Chromatic Adaptation Post-Filtering in Image Synthesis Reproduction of Ancient Building for Restoration Support

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ABSTRACT
Within the field of cultural heritage restoration, experts are interested in the analysis of data describing the condition and history of ancient monuments. Data are usually distributed over many sites. VRML and Java technology, which are well-suited for describing geometrical models and data interaction over the Internet. Unfortunately, the poor quality of VRML real time rendering is a bottleneck for any analysis based on accurate image synthesis methods. Another problem in reproducing images with photorealistic rendering derives from the adaptation mechanisms of the human visual system. We describe a method and its implementation for providing high quality photorealistic image synthesis of ancient building materials. In this method, a network based Java application manages geometric 3D models of an ancient building to provide an editing interface and to manage high quality photorealistic snapshots. Simple 3D VRML data are enhanced with radiometric data derived by gathering measurements on the actual material taken from the site which is being reproduced. In the example presented in this paper, we have used actual measurements taken from the ancient Roman Aosta Theatre. A server-based optimised rendering application computes photorealistic images on radiometric data, that are subsequently applied as input to an algorithm simulating the human visual system perception. This latter phase is able to emulate most of the human adaptation mechanisms, including factors such as colour constancy, local lightness, and chromatic adaptation. The enhanced interaction with high quality images of the model through the Java application, allows a visual qualitative evaluation of restoration hypotheses. It also provides a tool that is able to show the final appearance of the model under assigned lighting conditions, as observed by a human being inside the virtual environment.

KEYWORDS: restoration simulation, photorealistic rendering, visual appearance, color processing, chromatic adaptation

INTRODUCTION

A novel application of image synthesis deals with computer simulation of ancient buildings. Multimedia techniques supported on CD-Rom or based on networked hypermedia via the Internet provides methods to convey complex information in the field of cultural heritage to experts and non-experts through visual representation and visual interaction. While cultural heritage experts may be interested in using computer methods to explore hypothetical alternatives in order to select optimum techniques for restoring and preserving monuments, non-experts are usually interested in general information about all historical and artistic notes that may increase a deeper appreciation and understanding of cultural heritage site.

In this paper our main interest is in enhancing image synthesis quality to provide experts with a powerful tool enabling, through visual representation, qualitative evaluation of materials surface modification of ancient buildings. We suggest that this methodology may be useful to explore hypothetical alternatives in order to provide essential information on techniques for restoring and preserving monuments.

The research field of image synthesis starting in the early '80 in computer graphics focused primarily on image-time optimization, and only recently turned its attention to the problem of accurate material reflectance and illumination condition reproduction. This means that the most of the image synthesis systems available around the world can now potentially be quickly reproduced in very light and color-precise images without the light distortion associated with the physical conditions under which the image was photographed.

In figure 1, we present an image synthesis pipeline that takes into account a photorealistic representation of the real world, depicting four different fields in which extensive research has been done. Much of this research produced in the last several years describes geometrical properties of objects such as solid and parametric surface modeling. Advances in research in local and global illumination models continues to produce increasingly better results, but the real problem resides in the description and reproduction of the results produced by the lighting model applied to the geometric and material reflectance description of environment.

Both simplified commercial and public domain rendering systems do not take into account radiometric properties of light but directly compute the lighting models in the colorimetric field. Therefore, by describing the materials in color reflection and light color as RGB triplets, the results can be only quantitatively represented. We suggest that this approach may be useful only for fast image production purposes. Our assumption is based on the hypothesis that it is incorrect to describe a complex phenomenon such as that of light-materials interaction in terms of perceptual values (RGB) that are the results of the Tristimulus Theory.

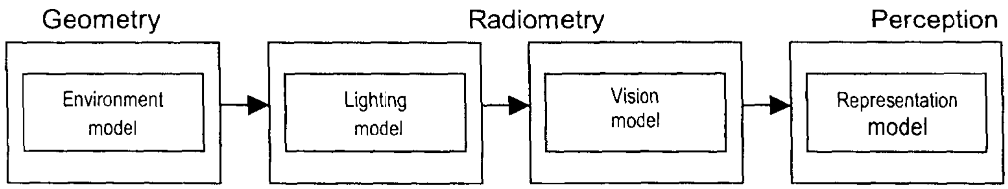

Figure 1 Image synthesis production flow

The results produced by computing the illumination model should be a spectral radiance functions of wavelength $L_e(\lambda)$. These may be then reduced to the CIE XYZ absolute perceptual field described by the Tristimulus Theory [18] with the integration:

