Color enhanced pipelines for reality-based 3D modeling of on site medium sized archeological artifacts

Fuentes de color mejoradas para el modelado tridimensional de artefactos arqueológicos de tamaño medio localizados in situ.

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Resumen

El documento describe un sistema mejorado de procesamiento de color, aplicado como caso de estudio sobre un artefacto de la zona arqueológica de Pompeya. Este sistema se ha desarrollado con la finalidad de mejorar las diferentes técnicas para la construcción de modelos 3D basados sobre datos de la realidad y para la visualización de artefactos arqueológicos. Este proceso permite visualizar las propiedades de reflectancia con fidelidad perceptible en una pantalla de usuario y presenta dos mejoras principales respecto a las técnicas existentes:
a. la definición del color de los artefactos arqueológicos;
b. la comparación entre los flujos de trabajo basados en range-based-modeling y en fotogrametría, para entender los límites de uso y la adecuación a los objetos específicos.

***Palabras Clave**: MODELIZACIÓN 3D, FOTOGRAMETRIA, LASER ESCANER, DENSE STEREO MATCHING, PROCESAMIENTO DE COLOR, DEFINICION DE COLOR.*

Abstract

The paper describes a color enhanced processing system - applied as case study on an artifact of the Pompeii archaeological area - developed in order to enhance different techniques for reality-based 3D models construction and visualization of archaeological artifacts. This processing allows rendering reflectance properties with perceptual fidelity on a consumer display and presents two main improvements over existing techniques: a. the color definition of the archaeological artifacts; b. the comparison between the range-based and photogrammetry-based pipelines to understand the limits of use and suitability to specific objects.

***Key words**: 3D MODELING, PHOTOGRAMMETRY, LASER SCANNER, DENSE STEREO MATCHING, COLOR PROCESSING, COLOR DEFINITION.*

1. INTRODUCTION

3D models from captured data are today an established technique for archaeological research, documentation, dissemination [SCOPIGNO et al., 2011; REMONDINO & CAMPANA, 2014]. Different workflows allow today an easy and consistent 3D models construction and visualization as 'replica' of the true artifact using well-defined steps: data acquisition, data registration and integration, modeling (geometry, textures, lighting), visualization (on large screen, on desktop, on PDA, mono or stereo) [GAIANI & MICOLI, 2005].

A key step of this process is the shape and color data acquisition of the artifact.

In the field of archaeological documentation, the goal is to acquire data that fall within a wide range of cases (from 10x10 cm to 50x50 m), with the need for a precision (uncertainty) from 100 μm to few millimeters. Applications could range from small objects to architectural artifact and monument, until arriving to the landscape. This variety of cases requires different tools capable of acquiring data relating to the real world and different methods to build 3D models that represent it. These may be more closely oriented to obtain a metrical accurate 3D model, or more focused to obtain a perception of the real object.
Basically, there are two approaches to the problem: using active sensors (like terrestrial laser scanner (TLS) or structured light projectors); and exploiting image-based reconstruction techniques.
Active optical sensors [BLAIS, 2004; VOSSELMAN & MAAS, 2010] provide directly 3D range data and can capture relatively accurate geometric details and the range-based modeling pipeline [BERNARDINI & RUSHMEIER, 2000; CALLIERI et al., 2011] is straightforward. However active optical sensors are not part of the standard documentation procedure in archaeology and serve only a very special purpose [ENGLISH HERITAGE, 2011], because they have been developed from an industry-oriented perspective and only a few are really useful for 3D archaeological applications [BLAIS & BERALDIN, 2006]. Laser scanners are not as versatile as cameras with regard to capturing data, as they require time to scan the object, whereas a camera can capture a scene almost instantaneously. They acquire millions of points, even on perfectly flat surfaces, often resulting in over-sampling, and not well capturing corners and edges. They generally lack of good texture information and present limited flexibility (having minimum and maximum ranges over that they operate). To overcome this last problem different technologies are used for specific ranges:

- Time of Flight (ToF): for long ranges (>100m), with an accuracy in the single point measurement of ~6 to 10 mm;

- Phase-based: for medium ranges (~1 to 50 m), with an accuracy of ~0.5 to 5 mm;

- Triangulation-based: for short ranges (~0.1 to 1 m), with an accuracy of ~0.05 to 2 mm;

- Structured Light: for short ranges (~0.1 to 1 m), with a high accuracy (~0.03 to 2 mm), but the need a high environmental control.

Finally, active sensors are still costly, usually bulky, not easy to use (technically trained personnel are needed), they require stable platform, and are affected by surface properties (such as marble or gilded surfaces).

Image-based methods [REMONDINO & EL-HAKIM, 2006], circumvent these drawbacks, allowing surveys at different levels and in all possible combinations of object complexities, with high quality outputs, easy usage and manipulation of the final products, few time restrictions, good flexibility and low cost [ENGLISH HERITAGE, 2005].

