GPU SPECTRAL VIEWER
A Tool for an Enhanced Colorimetric Perspective of Cultural Heritage

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Abstract: During the EU IST project CRISATEL the consortium made around one hundred multispectral scans of paintings conserved in several museums. The high resolution images obtained allow us to not only have an accurate colour rendering but also to perform in depth quantitative scientific measurement on the colour structure of these works of art.
One of these paintings in particular required special attention. It was Leonardo da Vinci's "Mona Lisa". In order to study it special GPU-based software was developed. In this paper we will present how GPU computation and computer vision can deliver the high performance and the analytic capability required to study complex works of art in a different and subtle way.

1 INTRODUCTION

The CRISATEL EU Project (RSPL05) gave us the possibility to design and construct an innovative camera. This new camera is able to scan at ultra high resolution (12,000x20,000 pixels) at 13 different wavelengths of light from the ultraviolet to the near infrared covering the whole of the visible spectrum. Multispectral analysis of paintings, available via a complex image processing pipeline, allows us to investigate and navigate within the details of a painting in ways that were unavailable until now.

To perform the analysis of the Mona Lisa in the limited time we had, it was necessary to develop a special processing tool to better perform our complex image analysis in a way suited to art preservation. GPU based software is better than common CPU driven computer visualization software because we offload the algebraic processing to dedicated processing units with the GPU, which are designed to handle these kinds of calculations. This allows us to provide the user with a custom image processing tool with the necessary precision and responsive high performance in order to analyze and simulate new case studies.

In order to better understand the functions of the different software modules built for this application we introduce the colour computations used to handle the multispectral images. The GPU core algorithm has been described in a previous, related, publication (CPP*06).

2 COLOUR COMPUTATION

The *CIEXYZ* system is based on the response curves of the eye's three colour receptors. Since these differ slightly from one person to another, CIE has defined a "standard observer" whose spectral response corresponds more or less to the average response of the population. This objectifies the colorimetric determination of colours.

The CRISATEL project produces 13 images which correspond to the following 40nm bandwidth filters: 400, 440, 480, 520, 560, 600, 640, 680, 720, 760, 800, 900 and 1000nm. Only the first 10 filters interact with the visible part of the spectrum. Considering this, the *XYZ* tri-stimulus formulae are:

$$\begin{cases} X = \sum_{\lambda=400}^{\lambda=760} x(\lambda).R(\lambda).V(\lambda).L(\lambda) \\ Y = \sum_{\lambda=400}^{\lambda=760} y(\lambda).R(\lambda).V(\lambda).L(\lambda) \\ Z = \sum_{\lambda=400}^{\lambda=760} z(\lambda).R(\lambda).V(\lambda).L(\lambda) \end{cases} \quad (1)$$

where $R(\lambda)$ is the reflectance spectrum, $V(\lambda)$ is the varnish transmittance and $L(\lambda)$ is the light spectrum (used as illuminant). Using these formulae we can compute the resulting *XYZ* values for each pixel of the source image. One of the modules of our application can simulate varnish removal using the known transmittance properties of the varnish based on this formulae. Of course, the obtained values are only an approximation of the values that would be measured in front of the original painting.

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$CIEL^*a^*b^*$ colour space is derived from *CIE XYZ* (1931) and is an attempt to linearize the perceptibility of unit vector colour differences and provide a scientific basis for the measurement of colour. The colorimetric difference measure is called ΔE and exists in different forms. In our software we use three of them:

- ΔE_{76} the Euclidean distance (CIE95);
- ΔE_{94} distance based on psycho-visual experiments (CIE95; LCR01);
- ΔE_{2000} complex distance also based on psycho-visual experiment (LCR01). This distance computation requires the use of some CPU consuming mathematical functions, which are more efficiently handled in the GPU.

