VIRTUAL RESTORATION OF BRONZE - 3D CAPTURE AND OPTICAL SIMULATION IN PARALLEL SPECTRAL RAY-TRACING

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Abstract

We present the main results of a complete study driven in cooperation with the "Musée National des Arts Asiatiques-Guimet" in Paris concerning a chinese horse bronze statuette, 20 centuries old. The visual appearance of bronze is studied, depending on their metallurgical composition and state of surface in normalized illumination and visualisation conditions. The results are presented on an example where a pluridisciplinary work was accomplished involving, engineering, art history, computer science, metallurgy, optics, material sciences, etc. specialists mainly from three academics labs, a museum, a rapid prototyping centre. The main results are presented here and summed up using many images of the original artifact and of the virtual and real replicas obtained. From 3D capture without any contact to plaster replicas with a galvano deposited metallic film, the complete process is described with images and objects during the conference. A didactic and scientific movie of 22 mn available in french, greek or chinese will also be presented.

Keywords: Spectral ray-tracing, optical constants, metals, roughness, bronzes, restoration, rapid prototyping

Zusammenfassung

Wir stellen die wesentlichen Ergebnisse einer vollkommenen Studie vor, die in Zusammenarbeit mit dem nationalen Museum für asiatische Kunst, Museum-Guimet, von Paris, ausgeführt worden ist.Es handelt sich um eine Statuette eines chinesischen Pferdes aus bronze, etwa zwei tausend Jahre alt..

Der visuelle Anschein des bronzenen Aspekts ist im Zusammenhang mit der Metallkomposition, dem Zustand der Oberfläche der Legierung und unter normalisierten Bestimmungen der Belichtung und Visualisierung, erforscht worden .

Die Ergebnisse sind an einem Beispiel dargestell, andem fachübergreifende Spezialisten der Engineering, Kunstgeschichte, Informatik, Metallindustrie, Optik, Materialwissenschaft, aus vornehmlich drei Universitätslobors, einem Museum und einem Zentrum für schnelle protoypische Wiedergabe, gearbeitet haben.

Die hauptsächlichen Ergebnisse sind vorgestellt und illustriet durch viele Bilder des Originals, so wie durch die von errechneten virtuellen Bildern, als auch durch Reproduktionen. Reproduktionen, die durch den 3D Auffang, ohne jeden Kontakt mit den Reproduktionen aus Gips, welche mit einem „Metallfilm“überzogen waren, hergestellt worden sind. Der vollständige Ablauf ist durch die Bilder und Ausstellung der Objekte beschrieben.

Ein wissenschaftlich-didaktischer Film von 22 min., in französischer, griechischer oder chinesischer Sprache, vorhanden, wird ebenfalls vorgeführt werden.

Schlüsselwörter : Spektraler Strahlenverlauf, unveränderliche Optiken, Metalle, Unebenheit, Bronzen, Restaurierung, schnelle prototypische Wiedergabe

Résumé

Nous présentons les principaux résultats d'une étude complète menée en coopération avec le Musée national des arts asiatiques-Guimet, à Paris, concernant une statuette de cheval chinois en bronze âgée d'environ 2000 ans. L'apparence visuelle des bronzes est étudiée en relation avec la composition métallurgique et l'état de surface des alliages dans des conditions d'éclairage et de visualisation normalisées. Les résultats sont présentés sur un exemple où le travail pluridisciplinaire effectué impliquait des spécialistes d'ingénierie, histoire de l'art, informatique, métallurgie, optique, sciences des matériaux issus principalement de trois laboratoires universitaires, un musée et un centre de prototypage rapide. Les principaux résultats sont présentés et illustrés par de nombruses images de l'original étudié ainsi que des répliques virtuelles calculées et répliques physiques fabriquées. Depuis la capture 3D sans aucun contact aux répliques en plâtre recouvertes d'un film métallique, le processus complet est décrit par les images et en présence des objets. Un film scientifique didactique de 22 mn disponible en français, grec ou chinois sera également présenté.

Mots clés: Tracé de rayons spectral, constantes optiques, métaux, rugosité, bronzes, restauration, prototypage rapide.

1. Introduction

We present the main results of a complete study driven in cooperation with the "Musée National des Arts Asiatiques-Guimet" in Paris concerning a metallic chinese statuette. In an excellent state of conservation the object appears to be very weakly corroded such that the actual form is very near the original one. No missing parts also help us in retrieving the most plausible visual aspect of this artwork.

