directly is comes from video games development, called "baking": a render-to-texture solution implemented in the majority of 3D geometric modelling applications for entertainment. It consists in storing specific data into the parameter space; in this particular case, baking techniques were used to restore the geometric detail of high-poly mesh on low-poly models through normal maps (FANTINI 2007).

From apparent colour to diffuse colour

Masonry walls represent the perfect object to use SfM algorithms and in general the resulting models are reasonably accurate in terms of shape description. Bricks, mortar, stone ashlar, etc. can be approximated to a Lambertian surface (perfectly diffused reflecting surface) and once photographed under appropriate lighting conditions, like an overcast sky producing omnidirectional environmental illumination, the output 3D model with texture applied is characterized by a high degree of realism. No problems can be detected if the output images from SfM-based applications are obtained within the software (screenshots, ortho-photos), but once 3D mesh and colour texture are exported to 3D geometric modelling tools, relevant problems arise. A first one deals with gamma output of render engines[3] in synergy with texture image gamma: they have to be

[3] Gamma output can assume different values: linear=1.0, intermediate=1.6, sRGB=2.2, etc.

compatible complying with the values included in the following table (table 1), easily obtainable through a simple relation[4]:

Output gamma	Applied texture gamma
Linear = 1	1
Intermediate = 1.6	0,625
sRGB = 2.2	0,454

Tab. 1 – The gamma output of a rendered image and the corresponding gamma of diffuse colour images required.

A second aspect of the problem must be pointed out: the texture obtained using Agisoft Photoscan or similar applications is not a conventional diffuse colour texture such as those used in CG applications. It can be defined as an “apparent colour” texture, given that it already includes all the physical effects due to the interaction between light and matter (direct shadows, diffuse shading, colour bleeding, etc.). Once the apparent colour texture is applied on the channel in charge of diffuse colour of the mesh, several problems can be detected. The main one is called “double shadow” effect, meaning that an undesirable superposition of shadows is present on the rendered model (fig. 7): dark areas seem darker, light areas are overexposed. In addition, ray-tracing shadows can be conflicting with those included in the texture. A possible solution is then to move the texture from diffuse colour to luminous colour, while other BRDF parameters must be set according to table 2:

BRDF channels	values
Diffuse amount	0
Specularity amount	0
Mirror reflection	0
Luminous amount[5]	1 W/srm^2 (radiometric). 179 cd/m^2 (photometric)

Tab. 2 – BRDF main values corresponding to representation of apparent colour, avoiding any interaction with light simulation.

[4] $Texture\ Gamma = \dfrac{1}{Output\ Gamma}$

[5] Light unit system can be expressed both in radiometric and photometric units:

- radiance = watts per steradian per square metre (W/sr·m^2).
- luminance = candela per square metre (cd/m2).

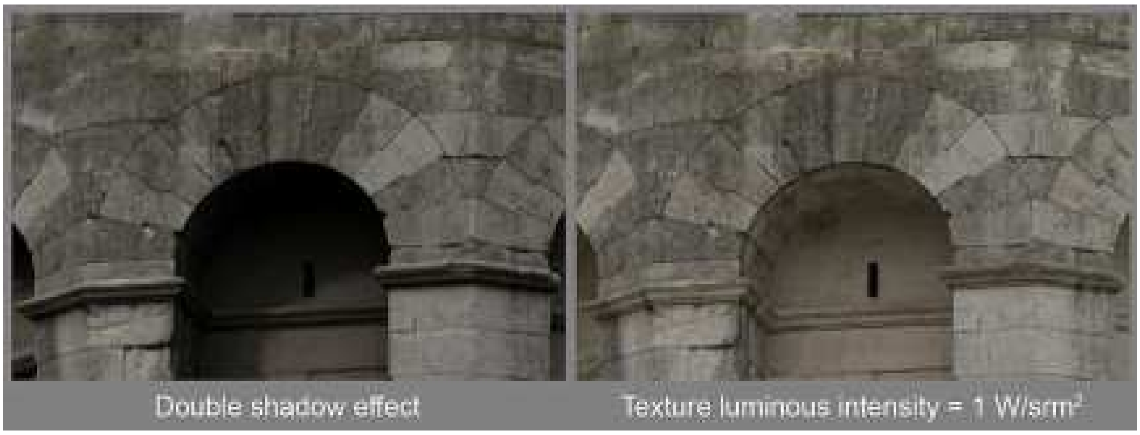

Fig. 7 – On the left, the typical double shadow effect due to apparent colour applied as a diffuse colour texture. On the right, the same texture applied as luminous colour. In both cases render gamma output was set to linear (gamma = 1).