$$X = K_{max} \int_{380}^{780} L(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = K_{max} \int_{380}^{780} L(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = K_{max} \int_{380}^{780} L(\lambda)\bar{z}(\lambda)d\lambda$$

where K_{max} = 683 lm/W is the maximum value of the human photopic luminous efficacy function. The XYZ absolute color triplets then must be transformed to the display relative RGB color space [4] with the linear transformation:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}^{-1} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

where M is the matrix of CIE XYZ tristimulus values of the three R,G and B phosphors of the monitor. All these steps are represented in figure 2. Unfortunately the CIE Tristimulus approach does not take into account notable phenomena of human visual perception. So an image produced only with the above described steps may be affected by adaptation mechanisms that the human visual system uses to produce a stable reality perception [9][11].

Therefore, another interesting feature in the restoration support field is the capability to generate images of restoration hypothesis that have to appear as real restorations. The term "appear" understates various problems of visual match and photorealism. Among these are the chromatic adaptation capabilities of the human visual system responsible for a variety of effects such as color constancy. These effects have to be added in the photorealistic image generation pipeline to augment the naturalness of an image.

To explore the feasibility and effectiveness of these approaches, an actual study has been used which collects a variety of data describing the ancient Roman theatre in the town of

Aosta in northern Italy. This is quite a rare example of a covered Roman theatre because its geographical position are under very inhospitable climatic conditions which include cold temperatures and significant amounts of moisture for several months during the year. For this reasons its constituent materials, consisting of travertine ashlars and pudding stones are strongly degraded and only the front and the foundation have survived (see figure 3).

In particular, information about this theatre includes geometric data, images, descriptive information collected by the cultural heritage experts and data generated by previous computations. These descriptive and pictorial data have been used to enhance other data to further improve the degree of detail and accuracy of the ancient building description and representation. In particular, architectural properties have been extracted by reconstructing 3-D models of stones by digital camera acquisition and a successive work of CAD refinement.

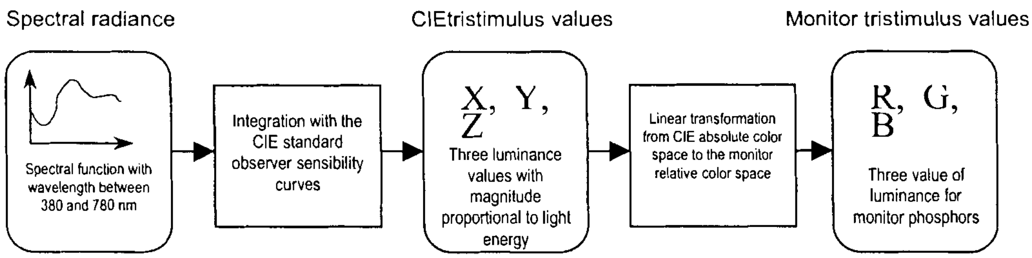

Figure 2 From light signal radiance to monitor light reproduction

Spectral properties of ancient construction materials have been measured in the laboratory under reconstructive conditions (that is, after cutting and/or polishing the samples, bringing them to their original conditions and after a cleaning process on site). A 3D reconstruction of the whole theatre front has been carried out to create a VRML model which becomes the basis for accessing the collected information using Web browsers. Advanced graphics rendering is necessary for using the system as a virtual restoration test bed. This is done exploring the effects of conservation simulation, or restoration hypothesis, and attempting to capture the architectural essence of the original building. Experts may use the link between photorealistic rendering and optical and physical properties of materials to better control conservation and restoration processes.

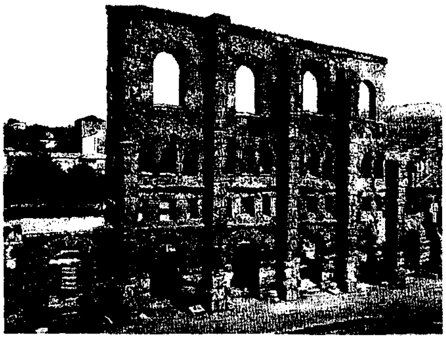

Figure 3 A photographic image of the theatre

Adding a chromatic post-filtering on the spectral data, not only helps to render a more realistic image, but also helps in avoiding metameric ambiguities in the light-matter interaction.