Our object of study offered the opportunity of a collaboration involving metallurgy, optics, computer graphics, archaeology and engineering specialists. Replication of the original object using rapid prototyping methods and virtual optical aspect computations obtained are described. The measurements on metallic reformulated tests samples and the corresponding rendering with our parallel and spectral ray-tracing algorithm illustrate the complete process of virtual restoration. That method was previously applied to the study of silver-lead alloys and gave very satisfaying results (Callet, Zymla, Mofakhami, 2002). Standard CIE specifications are used throughout the computations. Optical properties of the metallic surface are pre-calculated for an orthotropic ambient lighting and several illuminants (Callet, 1998). No internal scattering of light exists inside metallic objects, so that their "own color" is a physical non-sense. Diffuse lighting and directional lighting influences are expressed for smooth or rough surfaces, according to Walsh (1926), Judd (1942) and Mandelis (1990) previous works. The simulated visual appearance of the metallic statuette is founded on the exclusive use of the *complex index of refraction* of each compound inside the alloys. Obtained by spectroscopic ellipsometry, these data are also acquired for several states of surface of the formulated metallic samples. Thus *effective optical constants* are used for the visualization of the roughness influence on the visual appearance for the same normalized lighting conditions. The scientific study concerns a small statuette representing a horse originating from north China (Fig. 1) and dated of the "Fighting kingdoms period" (4th-2nd century BC). All the measurements and the choice of the statuette to study were placed under the responsibility of Catherine Delacour and Isabelle Loutrel, curators at the museum. The obtained results are relative to reasonable hypotheses on metallurgical knowledge and practice of moulding with bronze (Copper-Tin alloys) and depend on the relative concentrations of each species inside the resulting alloy. Some pictures whether captured from the real object or spectrally computed for 80 spectral bands using the digitized statuette are directly included within the text. The images, the metallic test samples and all the physical replicas will be presented during the conference.

Fig. 1. The original horse statuette at Guimet museum (15 cm x 14.5 cm x 5 cm).

2. The main phases and results of the complete process for visualizing and validating the visual appearance of bronzes.

Many experiments were leaded with a team of 4 second year students in Ecole Centrale Paris during the scholar period 2003-2004. The next paragraphs give an overview of the works accomplished by the whole team of students, engineers and researchers. At the beginning of the project was decided the realization of a scientific movie for communication purposes.

2.1 3D Digitization

3D capture without contact with the museum's statuette (Fig.1) was accomplished in a reserve room of the museum. All the specific equipments for 3D digitization were moved to the museum. The complete 3D acquisition process was made in about 3 hours with a structured light device from Breukman corp.(Fig. 2). The capture gives 1 million triangles for representing the object surface with a high level of geometrical details and accuracy (less than 0.1 mm in 3D coordinates). François-Xavier de Contencin for the CREATE (Rapid Prototyping Centre in ECP) was responsible for the 3D data capture and reconstruction with the team of students composed of the four second year students : Jérémie Ortalo, Christophe Gonzalès, JeanBaptiste Angelleli and Thomas Jourdan. A view of the reconstruction process with the CATIA CAD software is shown in Fig. 3.

Fig.2: The 3D sensor and the structured light projected onto the statuette during the digitization phase.

