# Analysis of painting materials on multimodal microscopic level

Barbara Zitová[a] and Miroslav Beneš[a] and Janka Hradilová[b] and David Hradil[c]

[a]Institute of Information Theory and Automation, Academy of Sciences of the Czech Republic, Pod vodárenskou věží 4, Prague, Czech Republic
[b]Academic Laboratory of Materials Research of Paintings, Academy of Fine Arts, U Akademie 4, Prague, Czech Republic
[c]Institute of Inorganic Chemistry, Academy of Sciences of the Czech Republic, Řež, Czech Republic

## ABSTRACT

Our paper introduces a system based on digital image processing algorithms designed to facilitate analysis of painting materials during artwork conservation. Microscopic images of minute samples - cross sections – from the artworks are scanned using visible and ultraviolet spectra and under scanning electron microscope. Firstly, the scans are registered to remove geometrical differences. The multimodal nature of the problem led to the application of mutual information. The image quality is maximized by means of blind deconvolution methods. Cross-sections are then segmented to individual layers and distinctive seeds. For the image retrieval part, which facilitates further analyzes and conclusions, the layers are represented by means of wavelet analysis and second-order statistics. The library of such features can be connected to the time of creation and differences between vectors of the same materials but from different paintings can help during a painter authentication.

**Keywords:** material image analysis, digital restoration, image retrieval, cross-section analysis

## 1. INTRODUCTION

The advantage of exploitation of digital image processing (DIP) approaches has been seen in the cultural heritage area already several years ago,[1].[2] The ability to provide flexible analyzing tools and to improve the quality and interpretability of input data obtained from processed artworks makes the DIP algorithms very useful and valuable for art restorers and conservators. They can use DIP methods often originally developed for other application areas such as medical research, industrial quality control, or remote sensing. However, recently new innovative approaches are developed particularly for cultural heritage purposes, reflecting their special needs and aspects of processed artworks. The main focus of our paper lies on the application of DIP methods in materials research for art conservation and in the following report management and archiving. Art conservation/restoration is a process that attempts to return the artwork to *original* previous state and by materials research we mean traditional part of the conservation science, based on objective identification of materials and painting techniques from materials micro–samples (cross-sections). Subjects of conservation can be canvas paintings, polychromy, and wall paintings.

The aim of the material analyzes of artwork, mainly its layers, is to identify inorganic and organic compounds using microanalytical methods, and to describe stratigraphy (learning about layers) and morphology of layers (see Fig. 1-right). The layer is defined as consistent and distinguishable part of a painting profile. Such artwork description can give important information about the age of the used paints and their possible place of origin. The results are used to interpret the applied painting technique and to support the choice of proper conservation method and materials.

Further author information: (Send correspondence to Barbara Zitová)
Barbara Zitová: E-mail: zitova@utia.cas.cz, WWW: zoi.utia.cz
Miroslav Beneš: E-mail: benem9am@utia.cas.cz

Computer Vision and Image Analysis of Art, edited by David G. Stork, Jim Coddington, Anna Bentkowska-Kafel,
Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 7531, 75310F · © 2010 SPIE-IS&T · CCC code: 0277-786X/10/$18
doi: 10.1117/12.838872

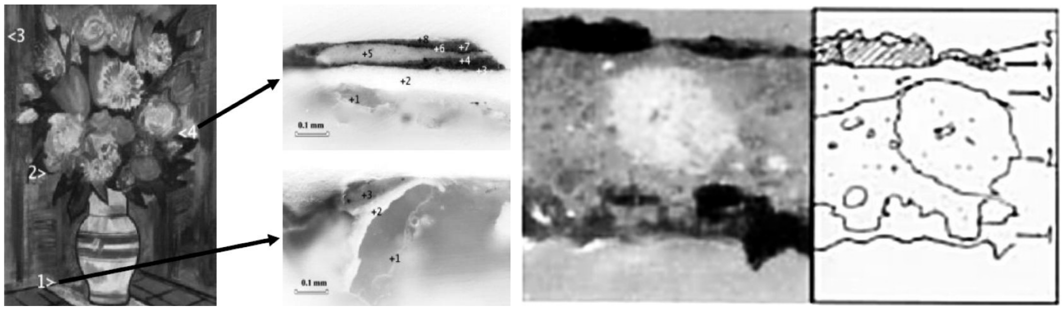


Figure 1. The microscopic cross-sections help to identify inorganic and organic compounds of the painting and to describe stratigraphy. The minute surface samples are taken form selected areas of the artwork (left). The samples expose individual layers (right) of the painting. The top layer (no.5) represents the surface of the painting, the bottom layer (no.1) corresponds to the deepest layer of the sample. Here, the layer segmentation was done manually.