THE RENDERING PHASE

The critical problem in realistic rendering of complex models, such as ancient buildings, is to control their visual appearance. One possible way of accomplishing this is the adoption of texture mapping methods to arrive at an "impressionistic" rendering. This is an efficient solution given the availability of a display system with specific hardware architectures to support real time navigation through textured surfaces, but it can give only a rough idea of "their real aspect". In order to increase the degree of accuracy, it is necessary to use photorealistic methods based on physically accurate lighting models; Ray Tracing [17] has been adopted as a global illumination model and a modified Cook-Torrance [3] as a local illumination model. The limitation of this method is the impossibility of real time rendering, but the results are of great interest when a link between structural and chemical characteristic of the samples has to be maintained in order to render their visual appearance.

Using Ray Tracing as a global illumination model leads to a well-known error in underestimating the mutual diffuse inter-reflection of light from objects of the scene. Nevertheless, this error in computing the illumination of an external building is lower than for the internal ambient where the Radiosity [5] method is more accurate. The choice for the Cook-Torrance local illumination model has been suggested by its radiometric properties and physically accurate description of light behavior in its reflectance interaction with surface materials. In addition we extended the original formula to include definition of light sources according to the lighting industry standard [6].

To better understand this approach, it is worthwhile to recall how the light-material interaction is simulated with the rendering system that we have used. Most of the rendering programs adopt an approximate illumination model to compute colors shading following an implementation of the Tristimulus theory, thus defining colors in terms of a display device, RGB triplets. On the contrary, in our advanced rendering system, based upon a radiometric illumination model, the reflected radiance is computed for spectral intervals between 380 and 780 *nm* with 5 *nm* steps. The program that we have used to generate the photorealistic images is based on a physical model for the light-material interaction which allows us to compute the reflected radiance $L_{e,R}(\lambda)$ in terms of the incident irradiance $E_e(\lambda)$ and the bi-directional reflectance (BRDF) $\rho(\lambda)$:

$$L_{e,R}(\lambda) = \rho(\lambda) \cdot E_e(\lambda) \qquad (1)$$

$\rho(\lambda)$ is approximated as described by Cook and Torrance [3]. The incident spectral irradiance on the sampled surface point is computed using the ray tracing global illumination model as the sum of spectral irradiance coming from the luminaries and the spectral irradiance coming from other bodies through specular reflection.

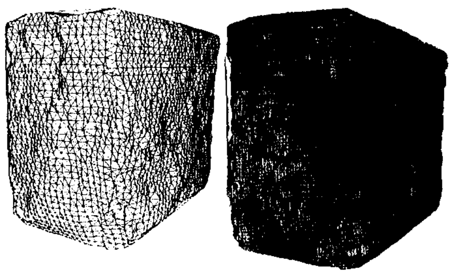

Figure 4 Single stone high-detail, wire frame and shaded with texture

Working in cooperation with the ITABC-CNR (Istituto per le Tecnologie Applicate ai Beni Culturali CNR, Roma) we collected data for this considered case study. Conventional geometric survey and reconstruction was made by a professional CAD refinement study on the whole building. These 3D data were converted to a VRML model and photos of the actual materials were digitally acquired and applied as textures to the geometrical model [12] to get an impressionistic representation of the building. In addition, much descriptive information coming from a visual inspection made by cultural heritage experts consisting of a large quantity of manuscript information, photos, charts and images [16], were linked to the 3D VRML model of the building. High resolution geometric reconstruction of 3D models of some sample stones have been acquired with multi digital camera acqusition [13] (figure 4). This geometrical data was also converted to VRML and textured. The data collected for this sample of stones was also included in the whole model as another level of detail structure.

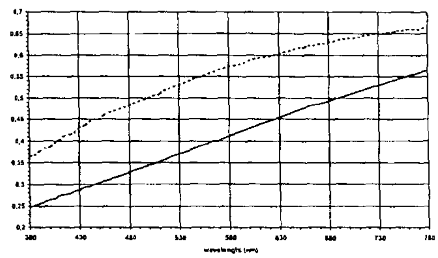

Figure 5

To apply the photorealistic lighting model described above in relation (1) we need to describe materials using spectral reflectance instead of RGB color or textures. Following this assumption we performed a spectrometric analysis of pudding-stones and travertine-ashlars samples that resulted in hemispherical reflectivity curves. These analyses have been conducted on samples in their natural state of degradation as well as after cutting and polishing to get reflectivity curves under different conditions simulating the effects of restoration of materials to their original state. We measured the hemispherical reflectivity as a function of light wavelength in the range of visible spectrum from 380 nm to 780 nm. All measured samples were taken from the stone's surface and pulverized to fit into a Beckmann reflectance spectrophotometer with a magnesium oxide coated integrating sphere.