Recently, Talvi Digital (Finland) developed an approach[6], which has proven useful in the case of Lambertian surfaces, that consists in removing shadows from the textures. The workflow consists in projecting the same set of photos twice in Agisoft PhotoScan. The first and the second set have been pre-processed supplying two different radiometric corrections: for the first set, grey balance parameters were obtained using a sample picture including the colour checker, positioned into a dark area of the Mausoleum of Theodoric (lunettes of the external arches). Then, the second set was processed using a different sample image where the coloured table was located on external surfaces. Subsequently, the two textures are “mixed” thanks to a transparency channel (greyscale) obtained by saving the resulting ambient lighting into the parameter space. Actually, this step may seem particularly complex; on the contrary it is not, because we have the complete 3D models of both architecture and surroundings at our disposal, as well as the orientation, position and timing of the photographic campaign.

These last parameters can easily be introduced while setting up environmental parameters into the render engine, whose output will be a greyscale image describing the amount of light interacting with the polygonal model.

The grayscale bitmap – not to be confused with a common ambient occlusion map –then provides important info about the way light penetrates into the arches and along the front of the building. This image, once it is converted into a mask or an alpha channel inside the bitmap editing applications, allows a blended “passage” of the colour stored into the two textures, keeping for each one of them the more appropriate areas (fig. 8).

[6] The technique applied to the case studies of Ravenna's late antiquity buildings was developed by Juhanni Karlsson and Jukka-Pekka Lyytinen of Talvi Digital and presented at IBC 2013 conference in Amsterdam (http://vimeo.com/77394718).

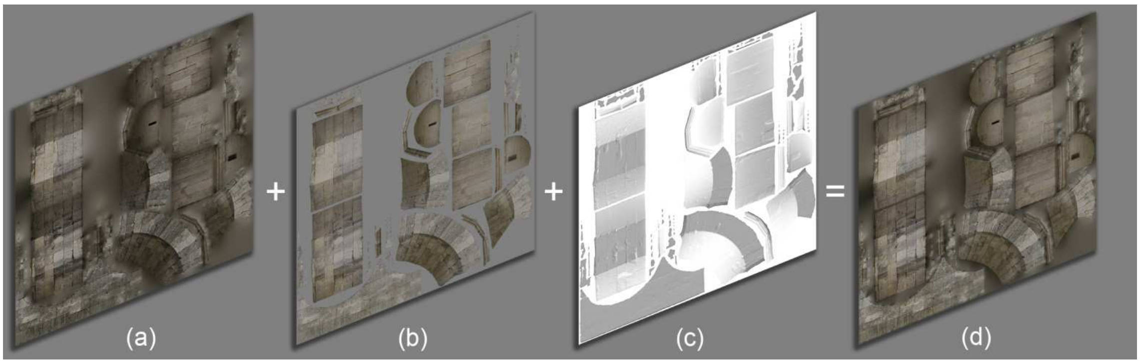

Fig. 8 – (a) texture map obtained from radiometric correction of external surfaces; (b) texture map obtained from radiometric correction of darker areas (arches, lunettes, etc.); (c) Alpha channel from baking environmental lighting into the parameter space; (d) the final image: shadows of darker areas result softened.

