ESTIMATION SYSTEM FOR PIGMENTS OF JAPANESE PAINTINGS

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Abstract: Common analysis techniques for artworks such as FTIR or Raman Spectroscopy usually employ high-energy radiation sources, which often require the removal of material from the sample making the analysis relatively destructive. This is unacceptable for samples with high cultural value. Therefore, there is a need to develop alternative non-destructive and non-invasive analysis methods. This paper presents an approach for pigment estimation software for Japanese paintings. Reflectance spectra were reconstructed from the RGB values of digital images with the help of multiple linear regression analysis. A reference database with measured reflectance spectra of the most common pigments used in Japanese artworks was established and used for identification by comparison. Results have shown that estimation can be successfully performed with only 2% error. The estimation results show some promise that the system could become a powerful tool after further addressing the factors which interfere to reconstruct the spectra.

1 INTRODUCTION

In 2002, UNESCO, through the Charter on the Preservation of Digital Heritage, put the importance of protection and conservation of cultural heritage into the world spotlight (UNESCO, 2003). At the same time the fields of imaging devices as well as image processing have been advancing to a great extent. Digital image analysis grew to one of the key technologies. It offers diverse tools and analysis techniques necessary to enable and support the preservation of digital heritage.

Due to the precious nature of cultural heritage, it was found necessary to develop an analysis method of paintings to support historical research as well as adequate restoration, by determining the materials used in the artwork. Conventionally, popular techniques that make use of high energy radiation such as X-ray Fluorescence (XRF) (Mantler, 2000, Moioli, 2000, Szoekefalvi-Nagy, 2000) or Accelerator Mass Spectrometry (Katayama, 2007) are employed in analyzing historical artworks and artefacts. Although XRF is categorized as a non-destructive analysis method, it requires radiation of high energy x-ray onto the object or even removal of material. Therefore there is a need for a "true" non-destructive and non-invasive technique. This paper presents a method for pigment identification of paintings using digital color images that were acquired by contact-less scanning. Since characteristics of a material and its color are related, a material can be identified by spectroscopy.

A standard spectrophotometer is not capable to measure small areas with sufficient precision. In other research this problem was solved by employing a goniophotometer for measurements (Andersen, 2005). Unfortunately this method is too convoluted for our approach and can therefore not be applied. At the same time various approaches to construct spectral characteristics from a digital image were proposed by Murakami (2001), Novati (2005) and others (Haneishi, 2000).

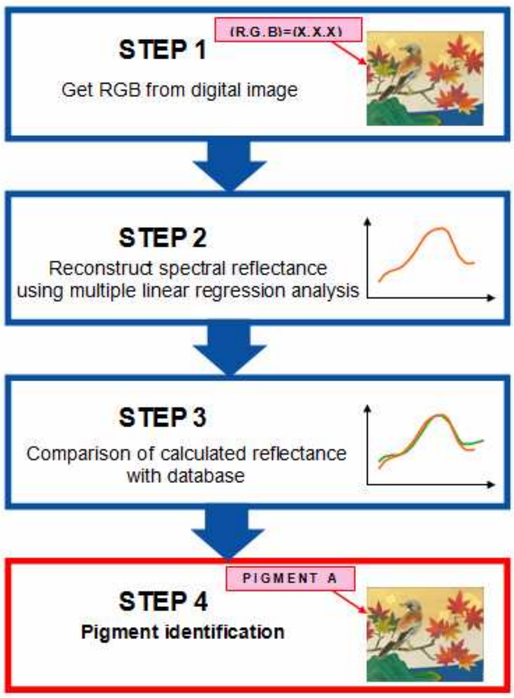

Figure 1: Flow chart of pigment estimation process

A simple approach for a pigment estimation method based on the comparison of reconstructed reflectance spectra in the visible light range with a reference database is presented in this paper. The sequence of the estimation process is shown in Figure 1.

2 METHODS

2.1 Image Acquisition

For digital image analysis it is crucial that images contain sufficient and correct information of the sample to be analyzed. Even though required accuracy might differ depending on the purpose, factors such as high resolution, true color recording or bit depth are always important to gain significant information. It is advised to refrain from using image acquisition tools which perform automatic image enhancement.

