THE MONUMENTS RESTORATION YARD: A VIRTUALIZATION METHOD AND THE CASE OF STUDY OF SALA DELLE CARIATIDI IN PALAZZO REALE, MILAN

M. Gaiani [a], L.L. Micoli [a], M. Russo [a]

[a] Dept. INDACO, Politecnico di Milano, Italy - (marco.gaiani, laura.micoli, michele.russo)@polimi.it

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ABSTRACT:

In this paper we present a method for applying VR techniques to simulate and analyze restoration projects of architectural monuments, starting from real world data. Our method is meant as a visualization and collaborative design tool and as a study aid in virtual rooms. We address the main issues in real-time visualization and interactive manipulation of highly textured surfaces. Moreover, key steps are specified for outlining a methodology to build from real world data and visualize digital architectural and archaeological models. Large attention will be given to reflectance capture problem for architectural buildings and color calibration problems in CRT projection systems. As a case study, we present the application of our method to the restoration yard of the XVIII century Sala delle Cariatidi of Palazzo Reale in Milan, Italy, a masterpiece hall of the Italian architect Piermarini.

INTRODUCTION

Nowadays, the restoration of a building or a monument is generally considered slightly more than a cleaning exercise of the surfaces ravaged by time, perhaps with some substitutions or replacements. Nevertheless, many case studies show that a restoration project depends on many factors and it's frequently necessary to set up a restoration site – often on just a small sample – in order to be able to assess the outcome. Two of the possible limits of such procedure are its invasiveness within the monument and the impossibility to study alternatives, leaving the overall result to the restorer's imagination.
The use of a virtual model in order to check out different restoration solutions, made possible by 3D modeling technologies, introduces a novel attracting scenario.
The Virtual Prototyping and Reverse Modeling Lab of the INDACO Department of Politecnico di Milano has recently developed a methodology for simulating restoration hypothesis, that, using virtual reality environment, can replace or support the traditional restoration yard, reducing the most invasive operations and allowing their encompassing to the entire restoration area.
The key point of the system is the preservation of color consistency along the whole virtual reality pipeline, from the data acquisition to the stereo visualization into a virtual room, a crucial requirement to have a correct simulation of the restoration project and extant state.
An easily applicable and low cost methodology was defined in order to avoid a typical Italian approach to keep low the restoration costs: the deliberate elimination of the survey and analysis phase from the restoration project.
Finally, we dealt with the issue of color management for visualization using OpenGL API, an extremely limited system compared to the perceptive quality of the human eye and to that reproducible with analogical systems.
This paper analyzes such issues and describes our pipeline from data acquisition to semi-immersive visualization, applied to a specific case study: the "Sala delle Cariatidi" (Hall of the Caryatides) of Palazzo Reale a Milano. Built in 1773, it is one of most important works of the neoclassic architect Giuseppe Piermarini.

Figure 1. Milan, Palazzo Reale, the Sala delle Cariatidi at beginning of XX century

Figure 2. Milan, Palazzo Reale, the Sala delle Cariatidi today

The Soprintendenza per i Beni Culturali della Lombardia and the Istituto Centrale per il Restauro started an experimental restoration yard to evaluate some restoration hypothesis of this hall, with the aim of discovering the right procedure to bring back a coherent image of the altered space. Such approach made it possible for our team to be involved in the project on the virtual yard side. Our goal was to allow more extensive analysis, independently from the physical availability of the object, and a more flexible evaluation of the visual impact of restoration hypothesis. The Virtual Prototyping and Reverse Modeling Lab of the INDACO Department was involved in this part of the project, working on the virtual reconstruction of a portion of this space and the simulation of different project hypothesis.
The overall restoration project of the Sala delle Cariatidi is articulated in two different phases. The first one is focused on the damaged but still surviving decoration. The purpose is first of all to fill the most visible gaps, complete the peeled plaster and restore the geometric and volumetric balance of the Sala.

1. THE METHODOLOGICAL FRAMEWORK

The methodological framework presents 2 fundamental issues:

a) 3D color and shape capture of the actual state of the monument;
b) semi-immersive visualization on a large screen.

A fundamental step to build a 3D database for Heritage architecture and archaeology is 3D shape and color data capture of the current state of the artifact. Today this is a well-defined methodological direction, along which in the last years the implementation of digital photogrammetry and 3D active vision techniques has moved toward. This has determined the rise of 3D modeling techniques as a working practice on historical buildings and archaeological artifacts.
In general, the pipeline for building 3D models from real-world is today clear and well-defined in the following step: data acquisition, registration and editing, modeling (geometry, texture, illumination), visualization (mono or stereo, immersive, semi-immersive on large screen) (Gaiani, in print).
In addition to this, there is the possibility of exploiting the new visualization domain offered by virtual reality systems.
At the end of the pipeline the use of virtual walls with retroprojection system on flat-screen, allow to have projected surface for a 1:1 scale project, both for orthogonal projection (such as large blueprint) and perspective projection (so to show both concave and convex objects). This configuration removes the problem of the shades produced by the observers, shows images without distortion and allows an excellent vision from every point of view. The project-team can therefore interact directly on the 3D stereoscopic model and evaluate the different solutions as being in front to the real object. From a visualization point of view, this allows to reduce the unnatural distance between visualized objects and users (i.e. in desktop system because of the screen size) or in other configurations (i.e. hemicylindrical, because of the impossibility to interact). In this way, when dealing with restoration works without a clear "a priori" etymological and operative approach and with a strong projectual feature, the users can use a suitable platform for the visual simulation.
The model generation of the Sala delle Cariatidi was divided into three main stages:

a) Data capture to determine the actual state of the hall, establish the three-dimensional geometric database needed to develop the virtual model and take photographs of the surfaces;
b) Data processing: this involves processing the captured data to produce the polygonal 3D geometric models, with varying degrees of accuracy and compatible with the various visualization requirements of the project. The geometric base taken as a reference and the corresponding mapping of the surface textures were optimized in order to be used in a virtual reality environment. Special care was given to the interactive management of the various levels of detail in the model;
c) Project simulation (El-Hakim, 2004): this involves modeling of some of the possible projects emerged from the restoration study. The aim was to be able to carry out a complete assessment of the different possible solutions.