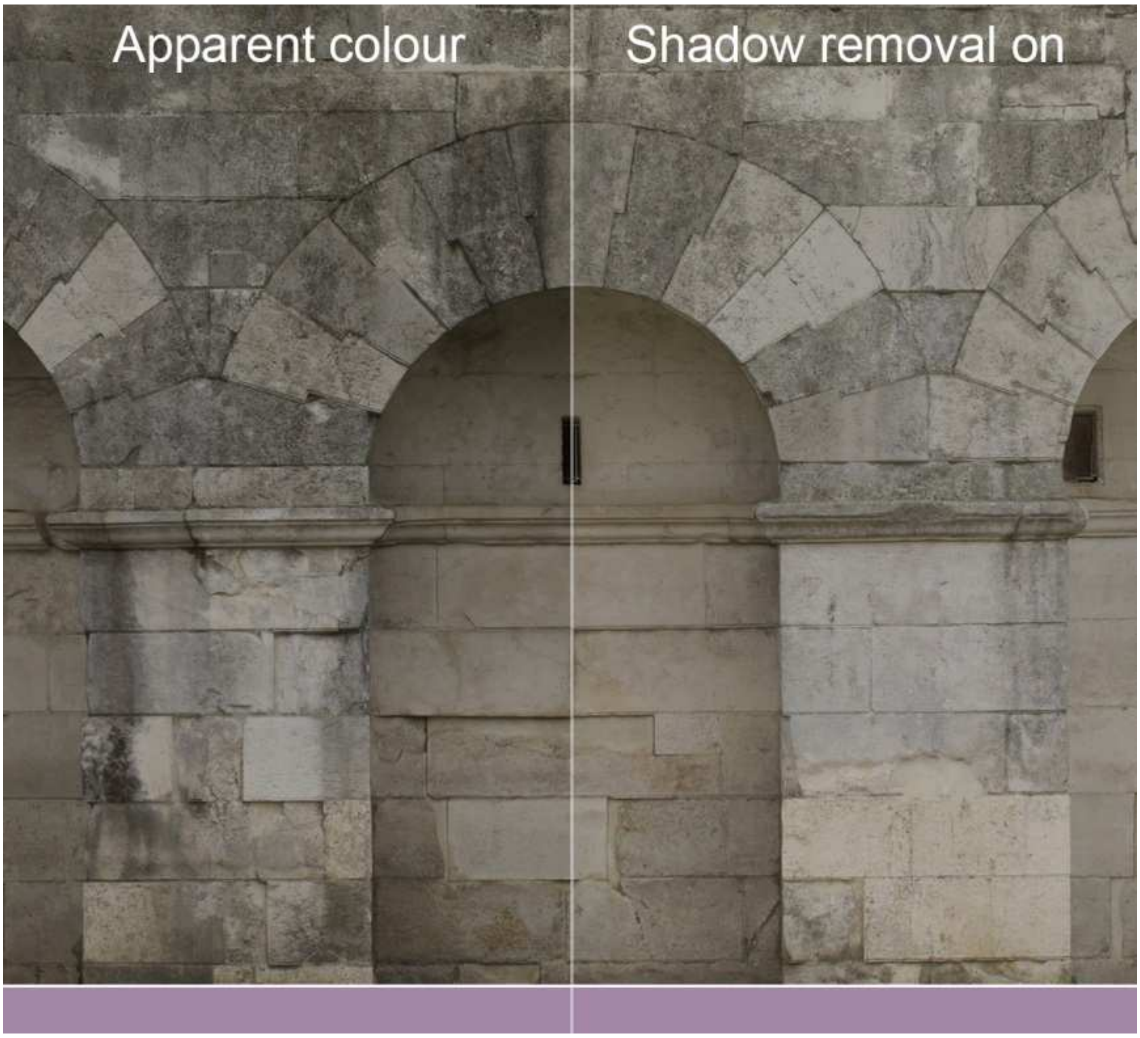

Fig. 9 – Comparison between the original texture (apparent colour) and the corrected one, obtained applying the shadow removal pipeline developed by Talvi Digital.

BRDF simulation of mosaics

A typical feature of Ravenna's ancient buildings is mosaic art. Domes, vaults and walls of many Late Antiquity buildings are covered with this kind of decoration that presents interesting points and problems uneasy to solve, in regards to their 3D simulation. In the case of the Arian Baptistery, heterogeneous materials - characterized by different BRDF behaviours - form small mosaic tiles applied to the dome's intrados: also in this case apparent colour texture from SfM cannot be considered a suitable solution inside render engines for the achievement of photo-realism.

A segmentation of automatically-generated SfM textures is then needed and its purpose is essentially to provide render engines with appropriate shaders related to different areas of the model, each one characterized by different optical behaviours.

Mosaic tiles (*tesserae*), are made out of different materials ranging from highly reflective to matte ones: they are produced throughout distinctive building techniques and materials, e.g. stone, glass of various colours and gold leaf covered with a thin layer of glass, etc. Automatic processing of SfM textures into applications like CrazyBump, ShaderMap, Adobe Photoshop plugins from NVIDIA, as well as the recent Quixel SUITE, are unsuitable for the achievement of accurate BRDF parameters.

Tests carried out among these image processing applications led to poor results in terms of realism, since they are designed for 3D artists, whose purpose is the achievement of impressive simulations rather than a reliable representation of masonry walls. Better results have been achieved during a second research phase: once automatic solutions were discarded, one or more shaders were assigned to each (u,v) island of the parametrical space using alpha channels obtained by the apparent colour texture.

In the case of the Arian Baptistery it is possible to detect two different BRDF behaviours (fig. 10):

- Approximately perfect Lambertian areas corresponding to brick and mortar, whose processing was explained in the previous paragraph (shadow removal).
- Specular and reflective areas split into two categories depending on the nature of the material (dielectric or conductor).