The material analyzes usually work with minute surface samples taken form selected areas of the artwork (see Fig. 1-left.), to get an idea about the chemical content. The samples (0.3 mm in diameter) are embedded in a polyester resin and grounded at a right angle to the surface plane to expose the layers. Stratigraphy of color layers is usually studied in visible spectrum (VS, Fig. 2-left), in ultraviolet spectrum (UV, Fig. 2-middle), and by means of the scanning electron microscopy (SEM, Fig. 2-right). These three types of input image channels support mutually themselves and they form ideal base for the following data processing.

The obtained information from individual sensors can be appropriately fused and combined together, leading to more accurate conclusions. Each channel brings something, which other data sources cannot capture. The UV analysis works with luminescence – this phenomenon can help distinguish materials not resolvable otherwise. SEM images bring very precise info about the layer content and structure. The all contained information is then combined to form final estimate of color layer borders, based on the image data and the experience of the experts (possible order and combination of materials for specific artworks, time period, area, etc.). Historically, this has been done manually; the possible output of this procedure can be seen in Fig. 1-right.

It has to be mentioned that next to this analytical invasive approach, the artwork can be as well studied by means of other type of sensors, such as infrared imaging,[3],[4] where the authors can compare scanned data with respect to know library of pigments. In this case the analysis works with full image and belongs to the category of non-invasive approaches.[5] The art conservators are not united in their opinion with respect to these invasive and non-invasive methods.

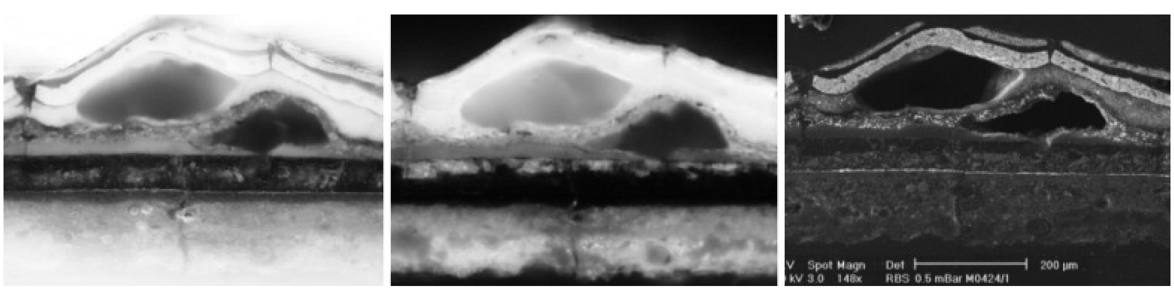


Figure 2. Cross-section images of an artwork specimen acquired in different modalities. Left – visible image (VIS). Middle – ultraviolet image (UV). Right – scanning electron microscopy image (SEM). The single color layers are apparent. The multimodal nature of the imaging channels is demonstrated here.

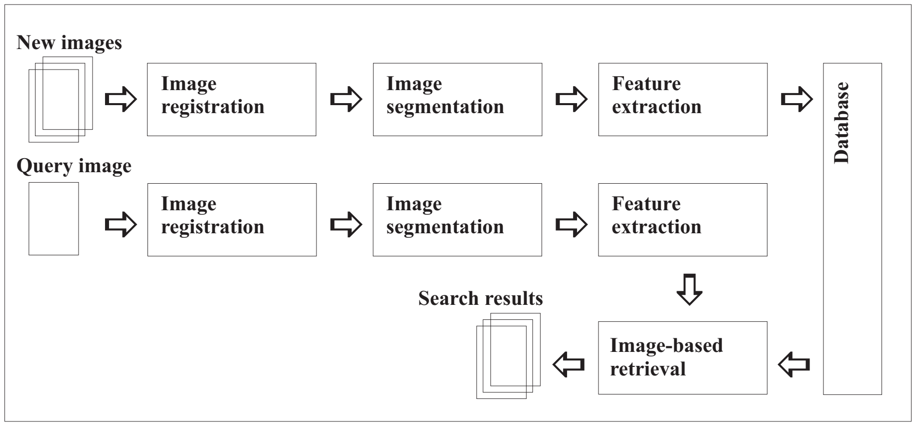


Figure 3. An overview flow-chart of the proposed system.