The application of such stages referred to a typical 3D acquisition procedure: acquisition and creation of geometrical model and its texture mapping (Bernardini, 2000).
The further data visualization in a semi-immersive real-time environment on a large screen was carried out through:

a) Conversion of the geometry into a polygonal model using tessellation;
b) Optimization of the textures to use hardware texture mapping techniques;
c) Set up of an illumination model matchable with real-time scan-line rendering system and stereo visualization without loss of luminosity level and quality of the diffuse component of the lighting;
d) Geometric and color calibration of the visualization system and digital workflow management of the end-to-end color in order to maintain coherence;
e) Definition of virtual avatar features and camera parameters to have correct visualization (in perspective and/or parallel projection) (Li, 2000).

Figure 3. The simulation of the Sala delle Cariatidi restoration yard at Virtual theatre of the Dept. INDACO

2. COLOR CAPTURE PROBLEMS FOR VISUALIZATION ON RGB DIGITAL SYSTEMS

The aim of chromatic and tone color definition is to identify the fidelity color and tone level of a digital image compared to the original or intermediate document used. The color reproduction coherence depends on a number of factors, such as: illumination level during acquisition, sensor characteristics, mathematical representation of color information along the whole digital pipeline. The principal reasons of the mismatching between colors are manifold and well described in literature (Gaiani, 2003).

In our specific case, the fundamental problem during acquisition is looking for relationships between incident and reflected light in a surface point. In general, the solution of this problem requires understanding and controlling environmental and artificial light sources over the measurement set. The color capture of masonry faces and historical architectural handmade is a very complex problem, because it's deeply connected to subjective aspects of visual perception, objective light source characteristics and the visualization modality. An accurate capture of the visible spectrum is quite difficult, especially if it's not well distributed (Seidel, 2001). The problem becomes even worst when we need to visualize 3D models taken from real objects, for which we need to identify color, texture, reflectance property and normal surface directions. For these reasons, if it's not possible to ensure the measured color fidelity, a basic requirement is to ensure the fidelity of perceived color.

Usually, in the restoration field, three methodologies are employed for color registration:

- sample transcription;
- visual comparison with color atlas (i.e. the 'Munsell book of color');
- diffuse reflectance measurement with instruments like colorimeters, spectrophotometers or telephotometers (Santo-Puoli, 2000).

Nevertheless, none of these procedures is able to guarantee the correct color perception on an RGB system for large surfaces.

The use of digital cameras (or analog cameras and following digitization of images) and software post-processing with color temperature control, vice versa, allows to identify color and diffuse reflectance of an entire building with just few shots and chromatic reproduction of a sample zone with very high approximation.

In case of built surfaces, we can approximately evaluate them as opaque, thus omitting the interreflection problem and carrying out the reflectance control using chromatic and reflectance sample patches like the Kodak or the Macbeth color control patch. The patch reference used along the entire digital pipeline allows to maintaining color consistency and to perform the typical white balance operation, for decreasing the influence of the light source on the acquired color of an object: the values of the tristimulus are multiplied by constant factors, so that the color of the lighting source is registered as white. The white balance satisfies a twofold goal. First of all, it is used for balancing the response of the sensor channel, which derives from the differences in the efficiency of color filters quantum and of sensors combination. In the second place, it helps to evaluate the ability of the human visual system to subtract the luminance color from the whole and approximately preserve the appearance of the object, according to a process know as "chromatic adaptability". The white balance was obtained by a fixed approach realized with a know illuminant (in our case, the patch's known values). The use of a color bar also allows an efficient color management on desktop device-independent color computer, because it's based on a standard and independent measurement system, relying on an unique color space to consistently transfer chromatic information between different devices from digitalization to visualization.

For such reason, in our case, both for texture definition and calibration of acquisition and visualization devices, we used the sRGB color space developed by Hewlett-Packard and Microsoft as a device-independent color space and became the International Electrotechnical Commission (IEC) default color space for multimedia application (IEC 61966-2-1). It is a rendered space based on the features of a CRT reference monitor: the standard defines the relationship between the 8 bit sRGB values and the CIE 1931 XYZ values measured in comparison to the reference monitor. The reference monitor's white-point and primary colors are defined by the ITU-R BT.709. This standard does not describe either the code method for image's data in the sRGB space, or how to map an output space (Bäuml, 2001; Wandell, 2000; Süsstrunk, 2001).