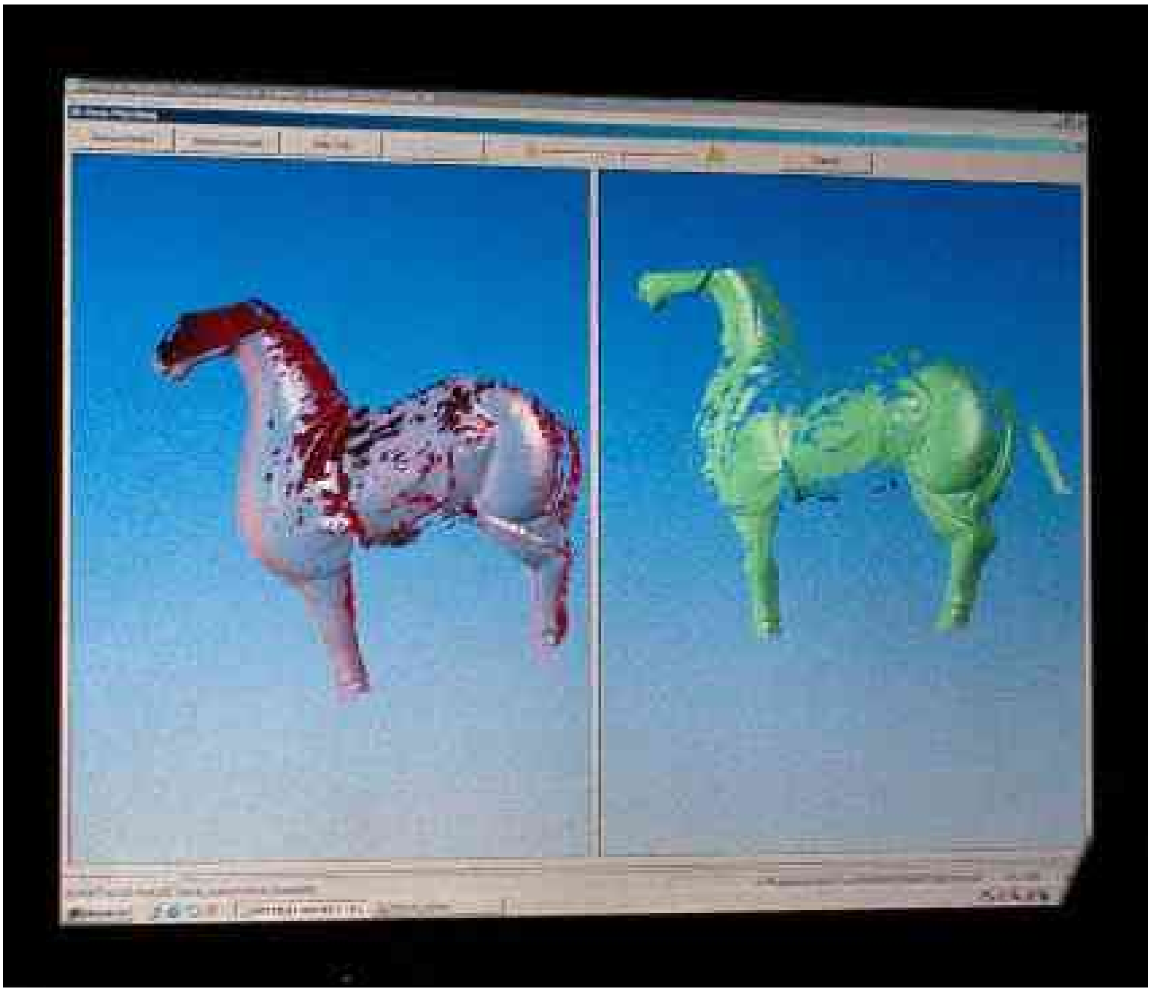

Fig 3: Assembling with CATIA software, the different 3D clouds captured to obtain a unique 3D triangulated database and an STL conversion (stereophotolithography file format common for rapid prototyping).

2.2 Metallurgy

The study and realization of a set of metallic samples in pure copper and 3 binary alloys with tin for 10-20 and 30 percent in mass concentration inside copper, was an essential phase of the project. That work was accomplished in LGPM (Material and Engineering Process Lab) at Ecole Centrale Paris, under the leadership of Anna Zymla.

2.3 Optical Microscopy and Scanning Electronic Microscopy

For metallographic structure and composition a SEM device was used and has given some nice pictures of the alloy near the surface. Since for metals or alloys the optical properties only depends on the interactions of light with free electrons lying in the 5 μm near the surface of the sample.

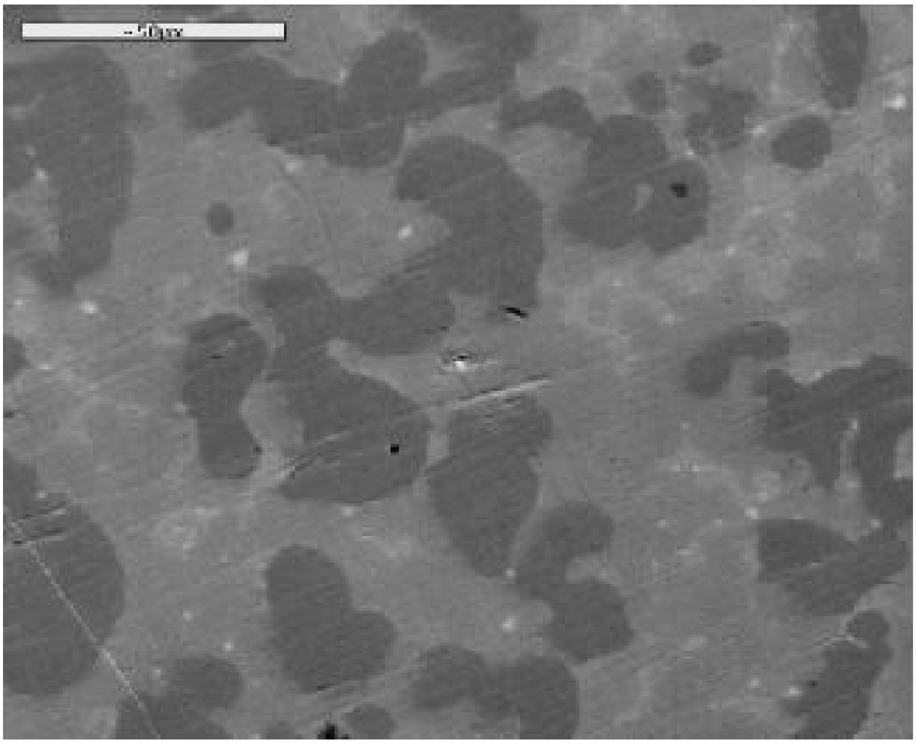

Fig. 4 : SEM image of the islands of tin in an ocean of copper for a grey bronze. Bronzes are solid solutions of tin and copper where no more than 30 percent of tin is possible.