## 2. SYSTEM OVERVIEW

Processing of acquired image data - VS, UV, SEM - for art conservation and following archiving can be divided into four phases (see Fig. 3 for the flow chart of the proposed system). Firstly, the images have to be prepared for the analyzes. They have to be put into geometrical alignment, eventually we can improve their quality by debluring and denoising, degradations caused by the data acquisition process. The introduction of noise is the intrinsic property of all sensors and image acquisition process, the blurring can be introduced due to the non-perfect camera parameter setting. Considering the spatial non-correspondence, the image data can be scanned in different times and possibly at different places so VS, UV, and SEM images of one sample are often geometrically misaligned due to the manipulation errors. They can be mutually shifted, rotated, scaled, to name the most possible spatial differences. The data preparation is unavoidable step for gaining correct results.

The second phase of data processing is about data segmentation. Combining all the modalities the notion of the layers (consistent and distinguishable parts) and their mutual relations can be done. Individual layers of different materials can be now estimated by means of the image segmentation techniques.

In the third phase segmented layers and material elements can be described by means of properly chosen descriptors. Good system of image descriptors, followed by pattern recognition module can provide better definition of used materials, it would improve the ability to uncover the authors of the artwork by revealing characteristics of their work with pigments, binders and other components.

The last phase of the system provides tools for archiving of achieved results. The important issue of materials research is future accessibility of its outputs. Each completed 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 a database of materials reports could serve as an expert database for future conservation cases. The system flexibility it is important to have efficient data storage method and retrieval algorithm. The look-up of archived reports based only on the text information is often not enough. The ability to fetch reports which contain visually similar specimens/materials can increase the helpfulness of the system. The content-based image retrieval methods can be the solution for our demands.

## 3. IMAGE REGISTRATION

As it was stated before, the acquired images can be corrupted by radiometric and geometric degradation. The first influence the quality of each channel separately, the geometric differences preclude the direct fusion of the information from individual modalities.

The radiometric degradations – in this case noise and blurring – are intrinsic to the acquisition process and sensors themselves. Due to the high amount of scanned samples and not every time perfect setting of the camera the acquired images can be blurred resulting in the loss of the details we are interested in (see Fig. 4-top row for blurred data). The blurring and the desired resolution are connected to each other and recently there are

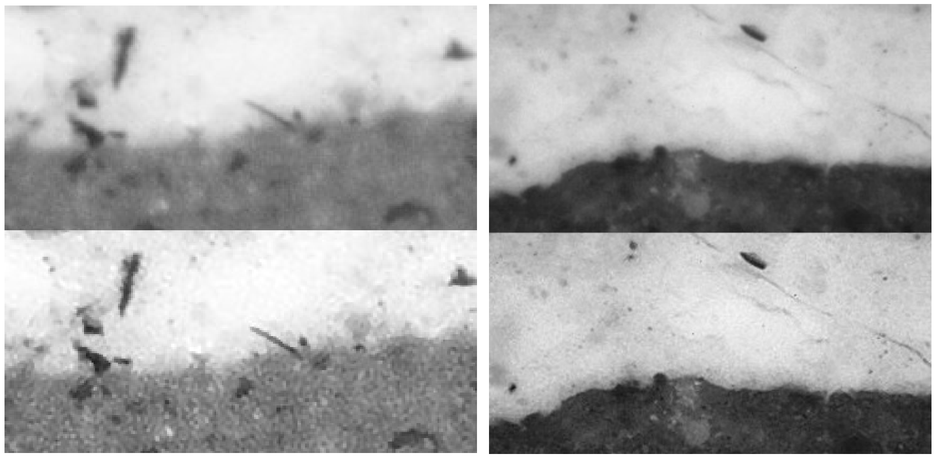

Figure 4. Examples of achievable results of the deconvolution method, applied on the defocused data. The close-ups of blurred cross-sections (top row) are shown together with the de-blurred results (bottom row). The sharper details such as small seeds are apparent. Data courtesy of Dr. Spike Bucklow, Hamilton Kerr Institute.

methods, which can improve the quality of the scanned images. For blur removal we propose to apply blind deconvolution method described by Šroubek and Flusser,[6] modified for the single channel case with the Gaussian kernel estimate. Examples of achievable results are presented in Fig. 4, where close-ups of blurred cross-sections (top row) are shown together with the de-blurred results (bottom row).