Each picture was associated with at least one Kodak color bar and a Kodak Gray Scale QT 14. In the Kodak Gray Scale QT 14 the grey is made of 20 density shades, with an increment step of 0.10 and relative density values starting from a 'nominal white' between almost 0.05 and 1.95. The background approximates a neutral grey up to a 18% value, to neutralize dazzling and other near effects. The marked "A", "M", "B" zones are pre-determined tone points to immediately allow their tone measurement during the acquisition setting and the file elaboration. The "A", "M" and "B" areas correspond to the reflection density values of 0.0, 0.70 and 1.60, which represent the average of highlights, medium tones and shades values.

The Kodak color bars have two visual aids: a grey scale and a SWOP (Specification Web Offset Publication) printed Color Patch. Both give information about tone, scale, color of the image. It is also included a combination of three colors with the same CMY, in order to differentiate a three-color black from a single-color black. Lighter colors correspond to a printing effect equal to nominal tone quarters, with a 25% aim. As in the greyscale bar the background approximates to 18% a neutral grey.

The Kodak greyscale bar is more suitable as it derives from a photographic process and it's more consistent throughout its copies. Vice versa, as the Kodak color scale bar is reproduced with a typographical process, it's less reliable and must be employed with much more awareness.

The color or greyscale bar allows performing the white balance, in order to minimize the influence of the lighting source over the captured color of an object. In the image processing phase, such procedure allows to determine the present dominant colors, confronting the sample color patch reproduced in the image with the original color patch and eventually making corrections to ensure a correct color reproduction.

Finally, some remarks about the tone depth. In digital modeling there isn't a clear separation between the shape model and the appearance model (Rushmeier, 2001). The microstructure scales and their rendering was originally described by Kajiya (Kajiya, 1986). Actually the classification of each feature depends on the whole scale of the scene to be rendered. In a building's façade, the aspect of a single brick can be captured and represented as a function mapped on a plane surface. A closer view may require to directly modeling a single brick and a different capturing method.

However, in general a physically-based material rendering requires the definition of the bidirectional reflectance distribution function (BRDF) or, better, the well-know Bidirectional Texture Function (BTF) (Rushmeier, 1998) (Dana, 1997). Nevertheless these methods are difficult to be applied outside a lab environment, because a large part of incoming light is practically incontrollable (something typical of architectural artifact). In the experience of the Sala delle Cariatidi we have noticed that generally for opaque objects with quasi-planar surfaces and real-time rendering output, a simple RGBXYZ formulation can assure an excellent perceived quality.

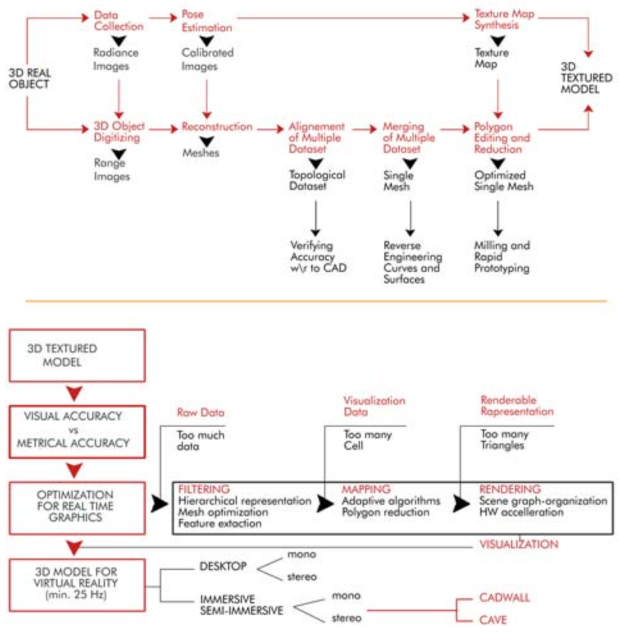

Figure 4. Our pipeline: top 3D modeling from real-world data, bottom the visualization process.

3. THE VISUALIZATION SYSTEM IN USE

The visualization of a portion (about 6 x 12 meters) of Sala delle Cariatidi on a 1:1 scale requires an high resolution visual device with wide field of view. Such field must be comparable with the human field of view, which is well known to be 208° horizontally and 120° vertically, presenting therefore a proportion similar to 16:9.

The adopted system is the Virtual Prototyping and Reverse Modeling Lab VideoWall, equipped with a 5.00x2.2 meters flat screen. The system allows high resolution, very interactive visualization, and excellent control of the project quality. The screen is made of a single rigid acrylic sheet with only one transmitting element, which offers a good luminance gain. The projector technology is an extremely flexibile Cathode Ray Tube (CRT), capable of high image quality at low cost and absence of latency in the image reproduction (which allows to reduce the overall latency of the system) .

An active stereo is enabled by two CRT projectors BarcoReality 909. This system allows high scan frequencies (over 240 Hz) and features 9” fast-phosphor green tubes offering a wide visualization dynamic range, from bright highlight to dark shadow areas. Compared to the brightness available with DLP projectors, the limited brightness of the CRT projectors (maximum 300 ANSI lumens) is well balanced by color fidelity and high resolution. Furthermore, the linear horizontal distortion at 1280 x 1024 pixels is < ±0.25 %.

Finally, the system is equipped with edge blending between the two projectors: this avoids the problem of the black line on the screen’s centre, due to the closeness of the two projectors. The solution consist of overlapping the edges of projected contiguous images and making a progressive transition of luminance and color between images, in order to obtain a coherent shading effect from the two distinct signals.