2.4 Profilometry

Laser profilometry was used for the measurement of the state of surface and employed for the rendering of each 3D replica; these measurements were obtained on the manufactured samples of copper and alloys. All that step of the project was accomplished under the leadership of Nathalie Ruscassier in LGPM at Ecole Centrale Paris.

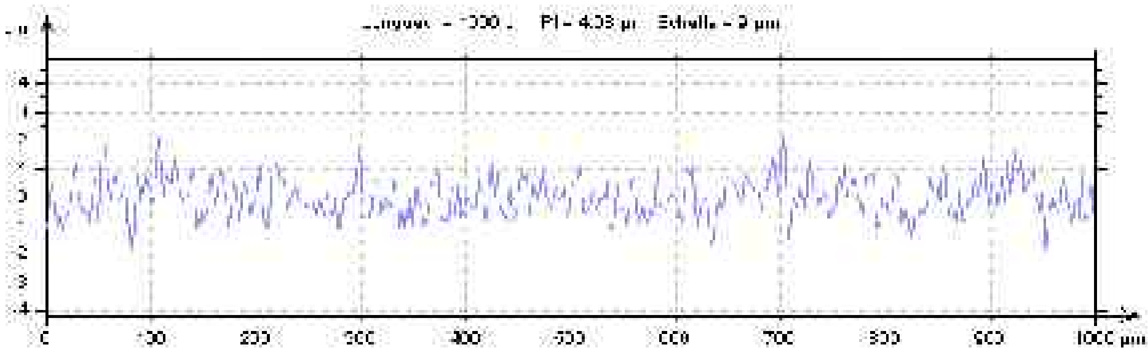

Fig. 5: Typical laser profilometer of a rough metallic sample. Roughness is characterized by the mean height variation around a mean plane defining the local surface (in an euclidian mathematical sense) and the characteristic correlation distance between two successive peaks.

2.5 Optical constants measurements

Optical constants are the real part and the imaginary part of the complex index of refraction of the metal or alloy. They are obtained by *spectroscopic ellipsometry*, an optical method based on Fresnel formulas and analysis of the amount of polarization for reflected light at large incidence on the smooth surface. We use throughout all the calculations the Max Born's notation for the complex index of refraction, i.e. : $n'(\lambda)=n(\lambda)[1+i\kappa(\lambda)]$.

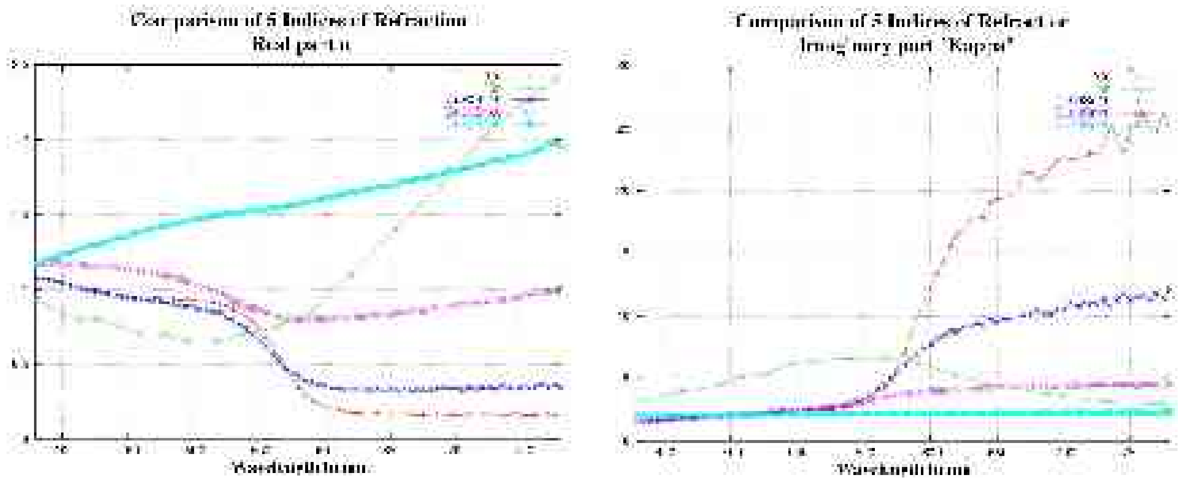

Fig. 6: Complex indices of refraction measured by spectroscopic ellipsometry for polished surfaces of Cu, Sn and three alloys. In red : Copper. In green : Sn. Blue, magenta and cyan curves described samples properties for increasing concentration of tin (10, 20 and 30 % successively).