The evaluation of the imaging process includes assessment of scanner noise, resolution, linearity, flare as well as true color acquisition. The latter is the most challenging factor, which is usually approached with a color management system.

The minimal color difference dE the human eye can detect is said to be at 1.0 (Dochev, 2008). This value is important when it comes to displaying images whereas from an analytical point of view dE should be close to zero to achieve results with high accuracy.

In this research a multifunctional imaging device with a dE of 1.2 was employed.

Information of a digital image is physically limited by boundary conditions during the digitalization process. It is desired to scan with high resolution to maximize the amount of pixels which contain the crucial colour information. A method to reconstruct the reflectance spectrum had to be developed because based on only the tristimulus value (RGB) identification of a material (pigment) remains ambiguous.

2.2 Algorithm

At first principal component analysis (PCA) was conducted on the reflectance spectra of Japanese pigments to investigate the feasibility of estimating the spectral characteristics of an object based on the three signals, R, G and B gained from a digital image.

The spectral reflectance of 440 different pigments was measured from 400 to 700 nm, with a step width of 10nm. The cumulative contribution ratio of the PCA showed that reflectance spectra could be reconstructed with approximately 97.5 % accuracy based on 3 principal components (R, G and B).

The tristimulus value T_i at position xy can be calculated by

$$T_i(x,y) = \int_{400}^{700} E(\lambda) s_i(\lambda) o(x,y,\lambda) d\lambda + n_i(x,y)$$

(i = B,G,R) (1)

where *E* describes the spectral power distribution of the illumination, *s* the sensitivity of the *i*th channel and the lens as well as the integral of the sensor sensitivity. Spectral reflectance is represented by *o*. The noise n will be neglected for further calculations for simplification. Formula (1) can be rewritten in matrix form with S as a matrix consisting of sampled values in the visible light range

$$T(x,y) = S^T Ar(x,y) \quad (2)$$

The vector showing the spectral reflectivity on the object is represented by r, E is a diagonal matrix for the spectral radiance. By putting $S^T A$ together as G the formula can be rewritten as

$$T = Go \quad (3)$$

The inverse of G can not be generated because the element count of the reflectance spectra $\boldsymbol{o}$ is larger than the element count of the sensor $\boldsymbol{v}$ .Therefore the pseudoinverse of G, called H is used with $\boldsymbol{o_{est}}$ as the estimated spectra:

$$o_{est} = HT \quad (4)$$

Reconstruction of reflectance spectra of commonly used Japanese pigments is performed. Figure 2 compares the calculated with the measured curve of four pigments. It is evident that the typical characteristics of the curves are correctly and sufficiently reconstructed.

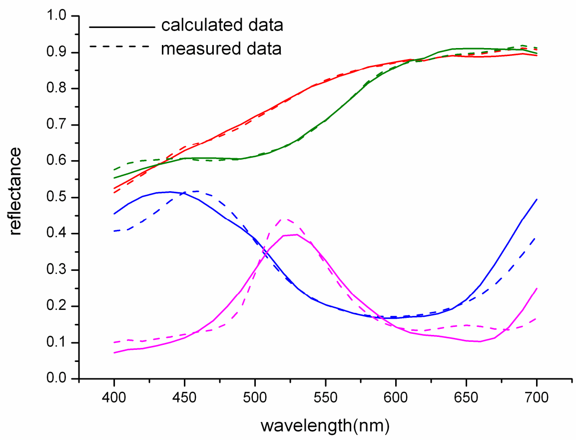

Figure 2: Comparison of calculated data with measured data

An average error $\Delta\bar{o}$ of only 2 % was calculated between the computed and the measured value at every wavelength for all 440 pigments in the database by the root mean square

$$\Delta\bar{o} = \sqrt{\frac{1}{l}\left(\sum_{400}^{700}(o_\lambda - o'_\lambda)^2\right)} \quad (5)$$

where l is the number of single wavelengths considered and o' represents the computed spectral reflectance. During the matching process the software compares the reconstructed spectra with the database and puts out the three pigments that yield the least estimation error.