3D modeling from images provides sparse or dense point clouds, according to the employed measurement methodology (manual or automated), project requirements and aims. For simple structures (e.g. buildings) interactive approaches are satisfactory, but for complex and detailed surfaces need automated measurement approaches. Recent developments in automated and dense image matching [FURUKAWA & PONCE, 2010; HIRSCHMUELLER, 2008; REMONDINO et al. 2008a; VU et al. 2012], allows getting dense and well-calibrated point clouds semi-automatically from images. Main drawback in the image-based methods is in that images contain all the useful information to derive 3D geometry and texture at low cost, but require a mathematical formulation (perspective or projective geometry) to transform 2D image observation into 3D information. Furthermore, the recovering of a complete, detailed, accurate and realistic 3D textured model from images is still a difficult task, in particular for large and complex sites and if uncalibrated or widely separated images are used.

Comparisons between photogrammetry and range sensors are e.g. in [BOEHLER, 2005; REMONDINO et al. 2005; GRUSSENMEYER et al. 2008].

To achieve an accurate and realistic 3D model previously mentioned capturing techniques, as a single, are not able to give satisfactory results in all situations. Image and range data could be combined to fully exploit the intrinsic potentialities of each approach [STUMPFEL et al., 2003; EL-HAKIM et al., 2004; DE LUCA et al. 2006; GUARNIERI et al., 2006; STAMOS et al. 2008; GAŠPAROVIC & MALARIC, 2012].

In a previous work [GAIANI et al., 2010] we determined, for object classes, most appropriate 3D capture techniques and pipelines, the correct instruments to be used, and the requested/needed level of detail to visually display as 'replica' each item or part of it.

In this paper we want to face two problems only partially addressed and resolved by our previous and other authors recent studies:

a. The color definition of the archaeological artifacts;

b. The comparison between the range-based and photogrammetry-based pipelines to understand the limits of use and suitability to specific objects.
We focused on the problem of data capture on the field for artifact whose volume can be inscribed in a cube from 1 to 2 meters and highly detailed. This is a critical area because, as you can see in our scanner technologies recap, it is at the limit for the use of the triangulation technology (with a lot of complexities to align, merge and edit the different scans) [EL-HAKIM & BERALDIN, 2007], and subject to inaccuracies using ToF laser scanner. The most appropriate solution is the use of phase-based laser scanner [GODIN et al., 2010], but recent tests demonstrated that the accuracy of these scanners could be not adequate when you have sculpted details with minimum feature of 1-2 mm. [KARSIDAG & ALKAN, 2012].

In section 2 we will review color detection and visualization issues in the archaeological field. In the last years, this topic received vast attention in the archaeological and in graphics fields [BOOCHS et al., 2013; DELLEPIANE et al., 2013b; HAPPA et al., 2012; MUDGE et al., 2010; SCHWARTZ et al, 2011], unfortunately most of these studies concern case with controlled illumination or are more devoted to problems of texture-to-mesh registration.

In section 3 we will address the 3D AH textured models construction pipelines comparison giving attention to the low-cost technologies based on structure-from-motion (SFM) techniques.

In section 4 we describe a new low cost color processing system allowing the enhancement of the different reality-based 3D pipelines. We have the aim to ensure fidelity of the perceived color on a consumer display. Compared to commonly used techniques, our workflow ensures camera color calibration and management using a limited number of well calibrated photos and avoids inaccuracy and multiple processing phases. It could be used inside range-based and/or photogrammetry-based pipelines and, above all, could be completely integrated in the SFM pipeline (e.g. VisualSFM pipeline [WU, 2013]), avoiding the problems of data fusion from multiple sources and limited color fidelity of the final 3D model. Our techniques consist basically in a pre-processing of the images used to define colors and shape and could be used from non-expert operators (i.e. archaeologist and architects), directly on the field, and without the need of sophisticated equipment. Workflow, methods, standards and operational best practices developed are completely device-independent; consequently, our choice of instrumentation, within certain limits, does not affect the results.

Finally in section 5 we give comparison of pipelines from TLS (ToF and triangulation laser scanner to cover the full range of active sensors) and SFM after our improvements. The SFM pipeline used is based on Agisoft Photoscan [AGISOFT, 2014], a commercial package able to automatically orient and match large datasets of images with SemiGlobalMatching-like image matching algorithm stereo [HIRSCHMUELLER, 2005].

Fig. 1- Pompeii archaeological area: the Altar of Augusto in the Temple of Vespasian.

We demonstrate the effectiveness of our method and pros and cons of each pipeline using as a case study an artifact of the Pompeii archaeological area: the Altar of Augusto in the Temple of Vespasian, a Roman temple also known as Aedes Genii Augusti. This is an artifact in marble of m. 1.10x0.90x1.30 imaged during an acquisition session in 2008.