All the theory of the reflection of light by a metallic surface is available in many optics books and the reader is invited to consult Born (1980) .

A polished copper sample and all the indices of the test samples were measured accordingly to that method for 10-20 and 30 % of Tin in Copper (Fig. 6). For 2 states of roughness for the surface samples, the same method leads to the **effective optical constants** of the metallic surface. Such a result is useful for the visual comparison between roughness influence as determined with the Beckmann and Spizzichino model [refer to (Callet 1998) for details] of the scattering of light by a metallic rough surface and the current measurements (Fig. 7). Increasing roughness tends to increase surface scattering of light and acts as a change in the visual appearance of lightness. The object look like if it was more lighted by the light sources (Fig. 8). All the optical constants measurements for polished metallic surfaces or rough surfaces were placed under the control of Jean-Marc Frigerio à Laboratoire d'Optique des Solides in University of Paris 6.

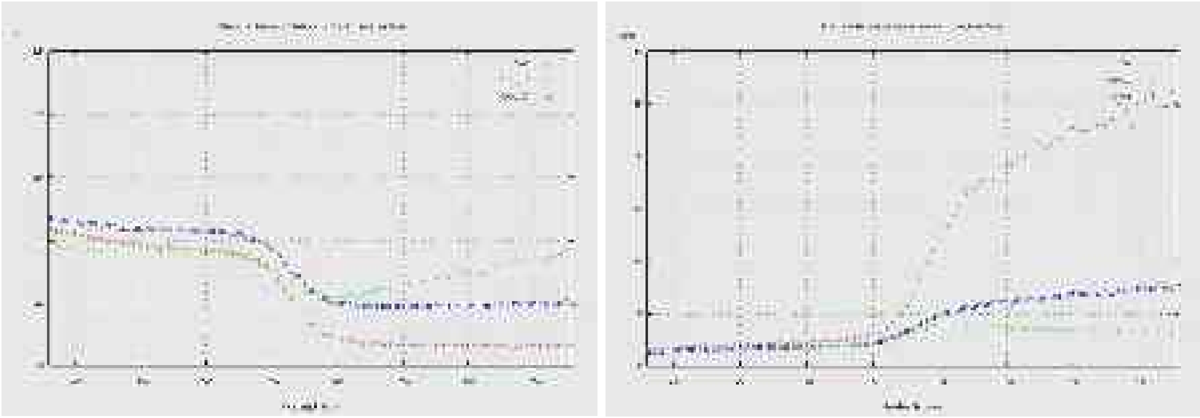

Fig. 7: *Complex effective indices* of refraction for two rough surfaces of pure copper. A polished surface is used as an optical reference (red cuvrves). Increasing roughness reduces saturation and increase lightness. The representative curves are more flattened for high roughness values.

Fig. 8: A smooth surface of pure copper (left) and a moderately rough surface of pure copper (right), placed in the same lighting and viewing conditions. The rough statuette appears lighter due to the scattering of the incident and reflected light from the surface itself.

2.6 Physical replication

An initial physical replica of the original metallic statuette was produced with our specific equipment (SLA 500 device) in a translucent resin by stereophotolithography. This object was used for didactic purposes of moulding by students. An elastomer mould was also produced with the first replica while a direct manufacturing of 4 plaster replicas by a new and more rapid prototyping process was made by our partner Gilles Raffier at Axiatec company. A metallic film deposition of several compositions on these plaster replicas by galvanoplasty (pure copper and 3 alloys) has been realized by Axiatec. One among the four physical replicas was covered by an artistic patina, giving a high similarity of visual aspect with the actual state of the original. A photograph in Fig. 9 shows the replicas in a quasi similar presentation as in Figs. 13. However they differ by lighting conditions and the plane on which the objects are exhibited.

Fig. 9: Three physical replicas in plaster covered by metallic film electro-deposition. A pure copper statuette (left), a golden bronze (center) and a grey bronze (right)

2.7 Ambient lighting modelling for synthetic image generation

As we are interested in a simulation of the original optical appearance of the statuette, just like it was freshly cast by the artist, we have to consider the lighting process of a metallic surface. When light interacts with a metallic surface, there is no internal scattering phenomenon responsible for a coloured appearance. This is not the case with pigmented media such as paints or plastics where a continuum (a resin, an oil or water) is embeddind a discontinuum composed by the mixture of pigments. Pigmented media scatter, reflect and transmit light partially or totally while metallic media (if not deposited in too thin layers) are opaque and only reflect light.