Nevertheless, the most original feature of our virtual room is the visualization engine: a graphic cluster platform based on Microsoft Windows OS. Traditionally, multi-screen display environments have been driven primarily by powerful graphics supercomputers, such as SGI’s Onyx systems. Featuring shared-memory multi-processing and multiple synchronized graphics pipelines, these systems provided a stable and flexible platform for high-performance virtual reality and visual simulation applications. Unfortunately, nowadays they are still extremely costly whereas their performances are beginning to be comparable with high-end PC. During the past several years, high-performance and feature-rich PC graphics interfaces have become available at low cost. This new availability allows building clusters of high performance graphics PCs at a reasonable cost, from 1 to 2 orders of magnitude less expensive than systems based on a graphic supercomputer (Staadt, 2003).

Using the most diffuse operating system, we have the additional advantage of exploiting all the software developed on such platform. This makes such solution particularly versatile and suited from many points of view. For example the ICC management allows to quickly obtaining the gamma congruence between OS, videoprojectors and acquisition system. Furthermore sRGB can be used as standard profile.

Our PC cluster is based on two dual Pentium Xeon 3.0 Ghz equipped each with a 3D Labs Wildcat 7210 graphic card and 2 Gb of RAM and is organized as a master–slave architecture interconnected with a Gigabit Ethernet.

Cluster-based rendering engines can generally be described as the use of a set of computers connected via a network, using application programming interfaces (APIs) such OpenGL or DirectX. An important issue, however, is that the programming model for shared memory systems and clusters differ significantly. In shared memory graphics systems, the programmer does not have to worry about questions such as sharing data among different processors or distributing rendering information between different graphics engines. In cluster environments, it is explicitly necessary to deal with these issues and this might spawn some complications in the system setup. For those reasons, almost all virtual theatres installed in Italy are currently based on SGI technology and Irix OS, generally more affordable and modular. Or they are equipped only with one Windows PC exploiting the dual-view mode of high end graphic cards, but with a performance loss of 50%. Using a cluster-based approach requires the solution of problems such as data management and distribution, output synchronization and event handling. Solving these problems for an application can be very tedious, time-consuming and error-prone. However, this solution allows balanced distribution of computing power and graphics (i.e. in our case 2 PCs and 2 graphic cards for 2 pipes) and graphic and computational power at least equal to that of memory shared systems. Thanks to the spread of a widely adopted operating system, this solution also permits to modify the current situation in which designers or architects can verify and show their project only with the help of a specialized operator managing dedicated hardware and software.

The software package used for the visualization is a customized version of Opticore Opus Studio, the actual standard system in the industrial design field. The rendering system is a typical real-time scanline scheme based on Cosmo Open Inventor (SGI) libraries. To have full global illumination, we need to use multi-pass rendering and pre-computed textures or, more easily and quickly, pre-computed and pre-filtered environment mapping methods; our system support the Brian Cabral et alii SGI Clearcoat360 implementation (Cabral, 1999).

Figure 5. Phases of construction of the lightning environment map

4. COLOR CALIBRATION PROBLEMS IN CRT PROJECTION SYSTEMS

The CRT system calibration is a fundamental requirement to obtain fidelity between original and represented color. In our case, if it isn't possible/necessary to guarantee the full multispectral image fidelity, we however need to guarantee perceptive fidelity. Because the apparent image quality on the screen is dependent on the quality of the observer visualization system, the appearance color values are then dependent on the monitor's calibration and the observation condition.

The additive color systems are based on the three primary colors additive mix capacity of the human viewer: red(R), green (G) and blue (B). These systems include CRT and LCD monitors and CRT and digital projectors.

This viewed light is mapped to the input values (pixels or voltages) using the *intensity transfer function* (ITF). The ITF of a projection system is the non-linear, power function called *gamma function*, primarily defined by the graphics card of the electron beam that excites the phosphors. Most modern monitors and projector are manufactured such that they have identical gamma functions. The shape of the function can be modified, however, simply by changing the contrast and brightness adjustments on the display. The ITF is influenced by the system's operation on graphic gamma's setting and every application involving projector's color, contrast and brightness.

The intensity of emitted light (luminance) by each phosphor depends on the control tension, not according to a linear way but to the following power law:

$$L/L_{max} = (V/V_{max})^{\gamma} \quad (1)$$

where γ = positive number depending on the monitor (normally ≈ 2.5),
L_{max} = phosphor's maximum luminance obtained with the maximum control tension of V_{max}.

In theory γ doesn't dependent on phosphor, but this dependence does exist due the constructive imperfection of electron tubes. If the RGB tensions is modified (gamma correction) before they guide the tube, the non-linear luminance dependence can be correct. The adjustment is possible with a conversion table (lookup table) stored in the PC graphic card, which allows using $(V/V_{max})^{1/\gamma}$ instead of V/V_{max} to control the electronic tubes.

Characterization of additive systems is fairly easy because there is a linear transformation between RGB intensity values and CIE tristimulus values. This transformation can be defined by measuring the primaries red, green and blue. For most display technologies, this creates a 3x3 matrix transforming from RGB intensity to XYZ, so that *(X,Y,Z)= F(r,g,b)*.