The geometrical mutual differences are introduced due to different imaging conditions and possibly manipulation errors.[7] Image registration (rectification) is the process of overlaying two or more images of the same scene taken possibly at different times, from different viewpoints, and/or by different sensors. The images are then brought into geometric alignment. Image registration is a crucial step if the final information should be gained from the combination of various data sources, which is here the case. The task of image registration in the case of material analyzes data is complicated not just by spatial non-correspondence but as well by multimodal nature of information sources. UV, VS and SEM images are apparently visually different and there is no simple mutual dependency between intensity values of those images which pose a main complication to image registration. An appropriate multimodal registration method has to be applied, which can handle such intensity variances. A comprehensive surveys of image registration methods is.[8]

Mutual information (MI), originating in the information theory, is recognized solution for the multimodal registration problem.[9] 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.[10]

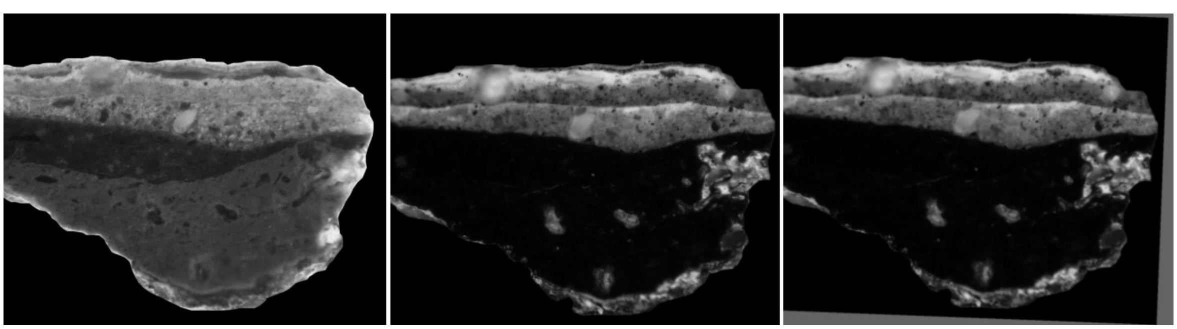

Figure 5. An example of the VIS (left) and UV (middle) images, mutually misaligned due to manipulation errors. The registered UV image (right) has been shifted and rotated with respect to its original position.

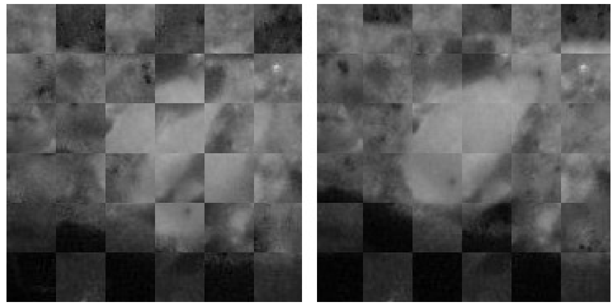

Figure 6. The close-up of the data from the Figure 5. The simultaneous chess-board visualization of the VIS and UV data before (left) and after (right) registration shows the spatial alignment. The smooth continuation of the depicted seed is apparent.

In proposed system, we use MI method proposed by Mattes et al.[11] The main difference from prior implementation[12] is simplification of evaluating probability distribution function (PDF) and entropy estimates. Only one set of intensity samples is used both for PDF and entropy. Hence the computation is faster and gives better results in our case. Fig. 5 shows the VIS image (left), UV image before the registration (middle), and UV sample after the registration (right) is processed. For the detailed close-up, see Fig. 6, where the simultaneous chess-board visualization of the VIS and UV data before (left) and after (right) registration shows the spatial alignment. The smooth continuation of the depicted seed (right) is apparent.

## 4. SEGMENTATION

After the image registration and quality improvement color layers and distinctively sized objects can be estimated. The tedious manual process of the operator can be facilitated by image segmentation methods. The aim of the image segmentation methods is partitioning of an image into several constituent components by means of the spatial as well as intensity information - in our case resulting parts correspond to color layers made of uniform material and grains. Survey on generic segmentation techniques and algorithms can be found here.[13]

The layer segmentation has been proposed using the method described by Haindl et al.[14] The segmentation is based on a weighted combination of several unsupervised segmentation results, each in different resolution, using the modified sum rule. Multi-spectral images are locally represented by random field models and the single-resolution segmentation is based on the Gaussian mixture model. Fig. 7 shows the achievable segmentation results on three samples. The VIS, UV, and resulted segmentation are presented.