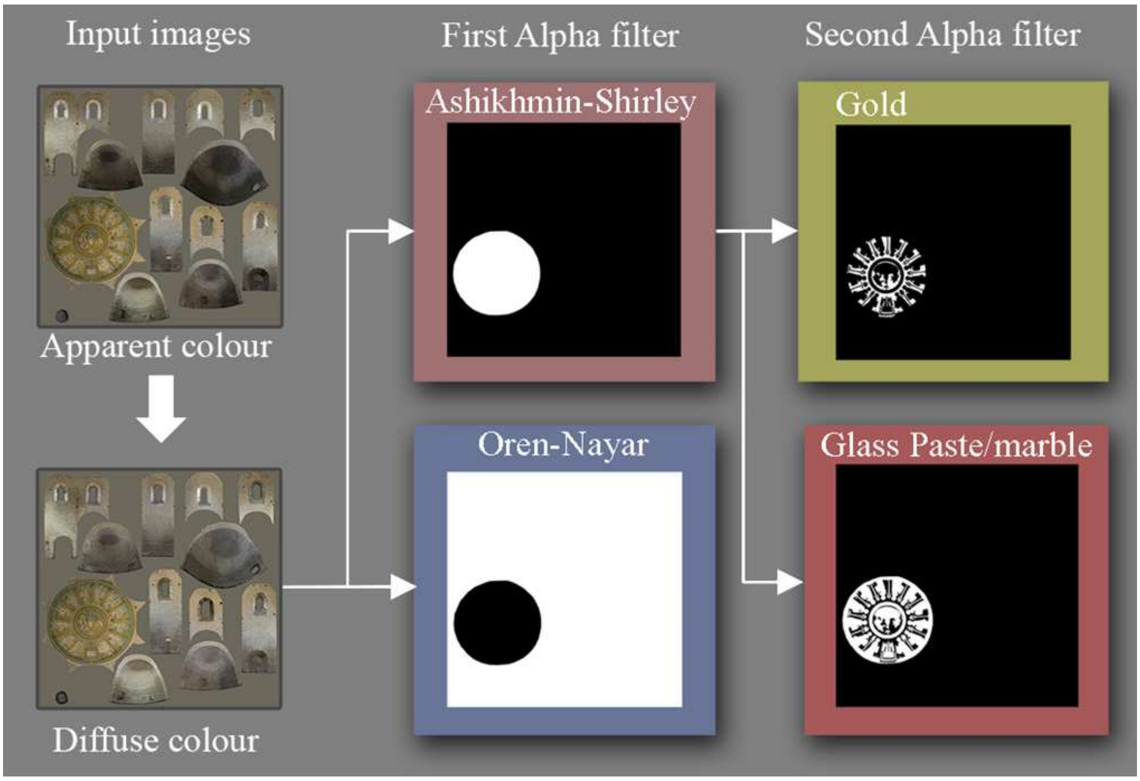

Fig. 10 – Different shaders for each kind of material or coloured tiles used in the rendering.

For Lambertian surfaces, a customization of an Oren-Nayar shader (OREN and NAYAR, 1994) was applied to the islands of the parameter space corresponding to matte materials (generally concrete, plaster, sand, etc.).

For the mosaicked intrados of the dome, different shaders are necessary in order to reproduce two different BRDF: golden areas and coloured tiles. They have different glossiness levels and reflective amounts. To both areas, a common shader with different customization was applied, an Ashikhmin-Shirley distribution model (ASHIKHMIN and SHIRLEY, 2000), which has proven to be effective with glossy and anisotropic materials. A second level of alpha channel was created to specify different mosaic typologies and to facilitate render engine to distinguish golden tiles from common dielectric materials, such as stone and vitreous glass (fig. 10).

Golden tesserae share with other metallic materials a common feature: they present coloured specularity and reflection, and in addition - due to their upper glass layer - they present the so-called “clear-coat” effect. Other tiles are simpler to simulate BRDF, as they feature a high degree of specularity and glossiness, even if they are less reflective. Ashikhmin-Shirley shader was used for both types of tiles, being flexible enough since it obeys to energy conservation and reciprocity laws; it supports anisotropic reflections (for metallic surfaces) and Fresnel effect (specularity and reflectivity increases as the incident angle decreases).

Fig. 11 – Rendered image of the mosaicked decoration of the interior dome in the Arian Baptistery of Ravenna.