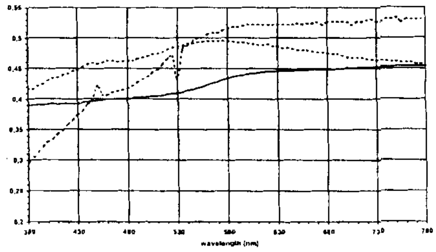

Figure 6

Figure 5 report the hemispherical reflectance of a travertine-ashlars sample: the solid line represent a dirty degraded material while the dashed line represents a cut and cleaned material. The dirty surface has little differences in the spectral response, but reflects less light than the cleaned surface. Figure 6 reports the hemispherical reflectance of a pudding-stone sample, the solid line represents a dirty degraded material while the two dashed line represent cut and cleaned material samples taken from two different surface positions. The difference in the two cleaned stone reflectances is due to the granular nature of pudding-stone that is a compound of different minerals while the dirty sample does not show these differences.

Considering only the hemispherical reflectance $\rho_e(\lambda)$ instead of the complete Bi-directional Reflectance Distribution Function $\rho(\lambda)$ (BRDF) results in a small error in relation (1) because travertine-ashlars and pudding-stones have a very diffuse reflectance properties, near the lambertian.

The second key point in the lighting model data preparation is in the light source definition. Following the purpose of describing the model with actual measures, we decided to describe the light source adhering to luminaries standard as defined by lighting industry.

Usually color properties are defined by the spectral relative power distribution, which is a function of wavelength λ:

$$S_e(\lambda) = 100 \cdot M_e(\lambda) / M_e(555) \qquad (2)$$

for $380 \leq \lambda \leq 780$ nm and were $M_e(\lambda)$ is the spectral radiant exit of the light source. The 555 nm wavelength value is used to normalize because in this point the human luminous efficacy function get its maximum value. The luminaries intensity distribution are defined by the photo goniometric diagram $I_v(\theta^\circ, \phi^\circ)$ that defines light intensity distribution (measured in candles) in all directions around the light source with respect to a reference position and orientation direction [6].

The problem arising when using luminaries standard definition in the relation (1) as light irradiance is in the different dimension of the computed factors, indeed $E_e(\lambda)$ is a *radiometric* function of wavelength, while the standard defines $I_v(\theta^\circ, \phi^\circ)$ which is the total *photometric* luminous intensity is a function of the direction with respect to the reference axis of the light source. But what we would get is the incident spectral irradiance coming from the light source. In our method we suppose that the color of the light source, that is to say, its spectral relative power distribution $S_e(\lambda)$ is known. This is a function generally available from lighting industry and CIE international standards [1][2]. Because ray tracing is our global illumination model, light coming from luminaries is sampled with rays of assigned direction and in the computation of the contribution of a single ray we can ignore the luminous intensity dependence from direction and treat it as a single assigned total value I_v.

To solve this problem we follow the way recently presented in [14] that lead to the relation:

$$E_e(\lambda) = \frac{I_v \cdot S_e(\lambda)}{r^2 \cdot \int_{380}^{780} K(\lambda) \cdot S_e(\lambda) \cdot d\lambda} \cdot \cos\alpha$$

(3)

this is fundamental because it computes the incident spectral irradiance function $E_e(\lambda)$ on a sampled point of a surface, due to a light source at distance r, on a ray which has an angle α (with respect to the surface normal) with a "spectral color" $S_e(\lambda)$ and total luminous intensity I_v on the sampled direction, where $K(\lambda)$ is the human spectral luminous efficacy function [18]

Natural lighting is defined by a source, which has light rays coming from an infinite distance all parallel each other on a defined direction. This light model is defined by the total illuminance (in lux) $E_{v,0°}$ measured on an orthogonal surface to the considered direction. Some experimental measurement done with a luxmeter shown the following values for the natural light:

$E_{v,0°}$ [lux]	Source
100 000	light from the sun 50° over the horizon
10 000	light from the sun in a cloudy day
0.2	light in night with full moon

To manage objects and light source data, we developed a prototypal Java interface to enhance the limited VRML material and light source description capabilities. This application is the core tool for the management of the data described above. Since the VRML browser does not allow the user to interactively modify the data, this Java application assists the expert operator in accessing local or remote VRML geometrical model of the cultural heritage building, associating the spectral properties of the material to the model (figure 7).