The side that looks the entrance depicts the scene of a sacrifice: a priest pouring libations on a tripod and behind young people who give it the tools to the sacrifice, a flutist, two sergeants and an assistant with the bulls that must be sacrificed; in the background it denotes a temple with four columns, probably imitating that pompeianus. The decoration of the altar is completed, on the side facing the podium, with the representation of a crown of oak leaves, resting on a shield and two laurel shrubs, while on the short sides are depicted objects to make the sacrifice as a stick and a box for incense, under festoons of fruit and flowers.

2. COLOR DETECTION AND VISUALIZATION ISSUES IN ARCHEOLOGICAL FIELD

Color detection of archaeological artifact usually highlights many operative difficulties due to several factors. The color investigation, usually, refers to three methods [SANTOPUOLI et al., 2008]:

- transcript of a sample;
- visual comparison;
- instrumental survey.

These methods, besides to present problems beyond the ability of an actual sample of existing matter, they aren't able to ensure the correct perception of color on an RGB monitor or its faithful reproduction on a print support. No one of these methods, in fact, is able to assure a right color checking on a wide surface, and with a non-uniform color.

In this context, using digital techniques offers many advantages such as allowing identifying color and reflectance properties of the complete artifact surface, just using few camera shots.

However accurate color reproduction remains a complex issue.

The purpose to determine the color and tone level of fidelity of a digital image compared to the original document/object can be obtained by chromatic and tonal definition [REINHARD et al., 2008]. The fidelity of color reproduction depends on a number of variables such as the lighting level during the acquisition step, the technical characteristics of the acquisition system and the mathematical representation of color information throughout digitization pipeline [GAIANI et al., 2003].

The values of a color image are the result of the interaction of the incident illumination, the object geometry, the object reflectance and the camera transfer function. When illumination is reliably known, parameters for a surface reflectance function can be estimated using the image values

[LENSCH et al., 2003]. Archaeological artifacts implies outdoor settlement, where natural light characteristics are extremely complex and changeable; scenes are characterized by many elements belonging to different planes, curved surfaces reacting to light in several ways; we match with a wide range of materials characterized by different values of light reflection, porosity, transparency, etc. Therefore we cannot design a basis set of lighting conditions.

These difficulties increase using 3D reality-based models [ALLEN, et al., 2004]. The generation of a photo-realistic result essentially requires that there is no difference between a view rendered from the model and a photograph taken from the same viewpoint. Correcting the captured data relies in either obtaining high accuracy data for the object shape and illumination direction, or simultaneously solving for geometric properties, reflectance, and illumination to fit the acquired data and a model of reflectance as the Bidirectional Reflectance Distribution Function (BRDF) [NICODEMUS, 1965], or, better, the well-known Bidirectional Texture Function (BTF) to take in account of surface mesostructure [DANA, et al., 1999]. Unfortunately, state-of-the-art BRDF acquisition approaches rely on complex and controlled illumination setups, making them difficult to apply in more general cases, or when fast or unconstrained acquisition is needed.

When lightning conditions cannot be controlled, literature shows alternatives that try to measure illumination at sparse (or even single) spatial locations. These solutions - [YU & MALIK, 1998; DEBEVEC et al., 2004; ZHAO et al., 2012] lead to excellent results but are too complex to be implemented by unskilled operators and require extra acquisitions with instruments like probes or ToF scanners.

A less accurate but more robust solution is the direct use of images to transfer the color to the 3D model, using RGB color map. The basic approach, consisting in the acquisition of just the so-called apparent color and mapping those samples to the 3D model, is still widely used in most of the practical cases. A series of pictures can be taken with a digital camera, trying to avoid shadows and highlights by taking them under a favorable lighting setup; these photographs are then stitched onto the surface of the object, as described in [BERALDIN et al. 2002, EL-HAKIM et al., 1998]. The mapping method basically assigns the texture coordinates to each vertex or point of the 3D model using the collinearity equations that describe the view orientation of the 2D camera relative to the 3D object. Basic steps of color capture and rendering are generally related to model texture mapping or color-per-vertex assignment, while they are not linked to color definition.

Color capture and rendering have to deal with several issues, as: the registration of captured color and geometric data, the correction of captured data to account for surface and lighting geometry, the capturing of small scale (yet visible) geometry accounting for its effects, and problems in combining the results of multiple overlapping input data sets. It is clear that the complexity of this process exponentially increases as more images and more resolution is needed.

The most flexible approach starts from a set of images acquired either in a second stage with respect to the geometry acquisition, or simultaneously but using different devices, or finally in a unique solution (SFM techniques). In this case, illumination is not corrected at all, and the apparent color value is mapped onto the digital object's surface by applying an inverse projection. In addition to other important issues, there are a number of difficulties in selecting the correct color when multiple candidates come from different images. The basic idea is to rely on methods of adjusting overlapping images for consistency to produce an acceptable texture map.