For grain segmentation, the method based on snakes[15] was found appropriate. The performance of the method is shown in Fig. 8, where seeds are segmented from different background. It must be noted that the segmentation in the materials research applications can be very difficult due to the characteristic of the data. Due to this, the condition of full automation of the process was weakened to provide an estimate of the segmentation, which can be possibly modified by the experienced operator.

## 5. FEATURE EXTRACTION

Proper image-based features should be able to capture similarities as well as differences of individual used materials. Good survey of existing descriptors to start with can be found here.[16] The image-based data querying exploits the VS, UV, and SEM images of the specimens. For the feature selection, it has to be taken into account that the similarity of specimens is not based upon specific shape or structure elements which are the results of the random process of sample cut-off. The exact shape of the layer is not important and can be misleading. Thus, the color and texture characteristics were chosen as the main features – color features and co-occurrence matrices.[17] They reflect the joint probability of the occurrence of grey level pairs of two pixels with a defined spatial relationship, formed by a shape operator. The used shape operators were up to two pixels long and all color channels were processed separately.[18] Based on experiments the four Haralick descriptors were computed from the co-occurrence matrices (Contrast, Inverse difference moment, Entropy, Variance).[17] Apart from them,

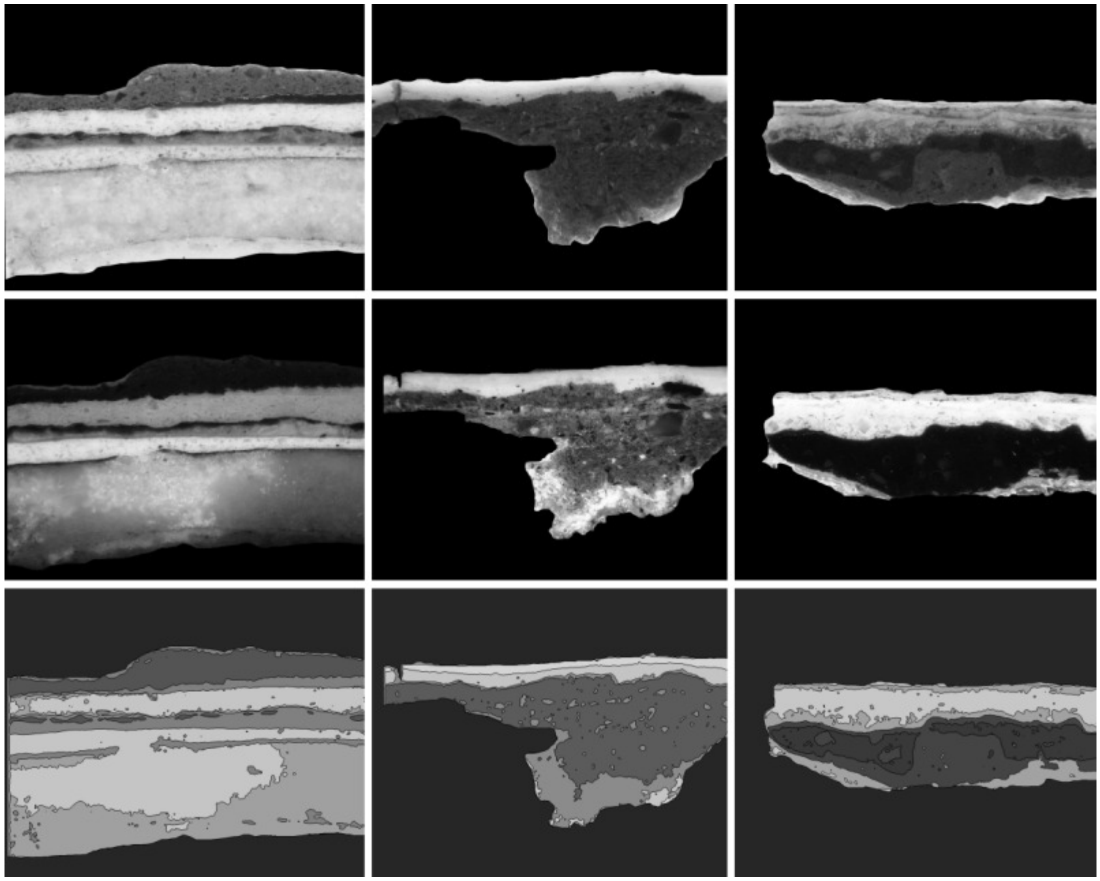

Figure 7. The results of the layer segmentation. The VIS (top) and UV (middle) images were used for the process. The detected layers are shown (bottom). Courtesy of Stanislav Mikeš, Institute of Information Theory and Automation, AS CR.