To obtain a good color reproduction, it is required input and output correspondence of primary's color and relative luminance. In such sense, monitor's calibration means the transaction from a 'native' to a known and precisely fixed situation. The calibration process is performed in three steps, which happen or might happen at the same time:

1. Measurement of the monitor initial values: chromatic coordinates of the RGB phosphors; chromatic coordinates of white point; values of one (or three) gamma. This operation is made after the device has been working for at least 30 minutes. The measurement is done through a software using a measurement instrument (either a colorimeter, a spectro-photometer or a spectroradiometer) or visually.
2. Definition of the final goal: white point, gamma, phosphorus (which can't be changed). The white point more adopted standards are the American (D50) and the European (D65) ones. The natural gamma in the CRT devices is 2.2: this is then the expected final result. If we choose a gamma value equal to 1, the monitor will be changed in a linear device. In this case the color is not the real scene color, but it's the original captured image color as read by the scanner or CCD camera.
3. Modification of the initial white point and gamma values to obtain the fixed values. The white point can be changed acting on the lookup table of the graphic card or directly on the electron tubes. The gamma value always can be changed acting on the lookup table of the graphic card.

Finally, calibration means to find the same white and the same gamma for all the monitors.

The color set recognizable by the human visual system, or the colors that a device can reproduce, is generally defined as "*gamut*". For the videoprojection system the *gamut* is typically limited to 8 bit for each RGB channel. This limited number of visible colors falls within the visual color spectrum, but it covers just a part of the spectrum. Therefore many original film colors out of this range could not be visualized. In order to avoid an incorrect visualization of colors outside the monitor *gamut*, these can be remapped in the visualizable interval with the process know like *gamut* mapping (Braun, 1999; Gentile, 1990).

A typical *gamut mapping* approach is to create a correspondence between two different devices, for example a scanner and a monitor, so that the *gamut mapping* is applied as transformations in this common color space. In current practice colors are projected towards the centre of the gamut in a way that reduces saturation, and, to a lesser extent, brightness, while maintaining hue.

In order to relate the recorded color to well defined standards, color management systems have become a standard tool. Such operation is therefore carried out using a color management system capable of ensuring color fidelity through different platform, by means of a International Color Consortium (ICC) profile. Profiling a monitor means to register the final situation in a ICC profile. With current software evolution, profiling is becoming more important than calibration, because it allows to visualize in the same way an image projected by different monitor (that is, different gammas, different white points, different phosphorus).

The fundamental problem using a multi-projection system - as in our case - is that color consistency between the different projectors and the colors have to be as much similar as possible. Significant differences in the color spaces of projectors, even of

the same trademark and model, can be find (Majumder, 2000; Stone, 2000; Stone, 2001; Li, 2000). These differences are caused by a number of different factors, as variations in color spectrum of the lamps used, dichroic mirror tolerances, lack of uniformity in the illumination system, poor gamma correction in the modulators, and lens vignetting (Clodfelter, 2003).
A video wall can result not calibrated even if displays have been set to the same white target (like D65): not just color balance but luminance as well can be different. This happens because our perception of uniformity is influenced by a combination of color balance and luminance. From another point of view, if side-by-side displays have different luminance, they will appear to have different color. Each color pairs can be matched in terms of chromacity (xy values), and still have different luminance (Y value).
To avoid this problem, it's possible to follow three generally concurrently procedures. The first procedure consist of matching all the critical components, using exactly the same filters and luminance sources. The second procedure concerns the projector color in a device-independent color space, and regulates the input pixel in order to matching color according to the criteria adopted in color management systems. Finally, problems deriving from photometric differences between overlapping areas projectors can be minimized using computer vision techniques (Wallace, 2003; Kunzman, 1998; Majumder, 2002; Stone, 2001).
Discontinuities in the overlapping regions between the projectors could be caused by geometric alignment problems. All projection lenses introduce small geometric distortions into their images. In the case of a single projection, these distortions are sufficiently small to be unnoticeable. However, when multiple projectors are arranged one to the other, differences in these distortions become very apparent.
To calibrate our system we used the procedure described by Kresse *et alii* (Kresse, 2003) for the HeyeWall system, based on the color and luminance matching approach. The drawback of this approach is that the common color *gamut* will always be smaller than the individual *gamut* (resulting in less saturated color reproduction), and the darkest display defines the highest visible luminance for *all* displays.
The major advantage of this procedure is the full color uniformity, as all color computations are performed in a device independent color space, such as CIEXYZ. For each projector and color component, luminance and chromaticity (CIE-xy) are measured at many input levels.
As in every static color model for visualization devices, it is assumed that every pixel color is independent from its neighbourhood both spatially and temporally. This is problem not completely true, but the effect is sufficiently reduced to be ignored.
In Figure 6 it is shown the full pipeline to calibrate a given input color value for a projector, to allow a photometrically consistent and colorimetrically calibrated display. The black calibration part in the figure isn't important in our case, because it's only necessary for LCD and DLP projectors.
As in our case, using images in a calibrated color space, the pipeline changes for a photometrically consistent display of already calibrated input data. In this case input and output should not only share the color transfer function (calibration), but also the profiling. The initial gamma transformation, as well as the RGB transformation, is no longer required, the color black can be subtracted directly. However, it is possible that the resulting color can no longer be displayed with the calibrated projector, as they may lies outside the common color gamut, or be too bright.
For luminance exceeding the range of the common primaries, tone mapping has to be applied to transform all colors into a luminance range the projectors are capable of. colors outside the gamut need to be clipped to the gamut, using either a straightforward technique such as clipping towards the white point, or a perceptual approach using gamut mapping. The pipeline is shortened accordingly, and a new step "Gamut Mapping" is added after the black level subtraction.
Finally, some considerations about luminous efficiency problems in the stereo systems and their specific calibration. The creation of different images for the right and left eye reduces the output light to an half.
In an active stereo system based on a single CRT projector, projecting left and right eye images, the duty cycle would be 50%. Furthermore, the extra blanking between the left and the right image that is required to ensure a good stereo separation further diminishes the light output, resulting in an efficiency of about 45%.
Due to polarizing, each eye receives less than half of the light left. As shutter glasses do not open and close instantaneously, and due to the light lost from the polarization, efficiency of the active stereo eyewear is rated at about 35%. The overall efficiency of the active stereo process is thus 45% x 35% or approximately 16%. We have to take in to account these parameters when we define the virtual scene illumination.