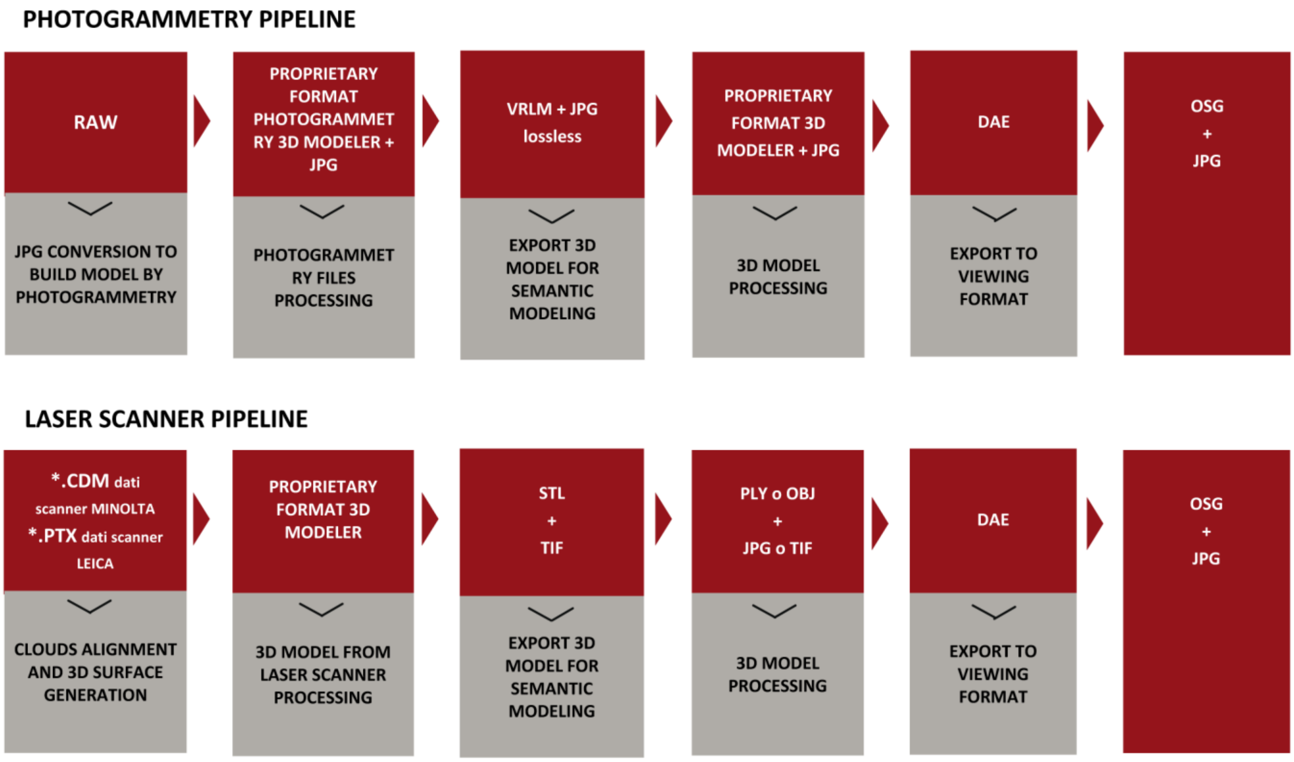

Fig. 2 – Our 3D modeling pipelines using Photogrammetry and TLS

Other solutions aim to 'blending' all image contributions by assigning a weight to each one or to each input pixel, and selecting the final surface color as the weighted average of the input data, as in [CALLIERI et al. 2008]. Again, further solutions have the goal to remove, undesirable ghosting effects, e.g., by applying a local warping using optical flow [DELLEPIANE et al., 2012]. A different class of solutions concern detecting and removing of cast shadows [TROCCOLI & ALLEN, 2005]. Finally some methods have the purpose of computing the inverse illumination [RUSHMEIER & BERNARDINI, 1999; STUMPFEL et al., 2003]. In Callieri et al. [2011] is a complete review of problems and solutions. The most critical point of these processes is related to the impossibility to achieve metric fidelity of color, texture and reflectance properties of surfaces. An acceptable goal is therefore to have at least perceptual fidelity.

3. 3D MODELING PIPELINES

Reality-based 3D modeling of archaeological artifact and sites is generally performed by means of either image-based techniques or active sensors, depending on surface characteristics, required accuracy, artifact dimensions and location, project budget, working-team experience, etc. following well-standardized workflows (Fig. 2).

SFM techniques [TOMASI et al., 1992], a recent key technology able to combine friendly use with accurate results [GONIZZI BARSANTI et al., 2013b; DELLEPIANE et al., 2013a], enable a variant of the photogrammetric pipeline where the output are dense points cloud as in the active sensors pipeline.