the color descriptors were included, too, to reflect the main color trends in the data. The image average color and the spectral standard deviation were chosen.

The second approach of the feature descriptors in our system is based on SEM images.[19] Here, the object representation is based on the multiresolution wavelet transform (see [20]). Wavelet transform can reflect distinctive details, thus it forms useful tool for characterization of textures.[21] The wavelet transform is processed (using Daubechies wavelet) on small patches of the specimen layers, where the texture is ensured to be homogeneous. The decomposed texture patch is then represented by feature vector formed by the energy of the individual high frequency bands.[22]

## 6. ARCHIVING AND RETRIEVAL

The material analyzes reports are often used as knowledge base for consequent art conservation. Effective tools to look-up relevant reports are the key issue of such database. 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 applied methodology of the analyzed artwork is similar as the mentioned one in the archived report.

In various application domains,[23] [24] image-based data retrieval is often used nowadays next to the traditional text-based search in database systems. The database entries with images are looked-up based on image similarity to the query image. The popularity of the so-called content-based image retrieval (CBIR)[25] is growing as well

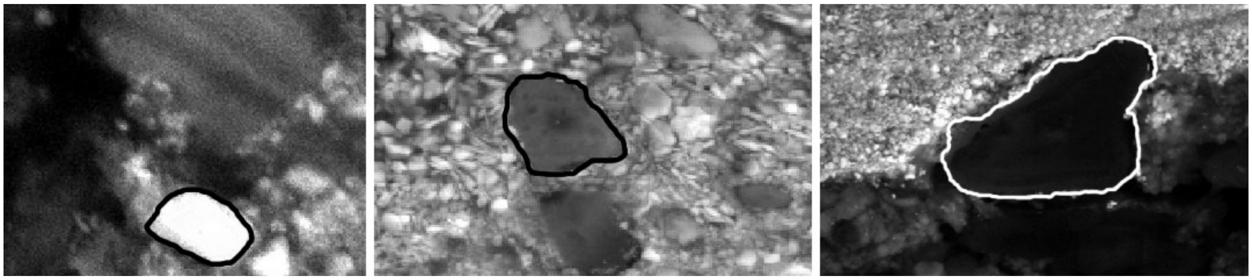

Figure 8. The detection of seeds. An example of seeds with different background.

due to the growing amount of images everywhere. 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.

The proposed system combines the listed features evaluated on the cross-sections with an adjusted data structure to speed-up the retrieval. Here, the R-tree indexing structure with weighted Euclidean metric[26] was implemented. Apart from the image processing methods, the system provides common functionality for the administration of materials research reports. These reports describe the whole process of the painting materials research on the artwork. All taken images are included as well as results of chemical analysis and other test results. 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 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). An example of the system GUI is presented in Fig. 9.

## 7. CONCLUSIONS

An application of digital image processing methods in the area of cultural heritage and art conservation in particular is on the rise today. Existing methods of image processing are applied under new circumstances and often original algorithms designed specifically for given tasks are desirable.

The proposed system can facilitate the work of material scientists and consequently conservator scientists and offer them better access to the archived reports they use. The introduced digital image processing methods enable acquired data preprocessing for further analyzes as well as improve the querying above the reports database. The processing of specimen images consists of image registration and quality improvement, layer segmentation, and feature evaluation. All these steps form the input for the archiving system with possibility of content based image retrieval.

The image registration makes use of the mutual information approach because of the multimodal nature of the data. The modified blind deconvolution method enables the decrease of the blur level in the acquired data. The segmentation produces an estimate of present color layers. The distinctive seeds can be detected by means of the snake-based algorithm. The image retrieval system is able to provide fetching of reports with visually similar specimen data. The image retrieval is built over the VIS, UV, and SEM image data. They are represented by the Haralic descriptors of co-occurence matrices, by color descriptors, and by the wavelet decomposition and the energy of its high frequency sub-bands. Art conservators, material scientists, and digital image processing researchers proposed and have been creating the system, which reflects demands of all participating sides.