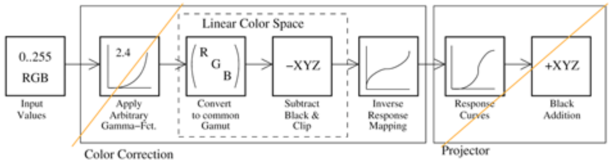

Figure 6. Videoprojectors calibration pipeline (Kresse, 2003)

5. CALIBRATION OF THE VISUALIZATION SYSTEM IN USE

Crucial parameters for the calibration visualization system are, as above mentioned, reciprocal luminance and chrominance of the two close projectors. We used a spectroradiometer to measure luminance and chrominance. Specifically, we employed a Minolta CA100 that allows the measure of the spectral emission of the luminance source in the visible color band with increments of 5 nm with an accuracy next to +/- 0.004 for chrominance and +/- 0.004 for luminance (multiple measurements were made in correspondence to the centre of the screen and in edge blending areas) and to work in device-independent calibrated color space. The spectroradiometer samples the three value of the standard observer curve from the wavelength of the visible field. Then it measures Yxy values, from which are calculated the RGB values. The procedure consist of single readings followed by iterative calibration, working on chrominance first and then equalizing luminance. We used like white point a color temperature of 6500 °K (D65 illuminant) and a sRGB profile whose xy values are shown in table 7.
Once the projector is calibrated, we can calibrate the entire VideoWall with a simultaneously matching of color and luminance on the visualization system.

	x	y	g
R	.64	.33	2.2
G	.30	.60	
B	.15	.06	
D65	.3127	.3290	

Table 7. sRGB profile xy and gamma values

Calibration and profiling are carried out according to a twofold application of the same initial profile to both projectors. The second projector is calibrated according to the *gamut* defined by the first projector. Correspondence of primary color is quite simple as it's possible to define an arbitrary *gamut* and set a new target with just one passage, starting from the current display.
A general rule with multi-display systems is that you have to calibrate all displays to the weakest display. Once white and primary colors are all matched across all displays, the videowall is considered calibrated.

Figure 8. The videowall before and after the calibration

A typical calibration routine for two projectors is the following:

1. Measure all projectors and determine the weakest hue unit.
2. Set the test pattern on displays to the first primary.
3. Measure each display and determine the weakest unit. Use that unit as the target.
4. Set all displays to match the primary of the weakest display.
5. Repeat the process for all primaries.
6. Set the test color to white on the weakest display, and use that as a target.
7. Adjust white on all other displays to match the target.
8. Repeat the process for white to determine how the adjustments to the primaries have affected white.
9. Adjust white, then repeat the check the primaries again to see if they are affected.

The process continues in an iterative fashion until the optimal calibration is reached.
The colors and luminance consistency along the edge-blending is then ensured by the electronic control (in the Barco projector this is called Soft Edge Modulation Unit - SEMU) that automatically corrects the gamma with respect to the video level signal, optimizing the gamma curve.
Geometric problems are deliberately left out in this paper, as there is specific automatic alignment software available.

6. DATA CAPTURE & MODEL CONSTRUCTION METHODS

Likewise most part of applications for built-heritage preservation, in our case as well the availability of detailed geometric models is a key point.
Whereas, the creation of real-time models from a real-life world is a complex task: more than 100 Mb are required only to describe models with over 5.000.000 triangles - as the ones we are considering. These huge data volumes introduce relevant problems about real-time visualization and interaction (typically 25 frames per second). The goal is to obtain a methodology both robust and effective, reaching an optimal compromise between information quality and high frame rate visualization.
In order to solve such issues, in the Sala delle Cariatidi we adopted a combination of different approaches both in data capture and 3D model generation, with the goal of making the most of each particular features for representing specific aspects of the model.
For what concerns capture, we defined shape and superficial reflectance properties using a combination of passive techniques (photogrammetry) and active 3D sensing (Beraldin, 2000; Guidi, 2003). Such mixture allows taking advantage of the best of each single system.
The same hybridisation occurs in geometric modeling techniques using both polygonal methods and polynomial parametric surfaces.
Finally, we adopted multiple resolution models both for number of polygons and texture size in the visualization phase.
For what concerns the link between data capture techniques and type of geometry selected for their representation, the identified methodology presents three different articulations:

a) Acquisition of sculptured shapes: the statues of the Sala delle Cariatidi present typically free-form geometry. In this case we used active sensing systems (laser scanner), exploiting their ability of capturing organized 3D data sets, which allows automatic modeling. A range camera can measure in few seconds thousands of 3D data, returning them as an accurate cloud of points. Such captured information is then converted in flat polygonal meshes. We used a Minolta VIVID 910 a light-stripe triangulation rangefinder, capable of scanning samples ranging in size from 110 x 80 x 40 mm to 1200 x 900 x750 mm, and distances ranging from 0.60 to 1.2 meters with two different measurement methods: one faster (one pass in 0.3

sec.), the second one more accurate (three pass in 2.5 sec.) for a total of 307.000 3D points for each image.
In our case, for each shot we placed the scanner at a distance of 1 meter from the object. The lens has been set for field of view of about 33x25 cm. As a result, we obtained a sampling step of 1 mm. For such capture distance, depth uncertainty has been estimated in about 0.15 mm (1 sigma). For view alignment based on the ICP algorithm (Soucy, Landreau, 1995; Bergevin, 1996), models generation and editing, we used the Innovmetric Polyworks and Inus Technolgy Rapidform software. Table 9 shows the number of shots, captured points, polygons and points of final models edited and decimated according to capture tolerance values specified.