SFM techniques rely on matching algorithms (e.g., SIFT [LOWE, 2004]) that identify accurate correspondences among images. These correspondences are then used in SFM algorithms to estimate the precise camera pose, which are finally used as input into multi-view-stereo (MVS) methods that produce dense 3D models [HIRSCHMÜLLER, 2005; ZHANG, 2005; SINHA & POLLEFEYS, 2005; PIERROT-DESEILLIGNY & PAPARODITIS, 2006; VOGIATZIS et al., 2007; REMONDINO et al., 2008b; FURUKAWA & PONCE, 2010; WENZEL et al., 2012]. MVS algorithms simultaneously correlate measurements from multiple images to derive 3D surface information in a nearly standardized workflow: a) images acquisition, b) feature detection, c) feature matching, d) sparse 3D reconstruction, e) dense 3D reconstruction, f) coordinate transformation, g) mesh generation (Fig. 5). Once the mesh is generated, color is projected onto the mesh from images that have been registered during sparse reconstruction.

Results presents comparable accuracy to laser scanners [SEITZ et al., 2006], and recent studies [REMONDINO et al., 2012] have shown that reliability and repeatability issues are encountered when SFM methods are used for complex and long sequences; however, the performance in terms of the computed object coordinates is often surprisingly positive.

As large amount of images might lead to inaccuracy and long processing time, a small number of well-calibrated photos - ensuring that mesh is fully covered - can be used for texture mapping by parameterizing the mesh surface [PIETRONI et al., 2010], as in our case.

SFM techniques guarantee costs considerably lower compared to other techniques.

Unsolved issues, as always in the photogrammetric pipeline, involve:

- efficiency of photogrammetric processing algorithms that can drop out for limited image quality, or certain surface materials to be acquire, resulting in noisy point clouds or difficulties in feature extraction;
- known distance or Ground Control Points (GCP), required in order to derive metric 3D results;
- variations from the use of different cameras by different working groups, that can affect many photo-consistency-based MVS reconstruction algorithms [XU et al., 2006]
- color capture, management and rendering.

4. COLOR PROCESSING

Our color processing essentially consists of a thoughtful revision of a classic pipeline of image calibration and enhancement using standardized methods, and on the basis of appropriate best practices to ensure color consistency and resolution in the acquisition and visualization procedures. Starting from captured raw images our workflow includes:

1. exposure compensation
2. optical correction
3. image denoise
4. sharpen
5. color balance.

The first two are a trivial step done using DxO Optics Pro version 9 using the DxO camera-lens database [DxO, 2014]. In addition, the third one was done in DxO Optics Pro to adjust edge definition in the image, and aims to compensate digital camera sensors and lenses image blurring explicitly, disabling it on-camera, without create artifact or leaving unwanted blur.

As reported in Kawakami et al. [2005], to reliably estimate the illumination colors in outdoor scenes analysis and filtering of noise is a key step, since its presence is inevitable in natural images, due to the sensors, the medium, or noise inherent in the objects, such as dust and imperfect painting. In our case it is common to have areas in the sun and areas in the shadows in the same image, with vast luminance differences, or underexposed images mixed with overexposed ones, all in the same dataset.

Fig. 3 - Detail of an image with exposure compensation and optical correction applied in DxO.

To give a simple solution to this complex problem, we choose to employ the patented commercial software Imagenomic Noiseware 5 [IMAGENOMIC, 2012; PETROSYAN & GHAZARYAN, 2006]. Noiseware uses hierarchical noise reduction algorithms, allowing easy solution for all the cases that we can encounter. It supports good quality, is easy to set-up, but is weak in detail. However this is not an effective problem because the fine detail captured in the images is four times oversampled compared to the geometric one, and it is, in any case, unnoticeable in the finished 3D model.

Fig. 4 - Detail of image denoised and color balanced.

The standardized method for evaluating and expressing color accuracy includes: a) a physical reference chart acquired under standard conditions; b) a reference chart color space with ideal data values for the chart; c) a means of relating or converting the device color space to the reference chart color space; d) a means of measuring and displaying errors in the device's rendition of the reference chart.

A key step, in this process, is the determination and consequently the use of an appropriate color space in which to render images on screen. We used the 8-bit Adobe RGB color space for textures acquisition and processing, and 8-bit sRGB as texture color space in order to display images of 3D models rendered on screen. This last choice is motivated by many reasons. The sRGB is the default color space for HTML, CSS, SMIL and other web standards; it is the standard color space for many input devices (cameras) and LCD monitors and video-projectors. This color space is also implemented in the OpenGL libraries, which our rendering software is based on [OpenGL, 2014]. Main drawback of the sRGB color space is the gamma value built inside. A second drawback is the range of colors, narrower than that of human perception (i.e., it does not display properly saturated colors such as yellow cadmium and blue cobalt). This last downside is not a problem in our case, because these colors are rarely found in our case studies.

