14th European Signal Processing Conference (EUSIPCO 2006), Florence, Italy, September 4-8, 2006, copyright by EURASIP

THE IMAGE PROCESSING SYSTEM FOR ART SPECIMENS: NEPHELE

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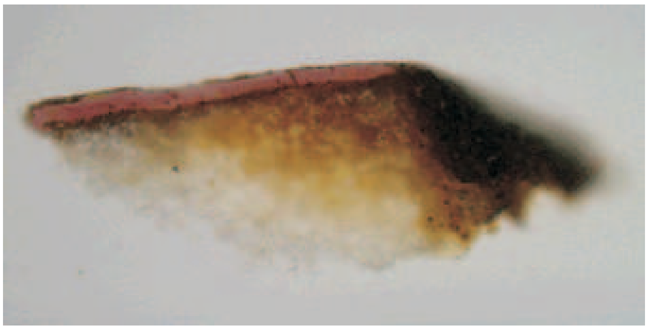
ABSTRACT

In our paper we introduce comprehensive solution for processing and archiving information about artwork specimens used in the course of art restoration - *Nephele*. The information processing based on image data is used in the procedure of identification of pigment and binder present in the artwork, which is very important issue for restorers. Proposed approach geometrically aligns images of microscopic cross-sections of artwork color layers - image registration method based on *mutual information*, and then creates preliminary color layer segmentation - modified *k-means clustering*. The archiving part of the *Nephele* enables creating database entries for painting materials research database, their storage, and creating text-based queries. In addition to these traditional database functions, advanced report retrieval is supported; based on the similarity of image data, comparing either the ultraviolet and visual spectra images (using *co-occurence matrices* and *color similarity functions*), or the electron microscopy images (using features computed from the *wavelet decomposition* of the data).

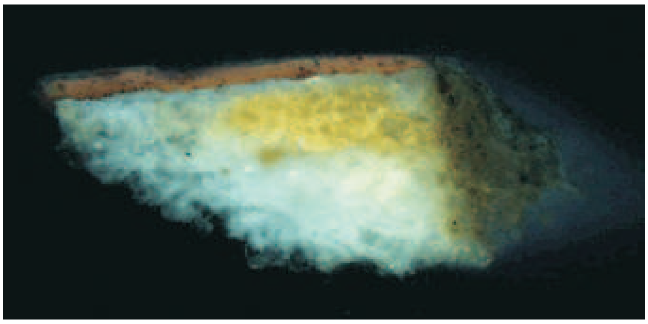
1. INTRODUCTION

Nowadays restorers of historical fine art make use of modern equipment and methods to study and restore damaged artworks. They often exploit various software preprocessing to achieve better input data for further analyzes of the restored artwork specimens. One of the information sources for restorers is painting materials research, which help them to choose the proper materials for the very restoration. Each painting materials analysis is precisely described in the form of the report, which contains general information about the artwork and description and results of analyzes which were hold. Such reports can serve as a knowledge database for further restoration cases.

Image processing algorithms can play important role in both the analyzing as well as in the archiving part. As already mentioned, for the artwork restoration, one of the most important issues is proper identification of pigments and binders in color layers, where the layer is defined as consistent and distinguishable part of a painting profile. This helps to determine the age of the used paints and their possible place of origin [1]. Stratigraphy (learning about layers) of color layers is usually studied in visible spectrum (VS) (Fig. 1(a)) and in ultraviolet spectrum (UV) (Fig. 1(b)). Digital preprocessing of the VS and UV images can help to achieve more accurate conclusions. In the proposed system, a method for removal of geometrical differences between VS and UV images is incorporated together with the creation of preliminary color layer segmentation.



(a) Visible spectrum (VS) image



(b) Ultraviolet spectrum (UV)image

Figure 1: The images of the artwork specimen in visible (a) and ultraviolet (b) spectra. The single color layers are apparent, especially on the VS (a) image.

For the archiving part of *Nephele*, our research concentrated on enabling easy access to archived data. For such database of painting materials research reports, the look-up of archived reports based only on the text information is often not enough. The ability to fetch reports which describe visually similar specimens/materials can increase the helpfulness of the database. However, such a task is very difficult for a human operator without proper software help. We have

This work was partially supported by the Grant Agency of the Czech Republic under the projects No. 102/04/0155 and by the the Ministry of Education of the Czech Republic under the projects No. MSM0021620838, No. 1M0572 (research center) and No. MSM6046144603.