Toward interactive visualisation

Once all the steps concerning geometric processing and image processing have been carried out, it is possible to export low-poly models and textures to game engines. In case of high-poly models for documentation, it is wise to use robust hardware for the production of still images and animations by means of common render engines. It is important to point out some aspects of the integrated methodology explained in this paper: this approach is more compact and easy to put into practice in comparison to time-consuming procedures, where active sensors played the main role in the creation of 3D digital data. Previous studies, despite providing excellent results in terms of visualization quality and portability of 3D contents, have shown how long and annoying the parameterization process resulted, camera resectioning, mapping and blending photographs (MERLO et al. 2012). The main problem was due to the lack of "dialogue" between applications, in particular between those coming from the entertainment field and those from the academic field of survey and measurement. Before SfM applications implemented the possibility to read and use (u,v) mapping reference systems (the product of parameterization), a long process was necessary: aligning cameras, exporting their internal and external parameters using .FBX format towards entertainment applications, un-distorting photos and then re-projecting them on meshes, etc.. Thanks to the progress in photogrammetry applications, the workflow has now gained clarity and less time is needed in order to overlap, on the same parameter space, accurate colour texture and other maps (fig. 12).

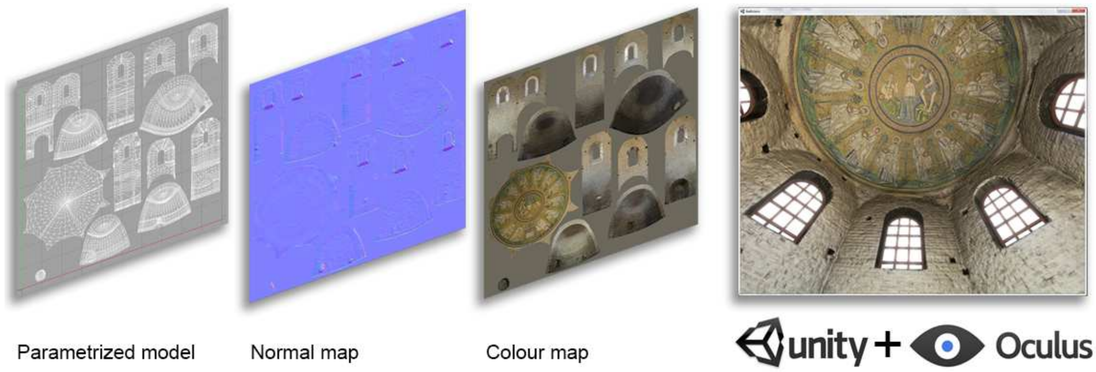

Fig. 12 – Texture set (parameterized model, normal map and colour map) specifically provided for the game engine Unity 3D and Oculus VR technology.

In addition, render to texture solution (baking), which is currently not implemented in SfM or mesh processing applications, can provide very useful potentials concerning the realisation of truly suitable textures for render engines (3D real-time interaction can exploit the increasingly robust render engine implemented in game engines). The research team opted for Unity 3D as the most fitting solution in this sense. This application, in addition to generating simulations in approximately every case and for almost all portable devices (PC and Mac computers, Android and iOS devices…), provides stereoscopic exploration of 3D digital environments. Oculus VR is a head-mounted display, also called helmet-mounted display (HMD), supplied with a small monitor (7", 17.78 cm) visualizing two computer-generated images (stereoscopic rendering) of the explored 3D environment, created through the procedure described in the previous paragraphs.

The visualization system is quite simple and is based on the use of two points of view that, through a plugin, are rendered at once and delivered to the monitor mounted on the Oculus VR; the integrated helmet/viewer provides a field of view of 110° (diagonal), while the LCD screen has a resolution of 1280×800 (16:10 aspect ratio). Each render computed in real-time is characterized by a consistent barrel geometrical distortion, corrected by pincushion effect obtained by means of special lenses in the headset: the perceived output is a spherical-mapped image for each eye.

These optical groups generate a high spherical deformation of the image that will be corrected by the plugin, that takes care of generating image purposely deformed to finally have a natural vision both in terms of perceived geometry and colour.

This device was developed for gaming and is equipped with internal tracking sensor (gyroscope, accelerometer and magnetometer) able to provide a realistic immersive perception of the user who explores a virtual environment (fig. 13).

Fig. 13 – The Oculus VR (virtual reality head-mounted display) provides the user a realistic experience. The small compact device, which has to be put on like a small helmet, visualises a stereoscopic rendering of 3D digital assets introduced in Unity 3D game engine.

The realistic experience provided by interactive stereoscopic exploration will soon become a standard, not just limited to video games, but also spreading into the field of cultural and social entertainment: museums, exhibitions, archaeological sites and monuments, whose real experience is not possible or is limited by restorations, maintenance activity and so on, may now enjoy this powerful tool.

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