3 SOFTWARE IMPLEMENTATION

3.1 System Structure

The algorithm presented in the previous section was embedded in user friendly software. The image file displayed by the graphical user interface (GUI) allows the user to easily select regions to be analyzed by mouse click. After selecting one of the analysis options, namely pre-estimation, standard estimation and target estimation, the material estimation system will compare the spectra reconstructed by the estimation algorithm with the database.

The results are displayed directly within the image file as well as stored in a project file which contains detailed data such as the result's reliability (see Figure 3).

The program works under Windows XP and it can be chosen between English and Japanese language. If required, the user can change the database by adding materials.

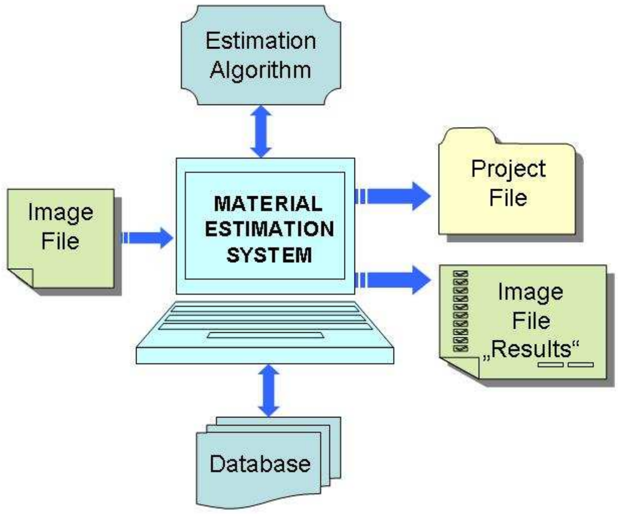

Figure 3: System Structure

3.2 Database

A database with information on 440 pigments was established. It includes not only the measured reflectance spectra but also pigment name, mineral name, molecular structure as well as color values (RGB & L*a*b*) and chemical composition. Furthermore additional information such as, references and explanations on the time frame, area and technique a pigment was used is available. Fed with numerous data on the pigments, the software is expected to become a useful tool for research on cultural heritage, as well as in the fields of material science and art.

3.3 Functionality/Options

In order to get good estimation results, digital file of paintings to be analyzed should be of high-resolution, contain low noise and are ideally a product of an imaging process with a "sound" color calibration.

Various optional conditions, such as "natural pigments only" or "old painting mode", can be set by the user, which will limit the candidates used for comparison and in turn leads to increased accuracy. The results are quickly displayed and each pigment's individual register card where all its information is collected can be accessed.

4. Results and Discussion

4.1 Pigment Test Chart

The software was tested on a reference pigment chart and a common Japanese paintings with all materials used known prior to the analysis.

15 different pigment types were arranged on the pigment chart (Figure 4) with number 1-14 being natural pigments and number 15 representing a new mineral pigment. Furthermore, pigments 1-10 depict samples used in old paintings. The paint was applied with a sufficient thickness, which does not necessitate an additional coating layer.

Three different conditions were tested.

a) Default mode (No limiting condition selected)
b) Natural pigments only
c) Old painting mode

In the case of an ambiguous result, the three pigments with the lowest errors were automatically selected by the software.

A successful distinction between the blue pigments "natural ultramarine blue" and "new mineral ultramarine blue" was achieved. This implies that accuracy can be improved by specifying some limiting conditions whenever it is possible.