In our processing the reference chart color image is neutralized, balanced and properly exposed for the gamma of the reference data set. Color balance was performed against a series of Gretag Macbeth Color Chart using X-Rite ColorChecker Passport Camera Calibration to create an ICC profile that was assigned to the RAW image. The color accuracy was computed in terms of the mean camera chroma relative to the mean ideal chroma in the CIE color metric (□ E*ab), using as reference values for all the color patches the 8-bit measured in the Adobe RGB color space by Denny Pascale [PASCALE, 2006]. Imatest Studio software suite version 3.9 [IMATEST, 2014] was used to evaluate the quality of the workflow and the master images. Since two shots cannot be taken in the same frame we developed a protocol to use the same calibration for groups of images with the same features (i.e., orientation, exposure, and framed surfaces), that means no more than 4

-5 different profiles for each building modelled, thereby maintaining consistency in the process and the results. □ E*ab surveyed varying between 3,5 and 5. Conversely, it could happen that the color of incident illumination spatially varies inside a single image.

From an operational point of view it should be noted that the calibration process leans to give results less reliable as wider is the angle between camera axis and the plane where the target lays and/or the difference between its light reflectance index and artifact one. Cause these conditions, in fact, the target leans to reflect more or less light than the material where is placed. The position of the target far from the photo center point is another element that affects the quality of calibration.

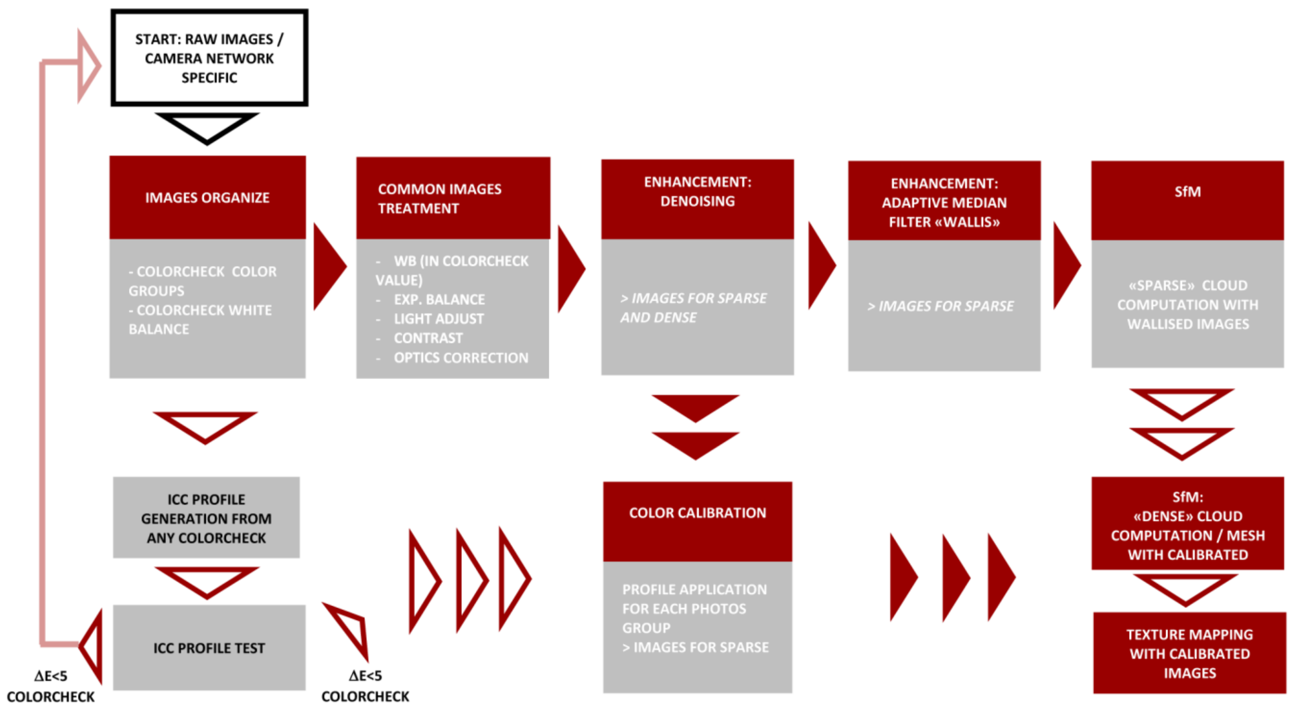

Fig. 5 – Our 3D modeling pipeline using SFM techniques.

5. Reality-based 3D and low-cost photo-modeling: a parallel

We experimented our customized pipelines (Fig. 2 and Fig. 5) using a Minolta Vivid 900 triangulation-based and a Leica ScanStation 2 ToF laser scanners and a series of images captured with a Nikon D200 digital camera equipped with a Nikkor 18-135 mm zoom lens, used at focal length of 18 mm.

The Minolta Vivid 900 is characterized by a high rate of capture/scanning (307,000 points in 2.5 seconds) and high flexibility, with the ability to scan variable volumes (from 100x80x40mm up to 1200x900x400mm) using three interchangeable lenses. The Leica ScanStation 2 is capable of a range of 134 m with albedo of 18% and a scan speed of up to 50,000 points/sec.