	N° range maps	*N° acquired points*	*N° polygons*	*N° points*
Caryatid 1	**98**	**29 400 000**	**1 029 864**	**519 601**
Caryatid 2	**56**	**16 800 000**	**1 808 352**	**914 134**
Caryatid 3	**82**	**24 600 000**	**1 427 052**	**735 131**
Statue	**28**	**8 400 000**	**1 565 269**	**739 152**
Capital	**38**	**11 400 000**	**1 162 036**	**643 113**

Table 9.

b) The architectural elements modeling has been carried out using feature-based modeling from orthophoto, a system originating from analog photogrammetry that allows to plot 2D drawings (Gaiani, 2001). The major difference consists in employing NURBS curves and parametric bicubic spline surfaces as primitives (rather than points and polylines), using the following process pipeline to build models from orthophotographies:

- Extraction of 3D profiles;
- Creation of the surfaces between the profiles;
- Insertion of the real life deformations by altering isoparameter curves and Control Vertex points.

The reference photo has been shot with a per pixel resolution every 3.35 mm., allowing a 4 mm. tolerance in modeling.

c) Finally, using digital photogrammetry we have built a reference grid which can assist the process of alignment different data sets captured with the above mentioned techniques. Digital photogrammetry allowed to define the points for re-aligning 3D models of sculptured elements obtained with laser scanning and feature-based modeling. Image-based 3D stereo techniques have been employed to define typically 3D but uncarved element sets, through correspondence of homologue points over corresponding images using epipolar lines. For the photographic work we used a Fuji FinePix S2 Pro reflex digital camera, with effective 6.17 million pixels interchangeable lens, and Realviz Image Modeler software.
Always starting from orthophotographies, the color of each single point is obtained by mapping the real-scene image generated by digital photography color mapping against the geometric model, by means of image perspective techniques (IPT) (Beraldin, 2002; Gaiani, 2000). Our method employs the collinearity equation to correct imaging distortion. From a practical point of view, then, it's difficult to find commercial software doing an accurate texture mapping on 3D cloud of points or 3D polygonal models. For this reason we have decided to use a technique based on orthophographies, to be manually mapped on 3D model with commercial software. Orthophotographies are very appropriate for architectural environments: because of the high distance between camera and object, perspective and tilt effects can be minimized. The major problem is that geometrical error in the projection process will diminish the accuracy. For this reason the method, which is applicable to both triangulated meshes and NURBS geometry, use only affine transformations based on commercial software (Cortellazzo, 1999). A-priori camera calibration is not normally needed. The only required condition is to consider surfaces as planar-like, which is practically always the case in an architectural monument. The only rule to follow is to have the smallest number of projection possible (El-Hakim provides a table of the error sources for visual discontinuities) (El-Hakim, 1998). The main problem is the distortion inherent in camera lenses (especially wide angles). To offset problems with large surfaces and close-range camera position, we applied differential straightening on objects presenting deep curvatures and mosaicking over large surfaces. The same projection direction was again used in the rendering software, to apply the orthophotographs as projection textures over the model as a planar projection, using the concept of view dependent texture map introduced by Debevec *et al.,* 1996 in the context of building models from photogrammetry and generic parameterized models. Even when several images are collated into a mosaic, the end results are excellent, also according to time-consuming criteria. For highly curved parts, the 3D model has been firstly segmented in mutually exclusive regions. Each part has been mapped into a fully encompassed region, which is a subset of one of the 2D images.

Figure 10. An original photograph used to obtain the texture map of the caryatid and the pilaster strip underneath.

Figure 11. The texture maps obtained from the image of fig. 10

Once the image projecting planes are identified, it's necessary to correctly define the model portions onto which apply the different maps. For this operation we highlighted polygonal surfaces with different colors, according to the prevailing direction of normals: in such way it was possible to assign the most appropriate texture. Angles adopted as discriminating are 45° e 135°. Another possible consists of segment the object in three portions, using the intersection with two vertical planes oriented according to selected angles. Nevertheless, such method was discarded as it only performs well on regularly shaped, cylindrical objects (it is the criteria adopted for columns and capitals), but it's not as much efficient for irregularly shaped objects. For instance the head of a statue clearly requires a lateral mapping which, being in a central position, would become part of the portion to be mapped as a frontal projection.
The edges between such different obtained regions have to be corrected, in order to hide the typical visible effects of:

– ghosting (images incorrectly calibrated with 3D data);
– color differences between images – a issue related to camera exposition and quality.

In our case such problems have resulted to be marginal and therefore were not taken into consideration.

Figure 12. Rendering of the final model obtained using the texture maps of fig. 11.