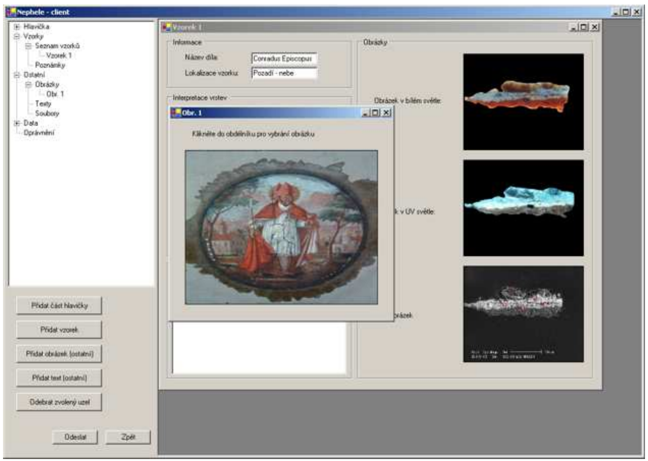


Figure 2: Illustrative example of the main window of the *Nephele* user interface. The restored artwork is shown, together with VS, UV and SEM images of one analyzed microscopic specimen.

incorporated image-based retrieval methods into the developed system. They are based on the feature descriptions of the specimen images. The co-occurence matrices, their compressed representation, and color characteristics are used as features for VS and UV images. The secondary option offering the possibility to exploit the specimen representation by means of scanning electron microscopy (SEM) (see Fig. 7) makes use of the wavelet decomposition of the image data.

The proposed system *Nephele* is in general described in Section 2. Section 3 introduces the image preprocessing part of the system, consisting of the image registration module and image segmentation module. The content-based image retrieval included in *Nephele* which is able to fetch corresponding reports with visually similar data is described in Section 4.

2. SYSTEM *NEPHELE*

The *Nephele* system is the database system for painting materials research reports, extended with the image preprocessing modules and the image retrieval facility. The reports describe the whole process of the painting materials research on the artwork. A report contains general information about the artwork, its author, and used art technique. The information about each studied specimen from the artwork with its localization is included, along with all undertaken analyzes and their results together with estimated color layers and used materials. All taken images are included (for example VS, UV, SEM images, to name the most usual).

The database model was created using the *entity-relationship model* in the cooperation with the experts. The implementation was realized by means of relational database with SQL querying language. The programming part of the system was implemented in C++. For more information about the database aspects of *Nephele* see [2]. The example of the main window of the user interface can be seen in Fig. 2. The restored artwork is shown, together with VS, UV, and SEM images of one analyzed microscopic specimen. The whole system was designed to be able to protect sensitive data, which can be stored in the database (the info about detected materials could be for example misused for creation of falsifications).

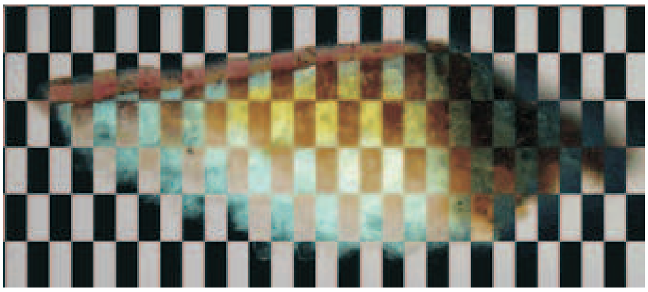


Figure 3: Chessboard mosaic of registered VS and UV images from Fig. 1. The geometrical differences were removed. The geometrical alignment is well apparent on the top border line.

3. IMAGE DATA PREPROCESSING

Proper identification of pigments and binders in color layers is one of the most important issues of artwork restoration. Stratigraphy is usually studied in VS and UV images (Fig. 1), where the UV analysis makes use of the luminescence. Different materials have different luminescence, which can help distinguish materials not resolvable otherwise (only in VS). The analysis works with minute surface samples (0.3mm in diameter) from selected areas of the artwork. They are embedded in a polyester resin and grounded at a right angle to the surface plane to expose the layers. The VS and UV image information is then combined and the final estimate of color layer borders is created, based on the image data and the experience of the experts (possible order and combination of materials for specific artworks, time period, area, etc.).

During the image acquisition process the VS and UV image pairs of the sample are often geometrically misaligned due to the manipulation errors etc. They can be mutually shifted and rotated in the scanning plane and this difference has to be removed before the analysis to be able to compare corresponding structures in the images. Up to now it was done manually by an operator. The proposed image registration module of the system solves the spatial alignment of the image pairs.