## ACKNOWLEDGEMENTS

Our system rises from the fruitful cooperation between the Institute of Information Theory and Automation, Czech Academy of Sciences, and ALMA, a joint workplace of the Academy of Fine Arts in Prague and the Institute of Inorganic Chemistry of the Academy of Sciences of the Czech Republic. Part of the work was done together with Filip Šroubek ( image quality enhancement) and Stanislav Mikeš (image segmentation). Methods were tested on the data sets from ALMA and from the Hamilton Kerr Institute (Dr. Spike Bucklow).

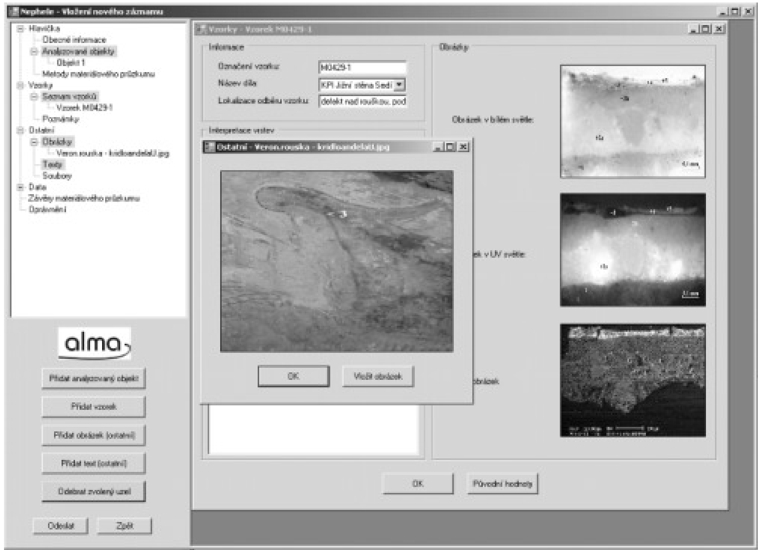


Figure 9. An example of the proposed system GUI. The overview image of the painting together with the three modality images – VIS, UV, and SEM data – are presented here.

The work was supported by the Grant Agency of the Czech Republic under the projects No. 102/08/1593 and 203/07/1324, by the Academy of Sciences of the Czech Republic (financial support for international cooperation) and by the the Ministry of Education of the Czech Republic under the projects No. 1M0572 (research center) and No. MSM6046144603.

## REFERENCES

[1] Pappas, M. and Pitas, I., "Digital color restoration of old paintings," *IEEE Transactions on Image Processing* **9**, 291 – 294 (2000).

[2] Rizzi, A., Voltolini, F., Girardi, S., Gonzo, L., and Remondino, F., "Digital preservation, documentation and analysis of paintings, monuments and large cultural heritage with infrared technology, digital cameras and range sensors," in [*Proc. of XXI Int. CIPA Symposium*], Greece (2007).

[3] Mazzeo, R., Palazzi, C. E., Roccetti, M., and Sciutto, G., "Computer-assisted pigment identification in artworks," in [*Proc. of the European Conference on Internet and Multimedia Systems and Applications EuroIMSA 2007*], 1 – 6, Chamonix, France (2007).

[4] Liang, H., Saunders, D., Cupitt, J., and Benchouika, M., "A new multi-spectral imaging system for examining paintings," in [*Proc. of CGIV 2004 - Second European Conference on Color in Graphics, Imaging and Vision*], 229–234, Aachen, Germany (2004).

[5] Pelagotti, A., Del Mastio, A., De Rosa, A., and Piva, A., "Multispectral imaging of paintings," *Signal Processing Magazine, IEEE* **25**(4), 27–36 (2008).

[6] Sroubek, F. and Flusser, J., "Multichannel blind deconvolution of spatially misaligned images," *IEEE Transactions on Image Processing* **14**(7), 874–883 (2005).

[7] Cappellini, V., Del Mastio, A., De Rosa, A., Piva, A., Pelagotti, A., and Yamani, H. E., "An automatic registration algorithm for cultural heritage images.," in [*Proc. of the International Conference on Image Processing ICIP 2005*], 566–569, Genoa, Italy (2005).