Anyhow, there is a wide literature on such issues and it's available software to solve the problem (Robertson, 2002; Bernardini, 2001; Rocchini, 2002; Agathos, 2003).
As above mentioned, color definition was obtained by calibrating various profiles and equalizing procedures against a color quality control target. Operatively, we made many orthogonal shots and a sufficient number of partial shots from different perspectives. The goal was to obtain information on occluded areas which cannot be orthogonally shot. We decided to do large format orthogonal shots, with a 13x18 optical bank, in order to obtain the image of the entire restoration work field with a limited but high resolution number of shots, simplifying the subsequent alignment. The Sala delle Cariatidi dimensions allowed to use a 210 mm lens from a completely rear position.
This is the normal focal for such format, allowing the elimination of perspective aberrations. We made both horizontal shots (from the bottom and the top of the interested section) and one central shot to be used for connecting and controlling.
The optimal positioning of the camera influences the chromatic output. We used a solid scaffolding, high enough to allow shooting from an intermediate point of view as regards to the field of view. The lens alignment at different shooting heights has been guaranteed where possible by plumb line references. After defining the shooting points, lights were positioned. This is a crucial aspect for the chromatic output of the picture, as the camera is in a poorly lighted interior. A uniform lighting is essential to obtain reflectance maps with enough fidelity to actually support the restoration project. For such reason, we used two big banks with flash light presenting an extremely

stable 5.500 °K color temperature, thanks to new-generation generators. Flash light avoided that eventual vibration could influence clearness. Overall power used was 16.000 w/s: this allowed to adopt a lens aperture of f/16, which for such distances proved to be enough ample to provide the necessary field length.
As for chromatic quality, the object natural light was absolutely inadequate and did not allow to verify by comparison with real-world colors. For what concerns the use of Kodak Control Patches, we had to deal with a number of factors invalidating this procedure:

– Colour patches available (even the biggest one) resulted to be far too small for the field of view. A possible solution would have been taking more orthogonal close shots, but such hypothesis was discarded from the start because of major problems in lens alignment and final mosaicking of the complete image. Therefore single sectors (colors and greys) were absolutely dimensionally inadequate to provide a reliable indication.

– The rough and irregular nature of the object does not allow placing the color patches such as to be lighted with the same angle of incidence. Colour patches are almost never parallel to the focal plane, so that it is impossible to light the patches in the same way. These aspects in practice defeat their role as control tools.

The adopted procedure has been further controlled using an entirely photographic methodology, which includes control of light quality, film used and processing laboratory.
Lighting sources have been regulated to satisfy the chromatic features of the film: using a termcolorimeter we provided to control color temperature up to 5.500 K and checking it was dominant-free. Flash light was helpful, as it is very chromatically stable even in case of power variation.
Finally, image digitization has been carried out using a A4 Agfa Duoscan T1200 flatbed scanner with a 1200 ppi (h) x 2400 ppi (v) optical resolution, dynamic range 3.2D and 14 bits per color input.
The last phase of our pipeline concern model optimization for visualization in real-time systems. To reduce the rendering time and obtain real-time manipulable models, we used methods which simplify objects polygonal geometry and downsample the textures according to their dimension and their distance from the viewer. The loss of visual contents is limited within the project tolerances. We then created static Level of Details (LODs), in order to obtain differently accurate representations of the detail of the same model. Details were eliminated according to the accuracy requirements of the interactive model (De Floriani, 1999). A conservative estimate of the resolution ratios involved indicates an 8:1 change in resolution. If we assume a 2:1 change for each level of detail, in the case of the Sala delle Cariatidi, keeping count of the hall dimensions and the distance from which a viewer can look at the scene, it follows that there will be at least 2 levels of detail, one for a close view and the other for a distant view. The two levels are required for each component of the scene undergoing an intervention which could guarantee a sufficient margin of reduction to justify the splitting.

7. CONCLUSIONS & RESULTS

Simulation of the restoration project of Sala delle Cariatidi has been made for a selected area of the hall, with the following features: volume area of 600x1200x150 cm - that is the basic module of the architectonic subdivision; different surface finishing: plaster, tiles, concrete and painted plaster cast elements. The area exactly corresponds to the real restoration yard.
The different parts were captured by laser scanner with different accuracy values: ± 1 mm for sculptural elements; ± 4 mm for walls and 1 pixel/mm for texture mapping. Each accuracy was respected in the final virtual model.
For what concerns the capture of sculptural elements, table 7 shows the number of range-maps, acquired points, points and polygons of the final models to be edited and decimated, according to capture tolerance values specified in the table.
For what concerns both the polygonal and NURBS models, table 9 shows the number of polygons of the extant and restored model, referred both to a near and far LOD visualization.
The visualization model features a 52 Mb texture, LZW-compressed TIFF format, derived from an original amount of 640 Mb down sampled following visual criteria.
The scene illumination was created in order to obtain the most neutral visualization of colors and volumes, rather than for natural or artificial condition. It was therefore generally used a frontal light with a strong diffuse component. The indirect light produced by the five windows at first and second order of the elevation was reproduced by five spot light sources. Centrally located in the area of each window, these spot lights effectively synthesize the indirect light passing through.
Calibration of the video wall is shown in Figure 12, where the same image is presented before and after the calibration process.
Results obtained until today confirm the appealing and innovative aspects of our project. In particular, our approach offers the possibility to exploit virtual reality visualization techniques in the Heritage restoration field, with projectual goals. This method allows to evaluate a number of different hypothesis, simulating a diffuse application associated with the inclusion of virtual replicas of irretrievable lost elements.

Figure 13. Real-time image of the virtual restoration yard of the Sala delle Cariatidi: current state.

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