After the image rectification, the color layers can be estimated. The tedious manual process can be facilitated by image segmentation methods. The segmentation module performs preliminary segmentation based on both VS and UV images. The construction of the full segmentation is a very complex task, because expert knowledge is often necessary (certain materials cannot be neighbors, others are always together). This is the topic of our further research.

3.1 Image registration

Image registration is the process of overlaying two or more images of the same scene taken at different times, from different viewpoints, and/or by different sensors. Image acquisition devices have undergone rapid development and growing amount and diversity of obtained images invoked the research on automatic image registration. Comprehensive survey of image registration methods can be found in [3].

The task of VS and UV images registration belongs to

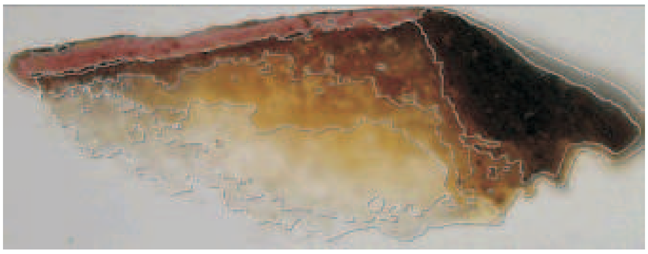


Figure 4: Preliminary estimation of color layer borders for the specimen from Fig. 1.

the multimodal registration category, where images of the same scene are acquired by different sensors. The aim is to integrate the obtained information to gain more complex and detailed scene representation. The main complication of such tasks is that the intensity values do not correspond to each other and it is more complicated to find an appropriate similarity function or features, which are invariant to such changes.

Mutual information (MI), originating in the information theory, is recognized solution for the multimodal registration problem. It is a measure of statistical dependency between two data sets and it is particularly suitable for registration of images from different modalities. MI was chosen because it does not impose strong limitations on used sensors. One of the first articles proposing this technique is Viola and Wells [4].

Mutual information between two random variables X and Y (the VS and UV images) is given by

$$MI(X,Y) = H(Y) - H(Y|X) = H(X) + H(Y) - H(X,Y),$$

where

$$H(X) = -E_X(\log(P(X)))$$

represents the entropy of random variable X and $P(X)$ is the probability distribution of X. The method is based on the maximization of MI.

In our approach, a speed up is implemented, exploiting the averaging pyramid together with discrete estimate of histogram. The optimization of the maxima location is a modified version of the method published in [5]. Moreover, we exploit one-channel data, either green channel of the RGB image representation or the first element of principal component transform (PCT), to reduce the dimensionality of the problem. Results of the registration were evaluated visually by means of ”chessboard mosaic” (see Fig. 3).

3.2 Image segmentation

The color layer estimation can be resolved by image segmentation. Input information consists of the set of three RGB channels of VS and three RGB channels of UV specimen images. Various methods [6] were tested and compared to the ground truth provided by experts. We found out that expert knowledge is used widely during the process (allowed and/or forbidden neighbor pairs of materials). Thus we restricted ourselves to produce preliminary estimates of the color layers. However, even this kind of the output can facilitate the work of operators.

The proposed method is based on cluster analysis using the above mentioned six color channels plus spatial information (x and y coordinates included as another two channels).

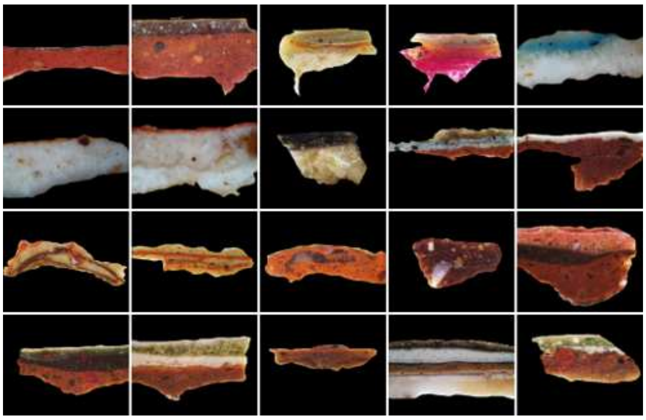


Figure 5: The example of the VS and UV database images of the specimens. It consists of samples taken from various kinds of artworks. Some specimens were scanned several times under different conditions.