In order to provide calibrated colour (similar to the effective colour stimuli) on a specific display device we must also make sure we characterize it (VT99). Visualization device calibration is based on the input (e.g. *RGB* input values of the display device) and the output (e.g. *XYZ* values measured on the display device by a spectrometer) values. This characterization process is used to calibrate the visual quality of the colour generated by our software using a custom virtual illuminant (fig. 3). A specially designed module in our software is in charge of the calibration process. It allows us to generate a 3D Look Up Table (LUT) that will be used to compute the *RGB* values needed to display, or to print, the closest colour stimuli corresponding to the mathematical $L^*a^*b^*$ model.

All these computations are done in the GPU providing a real-time interaction environment where the user can manipulate different parameters.

3 SOFTWARE MODULES

This section will present all the colorimetric measures and visualization modules that will be used in our application. This software is based on a 2D rendering engine developed in-house which uses OpenGL. This engine was designed to be platform independent and run on Linux, Unix, MacOSX and various versions of Windows. It requires, however a Shader Models 3.0 compatible graphics card (such as the latest *n*VIDIA^{TM}graphics cards) in order to work fully. A custom C++ library based on a composition engine has been designed for this purpose. This library allows us to build applications from a new set of widgets rendered using textures and frame buffer objects. The result is a fast and portable GUI with additional eye candy such as transparency and 3D effects that make the user interaction more friendly.

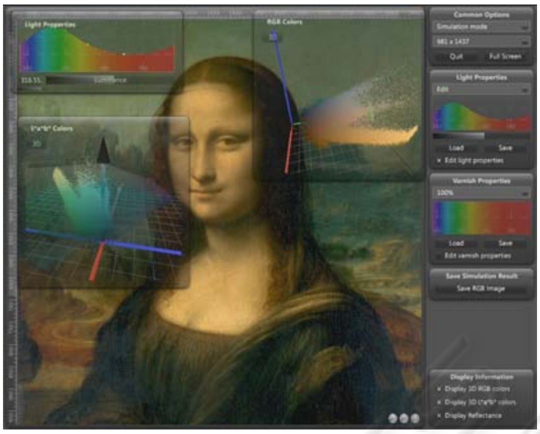

Figure 1: Simulation of a custom illuminant.

3.1 Multispectral Information Visualization

The multispectral information visualization module is used to display the reflectance image as a set of 16*bit* grey level images. Different LUTs and a gamma correction factor can be modified during the visualization process (fig. 2).

Figure 2: Reflectance image visualization.

From the perspective of the expert user, the ability to superimpose and compare different wavelengths or perform other mathematical operations, such as subtracting views etc, on the multispectral images at high resolution is a huge improvement on traditional analysis using low definition, separate and monospectral infra-red, colour and ultraviolet images. To search, for example, a drawing under the paint layer done using graphite we simply have to search in the infra-red (NIR, between 850 and 1050m) images.

3.2 Colour Reconstruction

Based on *XYZ* and $L^*a^*b^*$ colour spaces and on a our colour management process, this module allows the user to interact in real-time with a virtual environment light source (CBR03). All the generated and displayed images are High Dynamic Range images (HDR).

The graphic interface associated with this module includes:

- an *RGB* image viewer;
- a virtual light selector (based on standard illuminants or on customized spectra);
- a virtual varnish simulator;
- a $L^*a^*b^*$ colour cloud viewer, including the gamut of the current display (we use it in order to see if all the colours are visible on the current display device);
- an *RGB* colour cloud viewer (fig. 3).

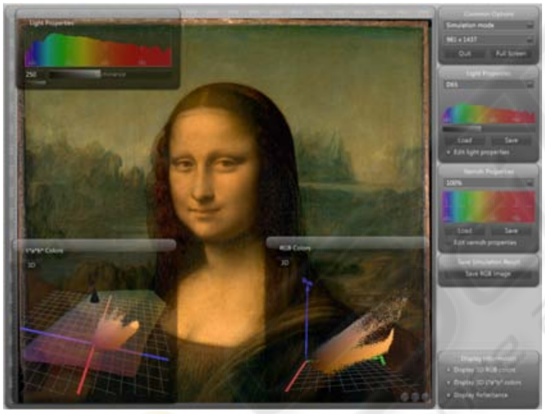

Figure 3: Colour reconstruction.