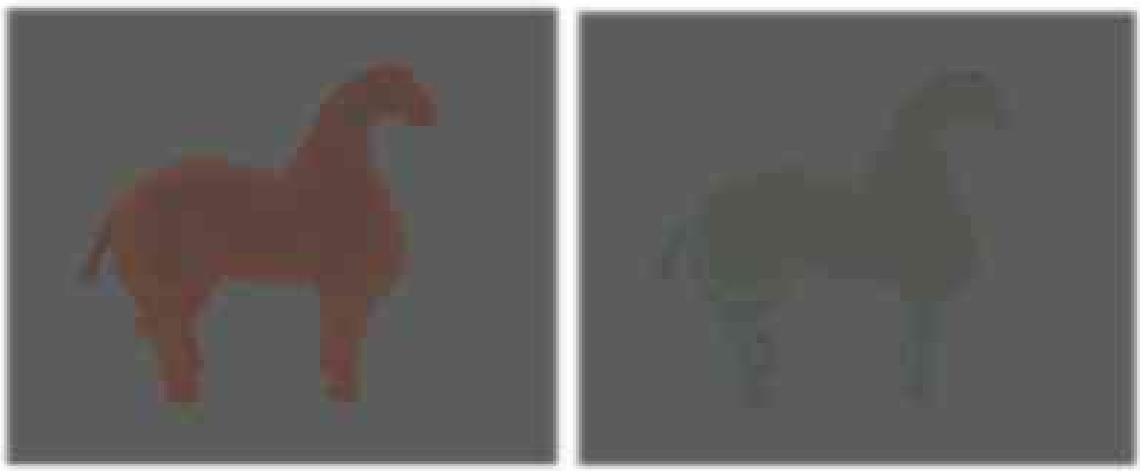

Fig. 10 : Visual aspect of the virtual statuette with smooth surface in orthotropic lighting conditions with CIE D65 illuminant only.

There is however an other kind of scattering of light by a metallic surface, depending on the state of surface and due to the diffraction of light by small irregularities. This surface scattering is due to roughness and acts as if the surface was whited. Let us consider an ambiant light having a very homogeneous spatial distribution and incident from all direction on a metallic smooth surface. If there are no localized light source at all, this metallic material appear completely matte (Fig. 10) and it may be difficult to understand that it is really a metallic object. As we know the optical properties of the metallic surface placed in such conditions, it is possible to compute the reflectance of the surface for such an uniform lighting. It is called orthotropic lighting and used for approximate an ambiant lighting. Generally, in ray-tracing algorithms this lighting is replaced by a pure constant term and no dependence on viewing angle. The calculation of this ambient term, based upon Fresnel reflection laws leads to the definition of the SWR (Surface of Whole Reflectivity). An historical approach of this lighting was described in previous results presented in 2001 at the AIC congress. This approach may be considered as an extension from the first due to Walsh (1926), followed by Judd (1942) and more recently Mandelis (1990). All the previous works are limited two a real complex index of refraction and obviously to a 2D representation. The 3D representation of all the possible reflectances due to an orthotropic lighting, called SWR, is drawn in Fig. 11.

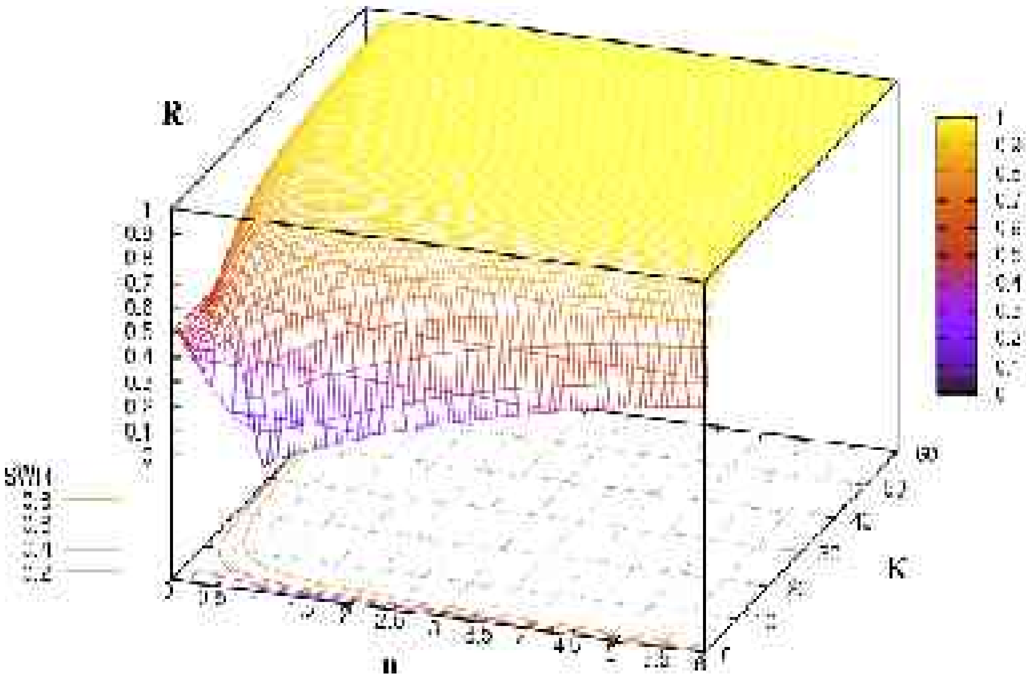

Fig. 11: The Surface of Whole Reflectivity SWR, drawn for **n** ranging in[0;6] and K in [0;60]