It starts with iterative *k-means* clustering. The number of classes is set a priori as a maximum expected number of layers by the user. More complex approaches based on texture analysis or other higher level information could bring slightly better results but without expert knowledge the segmentation still remains preliminary.

Often, relatively smooth transitions from one layer to the other produced ragged borders. First improvement of consistency was achieved by including spatial coordinates to the segmentation feature space. Even better results were obtained after applying morphological operators on detected segmentation and performing minimum class size check. Example of detected layers can be seen in Fig. 4.

4. CONTENT-BASED IMAGE RETRIEVAL

Painting materials research reports for each processed artwork contain the specimen images. They are usually VS and UV images, but there can be other image data like SEM images (see Figs. 5, 7), too. These reports are often used as knowledge base for consequent restorations. For such usage, it is very important to have effective tools to look-up relevant reports. One of the possible extension of the usual database functionality is to exploit the similarity between images contained in reports. The visual image similarity can imply that the used technique/materials on the analyzed artwork is the same/similar as in the archived report or it can point to the same author, therefore such information can be very relevant.

Thus, image-based data retrieval is often used nowadays next to the traditional text-based search in database systems. The database entries containing images are looked-up based on image similarity to the query image. The so-called *content-based image retrieval* (CBIR) is recently very popular [7], [8], and the growing amount of images everywhere ensures its popularity for future, too. The task of CBIR is not mathematically well defined thus most methods are based on heuristics and are combining various approaches from digital image processing.

In our *Nephele* system, two possibilities of image-based data querying were implemented. The first one exploits the VS and UV images of specimens, the second one makes use of the SEM images. In both cases, the similarity of speci-

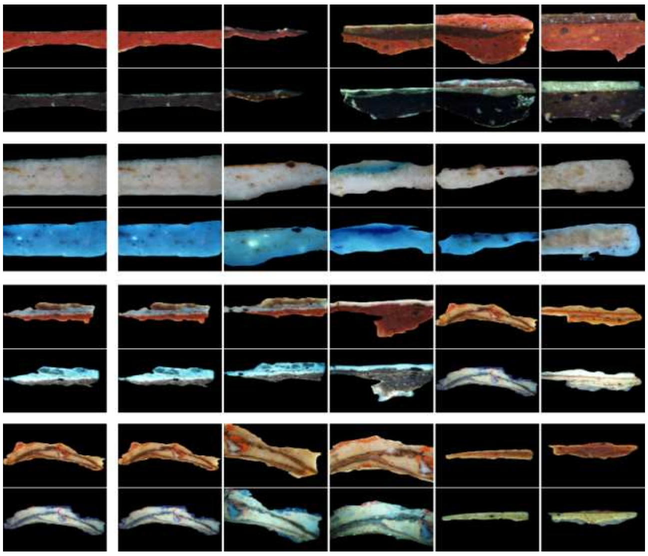


Figure 6: Results of image retrieval. Left column contains query specimens, next columns in corresponding rows are results of the retrieval in order of similarity.

mens is not based upon specific shape or structure elements, thus considered methods of image retrieval should use, as the main features, the color and texture characteristics.

4.1 UV and visible spectrum data

The proposed method is based on *co-occurence matrices* and color features. The co-occurence matrices were introduced here [9]. They reflect the joint probability of occurrence of grey level pairs for two pixels with a defined spatial relationship, formed by shape operator. Used shape operators had length up to two pixels and all color channels were processed separately. Based on preliminary experiments four Haralic descriptors were computed from the co-occurence matrices (Contrast, Inverse difference moment, Entrophy, Variance) [9]. Next to the Haralic descriptors, the color descriptors were included, too, to reflect the main color trends in the data. They are the image average color and the spectral standard deviation. Detailed description can be found in [2] and [10]. The weighted Euclidean metric was chosen for the system. Moreover, the R^*-tree indexing structure [11] was implemented to speed-up the retrieval.

The applicability of the method is presented in Figs. 5 and 6. Fig. 5 shows a few examples from the database of specimens taken from various artworks. Some of them were scanned several times under different conditions. They were used for testing of proposed image retrieval method. Achieved results are shown in Fig. 6. There are query images (leftmost column) together with the most similar responses (in the respective rows, in order of similarity from left to right) are shown. The visual similarity of the specimens in rows is apparent.

4.2 Electron microscopy data

The second possibility of image retrieval in *Nephele* is based on SEM images of the specimens. Fig. 7 shows a few detailed cut-offs of the color layers in SEM modality representation. The diversity of the materials is clearly visible.