This module is intended to help the simulation of different environments. For example to simulate the light used in an exibition, or to allow CMYK calibration for reproductions.

3.3 Colour Measurement

We use the same GPU processing graph for this module as that presented in (CPP*06) but the resulting $L^*a^*b^*$ colour image is different because we use the white reference as a virtual illuminant to do the computation. Using this new $L^*a^*b^*$ image we can provide a more usable and precise interface for colour selection (fig. 4).

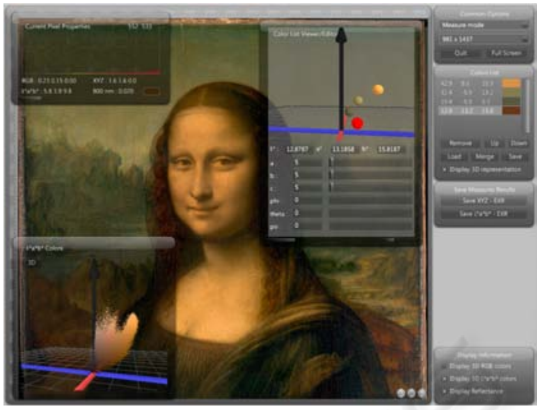

Figure 4: Colour measure.

3.4 Sensor Simulation

The analysis of a painting using colour can not be precise using a simple colour reconstruction based on different virtual lights (metameric analysis for example (S05; B01)). For this reason we have created another module which allows the user to choose interactively the sensitivity curves of a virtual *RGB* sensor. These sensitivities can be based on existing sensors (like in fig. 5) or interactively drawn by the user.

Figure 5: Simulated sensitivity of a Canon 20D.

3.5 Colour Segmentation

The segmentation process investigated for this application is based on colour clustering and threshold approaches. It can be time consuming, especially if we use a complex colour distance (e.g. measured with ΔE_{2000}) and a large set of reference colours. The two methods are described here:

- *threshold*: associate a ΔE threshold (ΔE_{76},ΔE_{94} or ΔE_{2000}) to a reference colour. This generates a 3D primitive (sphere, ellipsoid or cylinder) in $L^*a^*b^*$ colour space. The colours appearing in this 3D volume are associated to the same label (fig. 6);

- *clustering*: uses an algorithm which isolates and labels individual colours by finding in a colour reference set the closest match. With this step we provide a full segmentation of the image.

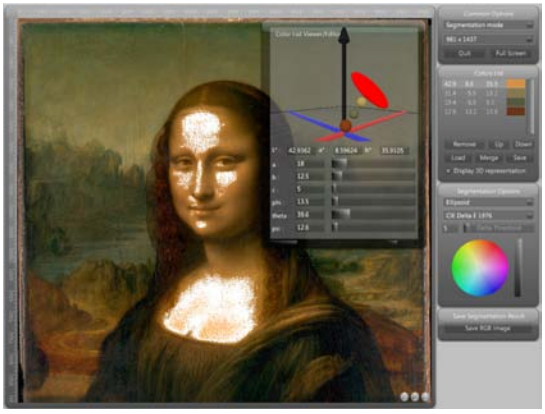

Figure 6: Segmentation.

3.6 Colour Cloud Analysis

The colour cloud analysis can be done using a 3D representation of the colours in the $L^*a^*b^*$ space (fig. 7). This module is useful in order to apply a statistical view of the colour distribution of the painting and it includes:

- the colour cloud
- the selected colour (associated to the corresponding 3D primitives)
- the 2D and 1D histogram (showing the colour density)
- a pigment injection utility (with the 3D representation of pigments identified by their reflectance)

Once we have obtained the colour map we can start investigating the relationships between the different colour groups looking at their position in $L^*a^*b^*$ space. For example, whether the pigment is pure or mixed, whether areas are composed of the same pigment, etc.