Notice that for noble metals the real part of the index of refraction over the visible spectrum has very low values (less than unity). There is no place here for describing all the properties of such a surface. The SWR results from the integration of the complex Fresnel reflectance factor for an orthotropic illumination over a smooth surface. For real and ordinary surfaces the roughness acts as a « radio button » for modifying the mean angular and spectral reflectance magnitude R.

For a best comprehension of the physical properties of all the compounds and of the resulting optical properties of these binary alloys, it is more convenient to draw the index values for each metal or alloy. This is shown in Fig. 12.

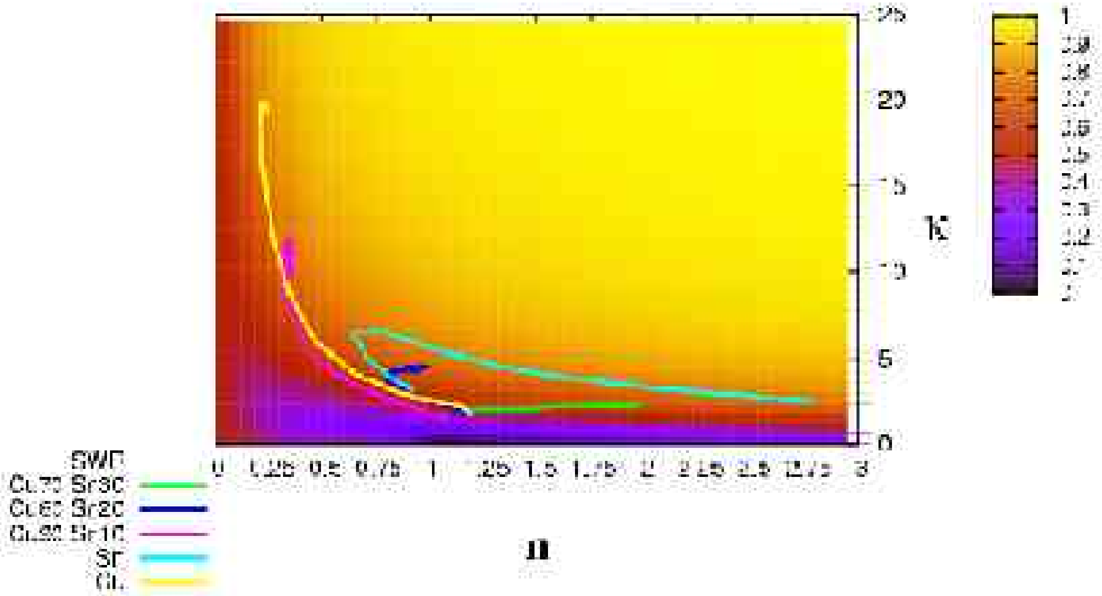

Fig 12: Viewed in the plane (n, K) are the complex indices of refraction of the compounds and the three manufactured alloys.

2.8 Spectral simulations

With a correct characterization of the metallic material, its state of surface, the lighting conditions and a standard colorimetric observer, we can compute a visual aspect of the statuette as it was just cast by the artist. The images are obtained by a parallelized ray tracing algorithm using 80 wavelengths bands of 5nm width. The virtual statuette geometrical data are hierarchically distributed inside hundreds of bounding boxes (Fig. 13). This is made to speed up the ray-surface intersections determination. However we could not take a small particle of the original statuette for a complete analysis since all prelevements were forbidden. As the object was not allowed to exit the museum building, a PIXE (Proton Induced X ray Emission) analysis was no more possible to identify the elementary composition of the metallic statuette, as it would be required to reach the most plausible visual aspect obtained by the artist in ancient times. Nevertheless, with these constraints we obtained a complet range of visual aspects based upon metallurgical composition of bronzes. The results are presented in the images placed in Fig. 14 and 15 for two kinds of lightings. In the two series of computations, the conditions are similar. In Fig. 15 there is no influence of the environment as the statuettes are placed in black universe with an orthotropic ambient light and three point light sources.