This application, based on the Java and Java3D technology from Sun Microsystems, can be executed on different operating systems. This programming language provides numerous tools for accessing and managing 3D virtual reality model and remote Internet data. Since Java3D is based in the OpenGL graphics library on systems with hardware support for the OpenGL, the display performance of the geometrical data could be quite effective even for very complex models. One primary benefit of the application interface is the capability for managing local and remote data assuming URLs as the basis for locating different types of data resources. In the field of cultural heritage management, this is a key feature since it could not exist a unique main database and data are usually recorded in a variety of different sites. Any kind of data could be linked and inspected to/from the model of the building with the support of an external browser.

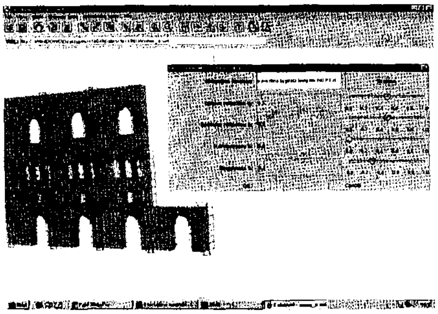

Fig. 7 The Java interface program. This application provides a tool to manage the 3D data of the cultural heritage building and associating spectral reflectance data to materials constituting the building. It also defines photometric light sources and prepares data for the photorealistic rendering phase.

The VRML specification does not provide the definition of materials based on a spectral basis but only from a classic colorimetric definition. Another obvious limitation of this standard is in the quality of the images rendered and produced with VRML browsers. To guarantee a virtual reality interaction and fast animation, the browser rendering is based on simple shading techniques without regard for global illumination effects and accurate light-material interaction. Spectral data are simply ignored by VRML browsers such as the interface in its main navigation window with the impressionistic rendering. Nevertheless, these data play a fundamental role when the user begins the photorealistic snapshot. The activation of the photorealistic rendering program is accomplished through a simple system call to a separate process, written in C language which has been ported to different architectures. The interface allows for associate reflectance spectra such as those defined in figures 5 and 6 to model objects. So expert restoration users may simulate any kind of material appearance based on the original constituting situation and the actual state of degradation, therefore allowing exploration on the hypothesis of the restoration and conservation.

Therefore in the interface application, interactive navigation is implemented using impressionistic rendering with textured images, while accurate rendering is used for single viewpoint displays. The expert user can interactively choose to generate the rendering of a particular element or the entire building from a desired viewpoint. As described above, the results of a "virtual" restoration (based in our example mainly on cleaning and/or polishing the stones, or enhancement with any kind of available spectral data) can be displayed and/or applied to either the entire building or any of its parts.

In conclusion, the Java interface is not simply another modeling system or VRML browser but rather a tool with extended features for the management of photorealistic data.

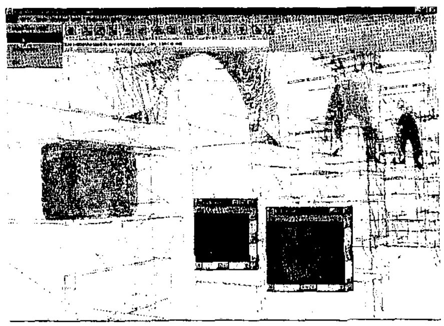

Fig. 8 The Java interface managing the photorealistic rendering of a travertine-ashlars block. The two small windows show two different renderings with simulation of two different level of surface material

situation. Smallest window: a degraded material. Bigger window: an ideally polished material by cutting and polishing the stone.

In Figure 8, the interface application manages an high resolution model of a travertine-ashlars block inserted as level of detail geometrical model in the VRML model of the Aosta Roman Theatre. The particular is then visible both degraded and ideally polished through photorealistic rendering. These images have been generated, giving the reflectance of each surface material's state and a white light source whom spectral composition is the CIE D65 standard illuminant.

A FURTHER STEP TOWARDS THE VISUAL APPEARANCE

In the computation of a highly detailed view, the appearance is preserved from a photometric point of view, but not from a human observer's viewpoint. To better realize a final visual appearance we propose to post-filter the synthetic images with the Retinex algorithm, which is able to simulate some of the adaptation mechanism of the human vision system [9].

We recall a mathematical treatment of the algorithm proposed by Land [7], from which our algorithm has been implemented. For each wavelength the relative lightness of a pixel is the mean value of relative lightness computed along a number N of random paths to that patch. The average relative lightness at the location i of the input image produced by the Retinex filter is the mean value of the relative lightnesses, computed over a number N of random paths ending at the pixel (figure 9), separately for each wavelength.