The Nikon D200 digital camera has a CCD sensor 23.6 x 15.8 mm, resolution: 3872 x 2592 pixels, and pixel size: 6,1 □ m. Dataset consists of 50 photos in RAW format at maximum resolution.

For the SFM pipeline, based on Agisoft Photoscan, besides our standard color processing, we preprocess images masking grass, elements occluding (i.e. railing), or in the background, to isolate the subject. This allows a better quality of the final mesh of the models as demonstrated by other authors [GONIZZI BARSANTI et al., 2013a].

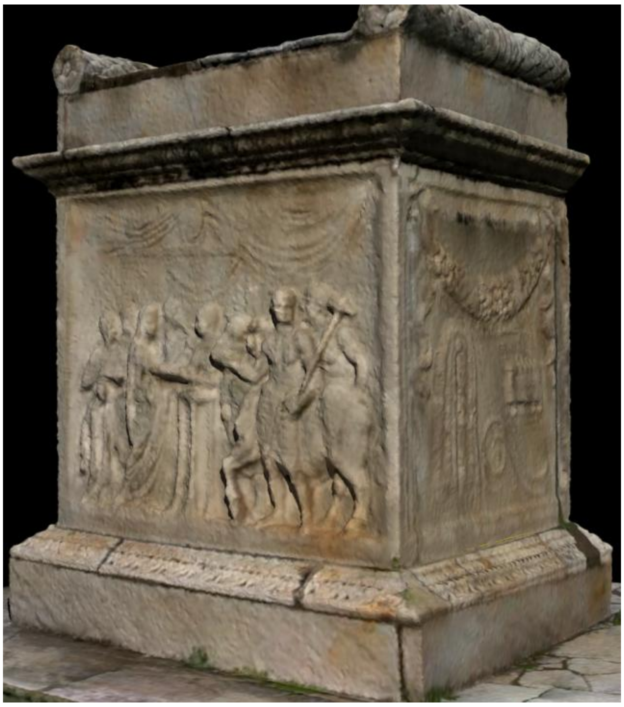

Fig. 6 - 3D model from LaserScaner ToF data.

Fig. 7 - 3D model obtained from Photoscan processing.

For texturing the 3D models from the laser scanner data we used MeshLab software [MESHLAB, 2014] for image alignment [CORSINI et al., 2009].

The results of our trials are two series of 3D models Altar of Augusto:

- Three models of the bas-relief slab depicting the scene of a sacrifice (see Section 1) from all the three pipelines;

- Two models of the whole altar from the ToF laser scanner data and the SFM pipeline.

The mesh of the final 3D models after filtering and decimation with control of quality (maximum distance of the models before and after processing less than half of our tolerance) are as follows:

MODEL: Bas-relief	*#Points*	*#Triangles*
Leica Scanstation 2	56.453	110.844
Photoscan	86.596	172.097
Minolta Vivid 900	566.032	1.127.232

MODEL: Altar	*#Points*	*#Triangles*
Leica Scanstation 2	193.215	354.413
Photoscan	935.000	1.866.298

In order to evaluate quantitatively the processing loss, a comparison between the initial and final models was done with Innovmetrics Polyworks [INNOVMETRIC, 2014], measuring the amount of differences and the presence of possible gaps. The final deviation between them resulted in the ± 0.3 mm range, that was considered negligible respect to the main details, resulting larger than few mm. We do it this comparison registering the models together for the final models from the different techniques.

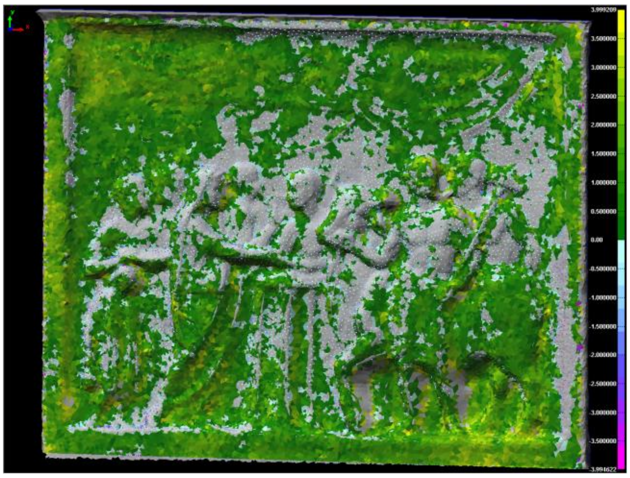

Fig. 8 - Comparison ToF and Photoscan bas-relief meshes: range error ±3.59 mm (98% p.ts).

Fig. 9 - Comparison Triangulation LS and Photoscan bas-relief meshes: range error ± 1.91 mm (99% p.ts).