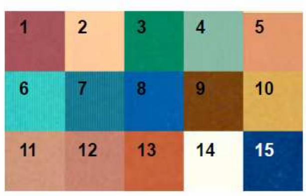

Figure 4: Pigment Test Chart

Table 1: Results of pigment identification of Japanese painting

NO	Image Color	Pigment Name	Estimation Results	
			Default	**Old Painting Mode**
1		Malachite	Artificial Ryokusho	Malachite
2		Gunjo (Azurite)	Gunjo Smalt Bi - Ultramarine Blue	Gunjo
3		Vermillion	Laccifer Lacca Kerr Peach Color Red Vermillion	Iron Oxide red Old Chinese red Vermillion
4		Yellow Tinge Vermillion	Strong Yellow Vermillion Mars yellow Red birch	Strong Yellow Vermillion Yellow Vermillion Colored Sumi Vermillion
5		Coral Red	Rachel Agate Branch Coral Red	Coral Red Yellow Ocher Dirty Brass Blue
6		Malachite	Malachite	Malachite
7		Burned Verdigris	Ryokuun Powder Ryoukai Powder Roasted Brown	Burned Verdigris Black Vermillion
8		Chalk	Chalk Lead White	Chalk Lead White
9		Yellow Rattan (Chalk underneath)	Dark Yellow Yellow Yellow Rattan	(out of range)
10		Pine Needle Verdigris (Yellow Rattan and Chalk underneath)	Artificial Gunjo Siskin Color Sabikicharoku	Burned Verdigris Yellow Ocher
11		Yellow Ocher	Rugged Yellow Ocher Rachel Yellow Ocher White Tea	Dirty Brass Blue Yellow Ocher Rachel Yellow Ocher
12		Burned Verdigris	Burned Verdigris Blue Green Tea Artificial Ryokusho	Burned Verdigris

4.2 Japanese painting

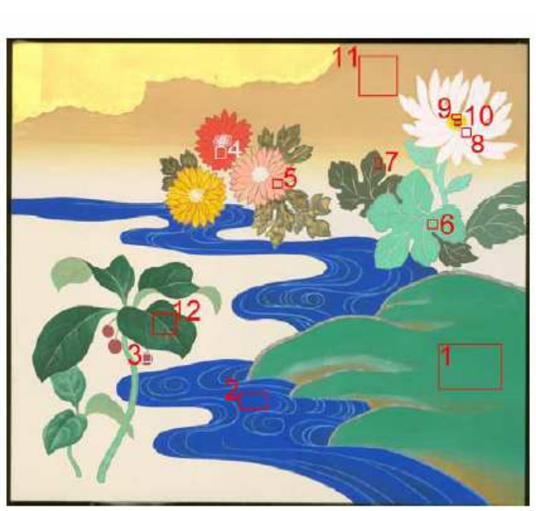

Figure 5: Japanese Painting

There are various techniques used in traditional Japanese paintings. These include brush strokes, pigment mixing, over painting and others. This makes the analysis more difficult. In the previous section where a predetermined pigment chart was used to evaluate the estimation method, the painting technique employed was simpler. The chart was painted using only one pigment with a single layer. To address this concern, the reconstruction technique was performed on a common Japanese painting created by using common techniques such as over painting and "shaded painting". As shown in figure 5, 12 different positions to be analyzed were selected. The test was performed using two boundary conditions given as follows:

a) Default
b) Old painting mode

Results are shown in table 1 where the pigments marked in red are correctly estimated. It was found again that by selecting an appropriate boundary condition (i.e. old painting mode), better results can be obtained.

Pigment identification of the red colors at position 3 and 4 was difficult. In addition, pigments applied by employing over painting or shaded painting at position 10 and 11 also posed some challenge.

Two reasons were identified that may explain why there were difficulties in identifying red pigments correctly. At first the number of red pigments in the database is comparatively high. In addition, the characteristic reflectance spectra of red colors reach into the infrared region which means a comparison only in the visible light range may not be sufficient. In case of position 10 and 11 it is believed that due to over painting the white-yellowish color below the main colors, it might have resulted to false reconstruction of the spectral reflectance.

4.3 Analysis of cultural heritage

To show the validity of the system for the analysis of actual cultural heritage a genre painting on a sliding door, exhibited in the Nijo castle in Kyoto was analysed. This artwork showing a scene of the daily life of Japanese upper class was drawn before the Meiji period. Analysis was performed on a selected area where more details can be seen as shown in Figure 6. No reliable information about this painting was available. Neither data on era and region nor on materials used was at hand. Therefore validity evaluation of the estimated results was supported by the judgement of a specialist on traditional Japanese paintings. Estimated Pigments are shown in table 2. Regions A and B were identified by the specialist with a high probability to be a blend of soil materials such as yellow and red ocher. Even though the pigment estimation system does not include the analysis of color blends yet, the results are promising nonetheless. A systematic method for the identification of color blends is to be integrated into the algorithm of the estimation software in future analysis. For region C the specialists assumes that it was a mixture of Ryokusho (Malachite) pigments of two different particle sizes. This is consistent with the estimation result regarding the material composition.