[8] Zitova, B. and Flusser, J., "Image registration methods: a survey," *Image Vision Comput.* **21**, 977–1000 (2003).

[9] Penney, G. P., Weese, J., Little, J. A., Desmedt, P., Hill, D. L. G., and Hawkes, D. J., "A comparison of similarity measures for use in 2D–3D medical image registration," *IEEE Trans. Medical Imaging* **17**, 586–595 (1998).

[10] Viola, P. and Wells, W. M., "Alignment by maximization of mutual information," *International Journal of Computer Vision* **24**, 137–154 (1997).

[11] Mattes, D., Haynor, D. R., Vesselle, H., Lewellen, T. K., and Eubank, W., "Non-rigid multimodality image registration," in [*M. Sonka and K. M. Hanson, Eds.: Medical Imaging: Image Processing*], 1609 – 1620, Proc. SPIE (2001).

[12] Maes, F., Collignon, A., Vandermeulen, D., Marchal, G., and Suetens, P., "Multimodality image registration by maximization of mutual information," *IEEE Trans. Medical Imaging* **16**, 187–198 (1997).

[13] Lucchese, L. and Mitra, S., "Color image segmentation: A state-of-the-art survey," in [*Proc. of the Indian National Science Academy*], **67**, 207–221 (2001).

[14] Haindl, M., Mikeš, S., and Pudil, P., "Unsupervised hierarchical weighted multi-segmenter," in [*Proceedings of the 8th International Workshop on Multiple Classifier Systems, MCS 2009*], Benediktsson, J. A., Kittler, J., and Roli, F., eds., *Lecture Notes in Computer Science* **5519**, 272–282, Springer (June 2009).

[15] Xu, C. and Prince, J. L., "Snakes, shapes, and gradient vector flow," *IEEE Trans. on Image Processing* **7**(3), 359–369 (1998).

[16] Costa, L. F. and Cesar Jr, R. M., [*Shape Analysis and Classification: Theory and Practice*], CRC Press (2000).

[17] Haralick, R. M., Shanmugam, K., and Dinstein, I., "Textural features for image classification," *IEEE Transactions on Systems, Man and Cybernetics* **SMC-3**(6), 610–621 (1973).

[18] Kašpar, R., Petrů, L., Zitová, B., Flusser, J., and Hradilová, J., "Microscopic cross-sections of old artworks," *Proceedings of the 12th IEEE International Conference on Image Processing, Genoa, Italy* **16**, 578–581 (2005).

[19] Beneš, M., Zitová, B., Flusser, J., Hradilová, J., and Hradil, D., "The image processing system for art specimens: Nephele," in [*Proceedings of 14th European Signal Processing Conference EUSIPCO 2006*], 1–5, EURASIP (2006).

[20] Mallat, S. G., "A theory for multiresolution signal decomposition: the wavelet representation," *Pattern Analysis and Machine Intelligence, IEEE Transactions on* **11**(7), 674–693 (1989).

[21] Lee, M.-C. and Pun, C.-M., "Texture classification using dominant wavelet packet energy features," in [*Proc. of the fourth IEEE Southwest Symposium on Image Analysis and Interpretation*], 301–304 (2000).

[22] Smith, J. R. and Chang, S. F., "Transform features for texture classification and discrimination in large image databases," *Proc. IEEE Intl. Conf. on Image Processing (ICIP)* , 407–411 (1994).

[23] Kushki, A., Androutsos, P., Plataniotis, K., and Venetsanopoulos, A., "Retrieval of images from artistic repositories using a decision fusion framework," *IEEE Transactions on Image Processing* **13**, 277 – 292 (2004).

[24] Lewis, P. H., Martinez, K., Abas, F. S., Fauzi, M. F. A., Chan, S. C. Y., Addis, M. J., Boniface, M. J., Grimwood, P., Stevenson, A., Lahanier, C., and Stevenson, J., "An integrated content and metadata based retrieval system for art," *Image Processing, IEEE Transactions on* **13**(3), 302–313 (2004).

[25] Veltkamp, R. C. and Tanase, M., "Content-based image retrieval systems: A survey," *Technical Report* **UU-CS-2000-34** (2000).

[26] Beckmann, N., Kriegel, H.-P., Schneider, R., and Seeger, B., "The r*-tree: an efficient and robust access method for points and rectangles," *SIGMOD Rec.* **19**(2), 322–331 (1990).