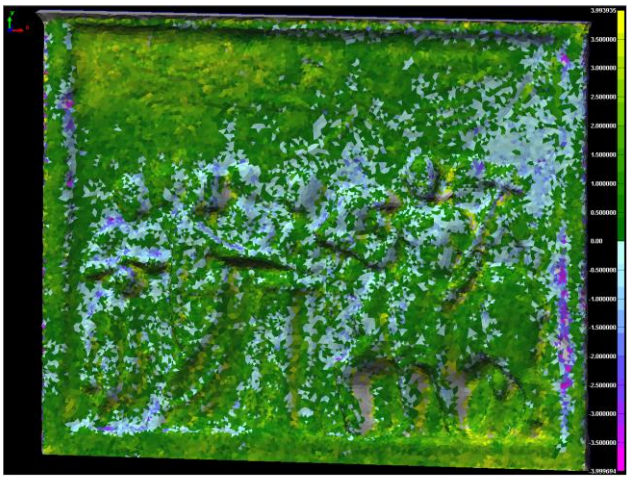

Fig. 10 - Comparison Triangulation LS and ToF bas-relief meshes: range error ±0.635 mm (98% p.ts).

The comparison between the three models of bas-relief shows values of of almost 95% of points within the range of ±1.91 mm, for models obtained with Triangulation-based and image-based; within the range of ±0.635 mm almost 98% of points of models obtained with Triangulation-based and ToF; within the range of ±3.59 mm almost 98% of points of models obtained with image-based and ToF.

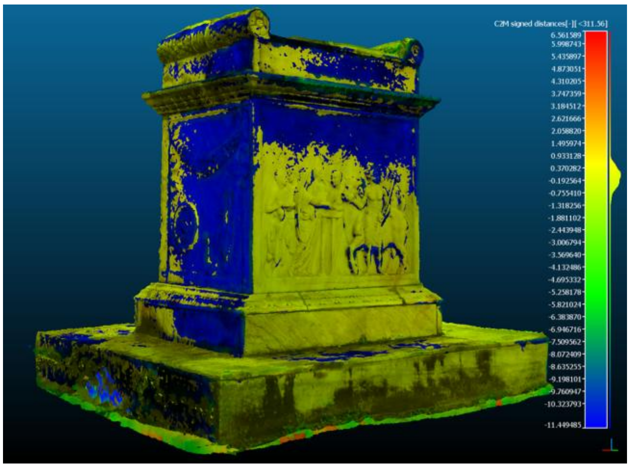

Fig. 11 - StdDev between ToF and Photoscan whole meshes = 1,633 mm.

The comparison between the two models of altar, obatined with Tof and image-based shows values of about 95% of points within the range of ±0.526 mm.

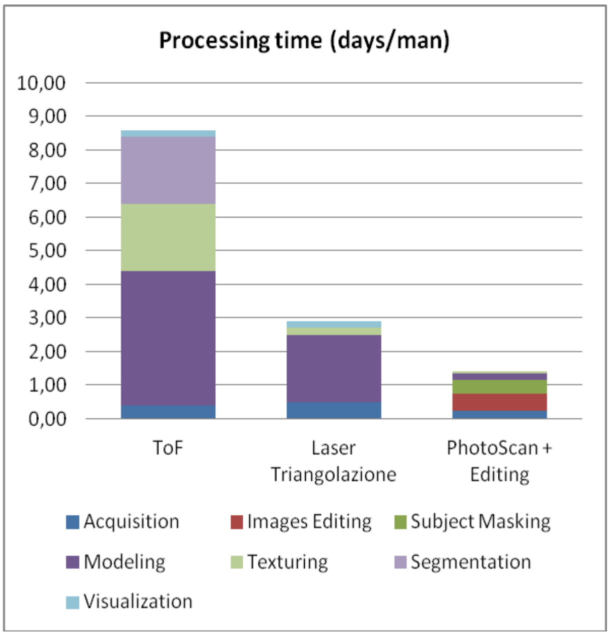

Fig. 12 - Parallel between modeling time using different pipelines.

Fig. 13 - Detail of bas-relief 3D model textured (l) and wireframe (r): Triangulation-based (top); Photoscan (middle); ToF (bottom)

The amount of these values, in both series of comparisons, may be intrinsic to the laser technology (i.e. beam penetration inside the marble), and to the problem of scale that characterizes the photomodeling. The 3D model obtained from images, in fact, has to be scaled according to a known length, which generally does not have the same accuracy of the measurements made with the laser scanner.

Whereas size and material of the object, the high level of detail of the final models and the limited differences resulting can be considered satisfactory.

The results shows as 3D models from SFM pipeline, even if is relatively easy to use and useful to be used by unskilled operators, can assure positive performance in terms of the computed object coordinates and rendering of the microscale compared with a ToF laser scanner, and absolutely comparable with those obtained by a triangulation laser scanner, though obviously with dimensional accuracy lower than the last.

At last we must not forget the overall cost in terms of time/man, required to complete the entire process, in the three different pipelines.

As we see in Fig. 12, which shows the time taken for each process, this comparison, in term of accuracy/quality obtained and cost, can allow a proper assessment on the type of pipeline and equipment to choose.

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