3.7 Luminance Elevation Map

This module is a useful tool for colour experts who wish to analyse separately each colour component (luminance for example). A colour component (L^*, a^*, b^*, X, Y, Z , R, G, B) is represented as the Z value

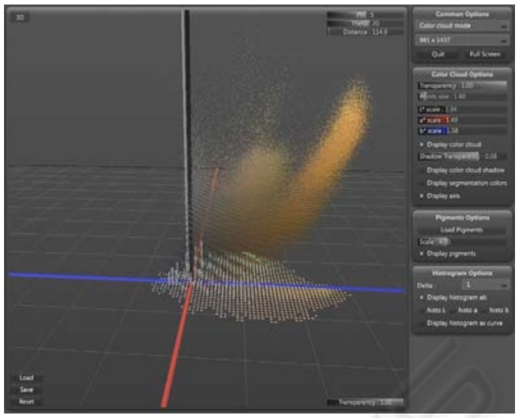

Figure 7: Colour cloud analysis.

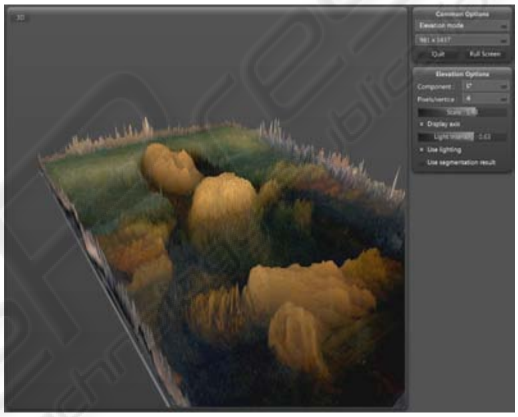

Figure 8: Elevation map. We can easily identify areas of higher luminance.

in an elevation map where the reconstructed image is mapped.

In figure 8 we can see that the highest luminance values are around the chest of the “Mona Lisa”. The high peaks that we can see around the border represent areas of pigment without (luminance reducing) varnish.

4 RESULTS

In this section we provide some benchmarks, such as the computational time of different processes for a 1963×2874 pixel $\times 13$ planes (using half float internal representation - 16bit per channel) reflectance image. We used a 3D graphics card based on an *n*VIDIA^{TM} G80 graphics processor (GeForce 8800 GTX) with the following specifications: 575MHz GPU core, 1350MHz stream processors and 768Mb of 1800MHz RAM (SDRAM DDR3).

All these operations (table 1) correspond to a

Table 1: Simulation Measure Process and Sensor Simulation Process.

processing type	Time	Images/s	Pixels/s
colour simulation	0.010311149	96.9824	$547 * 10^6$
sensor simulation	0.00648231	154.266	$870 * 10^6$

per-pixel process which requires the execution of a pipeline of several complex mathematical and vector calculations (FM04). As the GPU is more suited to these kinds of operations, the results obtained are an improvement in comparison to using only the CPU.

Table 2: Segmentation process.

colours	ΔE	Time	Images/s	Pixels/s
1	1976	0.000652175	1533.33	$8650 * 10^6$
1	2000	0.003529765	283.305	$1598 * 10^6$
5	1976	0.005996138	166.774	$940 * 10^6$
5	2000	0.043635729	22.917	$129 * 10^6$
10	1976	0.01042655	95.909	$541 * 10^6$
10	2000	0.086909666	11.5062	$65 * 10^6$

Table 2 indicates that the GPU performs very well in this particular case study; especially if we only segment one colour. Nevertheless, it looks like this algorithm grows linearly with the number of colour references used.

5 CONCLUSIONS

The main aim of this work has been to investigate and develop a new tool to help in the study and the analysis of multispectral images of paintings. The work was focused on developing something innovative for the Cultural Heritage domain using new technologies such as GPU-based computation systems. The potential offered by colour spectrum decomposition techniques opens up new ways to study works of art.

The Mona Lisa not only gave inspiration to Leonardo, but also to our group to develop an application capable of discovering details otherwise invisible to the naked eye. This approach based on the fusion between art, science and computer vision represents a valuable aid in the field of art conservation, restoration and art history and will require more in-depth investigation and a more multi-disciplinary community.

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