The lightness at the end of each path is computed as a ratio between the intensities I of the path pixels, in the following way:

$$Lr_{l,m,s}^{i,j} = \sum_{x \in path} \delta \log \frac{I_{x+1}}{I_x}$$

and:

$$\delta = \begin{cases} 1, & \text{if } \left| \log \frac{I_{x+1}}{I_x} \right| > threshold \\ 0 & \text{else} \end{cases}$$

These computations are executed independently for the three fundamental wavelengths: long, medium and short, corresponding to the three RGB chromatic channels.

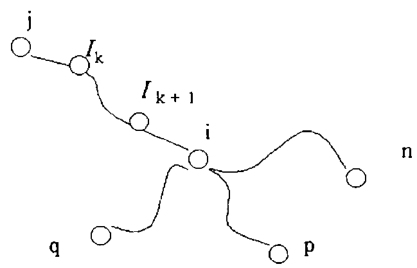

Figure 9 Computation of the average relative reflectance

The above model depends on many parameters. The randomness and the number of paths that are chosen for the computation of the relative lightness are critical for speed and accuracy of the result; the threshold plays the role of discounting non-uniform illumination, since it makes unessential low-reflectance ratios. Moreover, during a path computation, Retinex has a mechanism so that if a brighter area is found, the cumulated relative lightness is reset; this forces the computation to restart form the brightest areas. In other words, the effect of the reset mechanism is to consider the brightest area of an image as the reference value of the color white. Mimicking the receptive fields distribution of area V4, we have implemented a Brownian motion approximation to generate the random paths (figure 10) along which the ratio computations are made [10].

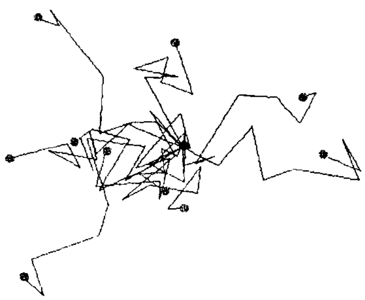

Figure 10 Example of 10 Brownian paths

The Retinex algorithm can be effectively used to equalize colors or to simulate chromatic illusion [9]. In order to test the effectiveness of this solution, we have generated different synthetic images under various CIE standard illuminants: A, B, C, and D65. Comparisons between images in figure 11 show differences in produced images without and with the Retinex post filtering. As for human colours perception the post filtering compensate for dominant chromatics reflections produced by a CIE "B" light which has the same spectral distribution as direct light from the sun. The post filtering effect does not affect the sample illuminated by the CIE "D65" light which is an ideal example of white light.

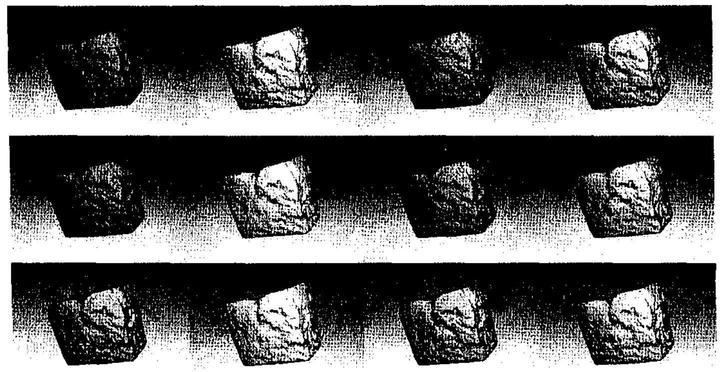

Figure 11 Samples stones with different material, different cleaning condition and different light source. Spectrally computed, reduced to RGB values applying the Tristimuls Theory and post filtered.

CONCLUSION

The Java interface application is still under development to enhance its functions to help the expert in exploring hypotheses of restoration and conservation. As described above, the results of virtual restoration (based mainly in this case study on cleaning and/or polishing the stones) can be displayed on single samples or applied to the entire building. The above described process for computing the (R, G, B) values from the spectral radiance $Le(\lambda)$ and then post filtering the results with the Retinex algorithm compensate the limitations of the tristimulus theory and the reduced dynamic range of typical display devices. Unfortunately, in the lighting model described above material colors are characterized by the spectral reflectance, which is a tabulated function of wavelength, so surface appearance must be uniform. This is not a great problem for the materials constituting the Aosta Roman Theatre, travertine ashlars and pudding stones, provided that they are observed at a distance that do not need to show their surface textures. We are working on the problem of defining and measuring textures for materials defined on a spectral reflection basis.

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