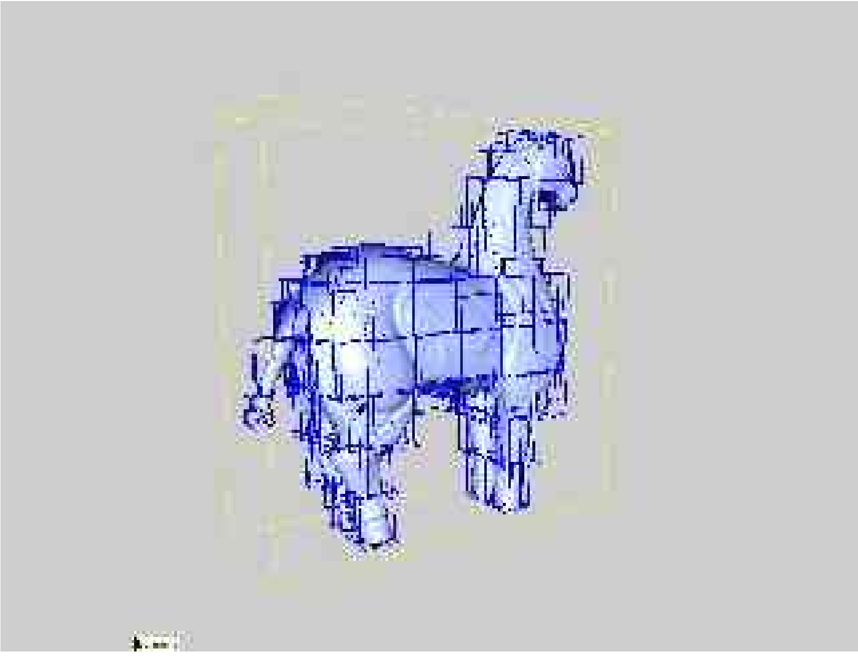

Fig. 13: The bounding boxes used for the spectral ray-tracing rendering of about 1 million triangles. Fast visualization, here, is made with a specific OpenGL viewer.

	
	CIE D65 ambient lighting and three point light sources represented by CIE D65 illuminant too. Same moderate roughness for each statuette. Same standard CIE virtual observer (1964 – 10°) The reference for the compounds are given by a virtual replica in pure copper on the left and of pure tin on the right of each simulated alloy. Notice the slightly bluish aspect of pure tin.

Fig 14: Spectral parallel ray-traced images of three replicas of the original statuette. Only the central statuette differs its material composition in each image : 30 % tin (upper left), 20% tin (upper right), 10% (bottom left)

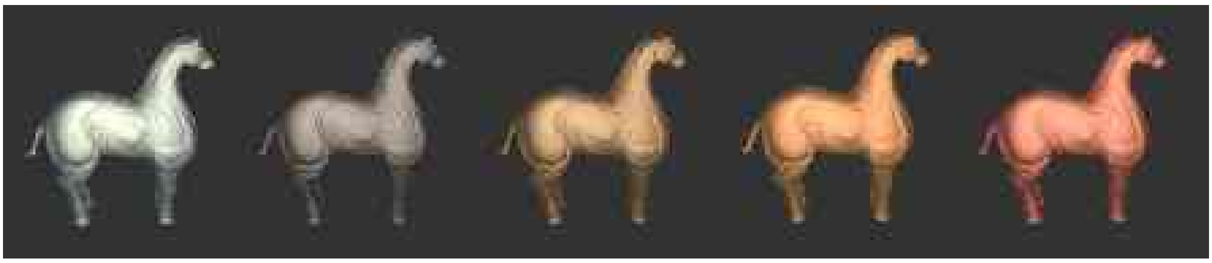

Fig 15: Three simulated replicas in bronzes between the fundamental compounds of pure Tin (left) and pure Copper (right)

2.9 Communication

A DVD presenting the main results of that project was produced with Philippe Denizet and Marie-France Monanges at the AudioVisual workshop of .Ecole Centrale Paris. It also was the opportunity to produce two other versions of the movie in greek and chinese languages. Other students, out of the specific team have contributed to these translations. Thanks to Milka Kartsonaki and Nikos-Richard Degleris for the greek version and to Florence Lai and Jia Jia for the chinese one. In september 2004 a public presentation of the virtual and physical replicas at the National Museum of Asiatic Arts- Guimet, in Paris, was given during a conference.

3. Conclusion

A scientific methodology, many physical experiments and measurements were necessary for this project to be a success. The spectral simulation of metallic surfaces based upon their metallurgical composition is now validated. It is possible to simulate any realistic bronze aspect based upon the optics laws when using the complex index of refraction and its simulation bounded by specific measurements. The original aspect of a large category of metallic material could be recovered by such an approach. The previous results obtained on silver-lead mesopotamian (Mille 1998) alloys confirm the methods presented at ICHIM'05.

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