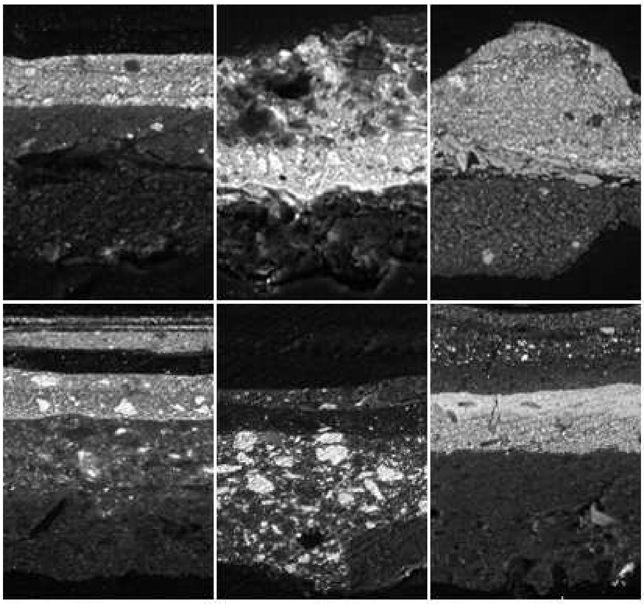


Figure 7: Example of the database SEM images. Small representative cut-offs of the samples with distinguishable material layers. Structures of the single layers are apparent and very variant.

Here, the image retrieval makes use of multiresolution wavelet transform (see [12], [13]). Wavelet transform can reflect local details and changes and therefore it can be a very useful tool for characterization of textures ([14], [15]), which is our case.

The wavelet transform is processed on small patches of the specimen textures, where the texture is ensured to be homogeneous. Each patch was decomposed to the depth of 2. For the decomposition, the Daubechies wavelet (db4) was used, which corresponds to the character of the analyzed textures and contained structures.

The decomposed texture patch is then represented using the energy of the individual high frequency bands [16]. These values form the feature vector, which was used for the texture classification using the iterative k-mean classifier. Fig. 8 shows three examples of the resulting pairs (in columns) of the textures which were determined as the most similar.

5. CONCLUSION

We proposed the system *Nephele* which could facilitate the work of material scientists and consequently restorers and offer them better access to the archived reports they use. The implemented digital image processing methods enable acquired data preprocessing for further analyzes as well as improve the querying above the reports database.

The preprocessing of VS and UV specimen images, used for the identification of pigment and binder present in the artwork, consists of image registration and segmentation technique. The image registration makes use of the mutual information approach because of the multimodal nature of the data. It removes the geometrical differences between the VS and UV images of the specimens introduced during the image acquisition. The following segmentation based on the

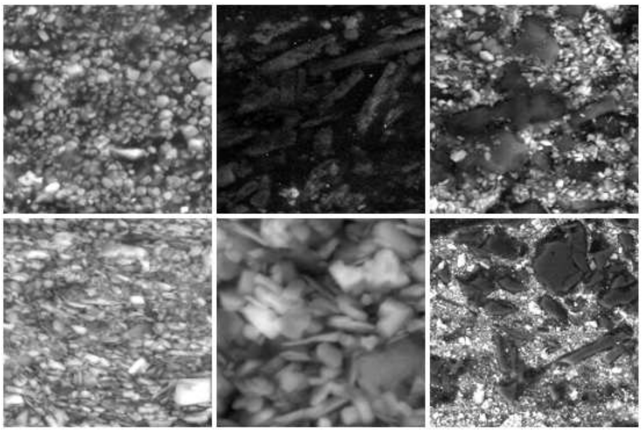


Figure 8: Examples of layer cut-offs from SEM images, rated as similar by the image retrieval system. The corresponding pairs form columns.

modified k-means clustering produces preliminary detection of present color layers.

The proposed image retrieval system is able to provide fetching of reports with visually similar specimen data. This can offer better usability of the database as the knowledge base. The image retrieval is built over the VS and UV images as well as over the SEM images of the specimens. They are represented using the Haralic descriptors of co-occurence matrices together with the color descriptors in the VS+UV case, in the case of SEM images the wavelet decomposition and the energy of its high frequency subbands was applied. Presented examples of achieved results show the applicability of the system.

All work was realized in close cooperation with the experts from Academic Laboratory of Materials Research of Paintings, joint workplace of the Academy of Fine Arts in Prague and Institute of Inorganic Chemistry AS ČR.

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