By burning ryokusho, color degradation due to aging can be simulated. This is a common technique in the old days to vary the shades and hues of a pigment.

In case of area D the specialist’s diagnosis is that it was Japanese ink, which might have been applied with a mixture of chalk. Finally, region E was judged by the specialist to be verdigris or vermillion which is not in accordance with the estimated result.

Even though this experiment delivered quite satisfying results it is recommended to further verify the results by other spectroscopic methods.

Figure 6: Selected part of genre painting for analysis

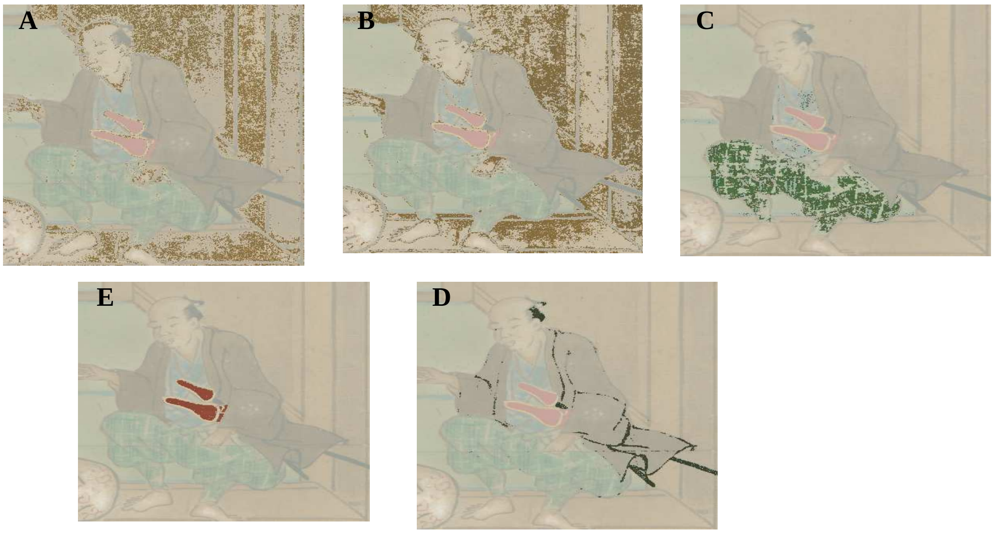

Figure 7: Display of estimation results for genre painting

Table 2: Estimation Results of Genre Painting

Area	Estimation Result	Paint composition
A	Dark Yellow Ocher	Natural soil from silica and clay (color tone ranges from dull light to red bronze)
B	Yellowish Red Ocher	Fe_2O_3 (Color depends on content of trace elements such as Mn)
C	Burned Ryokusho	$CuCO_3 \cdot Ca(OH)_2$ (calcined)
D	Japanese Ink with Chalk	Composite of C and $CaCO_3$
E	Red Ocher	Fe_2O_3 (Color depends on content of trace elements such as Mn)

5 CONCLUSION

This research was aimed to create image analysis software for the identification of pigments in Japanese paintings. It was shown that pigments can be successfully identified using spectral reflectance reconstruction from digital color information. Additional findings were made such as:

1) Pigments have to be applied in a optically thick layer for a decent result
2) A distinction between new mineral pigments and natural pigments was shown to be feasible with the software
3) This approach is superior to other analysis methods, such as XRF, when it comes to differentiation between pigments with same components
4) Accuracy can be improved by having prior knowledge, e.g. about the era when a pigment was used, and therefore being able to select proper boundary chemical constituents
5) Difficulties were encountered in identifying pigments when over painting or shaded painting techniques were employed.

In order to improve the accuracy of estimation, the algorithm should include dependencies of changes in pigment color due to aging processes and influences of environmental conditions. Furthermore it is proposed that by using more than 3 values (RGB) through the use of a spectroscopic scanner or a multi-band camera the accuracy can be improved further.

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