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Plátna starých mistrů pod drobnohledem počítače

Computers analyzing old masterpieces

Summary

This lecture deals with the usage of digital image processing methods in cultural heritage applications. Several main goals and issues will be discussed and examples of solutions will be described.

Following groups of methods will be addressed: data acquisition, where recent technology progress has enabled hyperspectral representation of artworks and new methods for the data analysis and processing are needed; data preprocessing, which increases the quality of the acquired dataset, using deblurring, denosing or even removal of more complex artefacts. Then, the mentioned higher level methods are change detection, trying to use multimodal dataset to uncover hidden changes, an authorship verification addressing possible forgeries using texture and high frequency based features, and geometry analysis, where the geometry of a painting scene is recreated and used for hypothesis disproval. The last covered topic will deal with the analysis of unseen data, having on mind microscopic data used during material analysis and data fusion from different modalities, where information acquired in non-visible spectra can bring information about hidden layers of a painting and thus recover original painter's intentions.

Souhrn

Tato přednáška se zabývá použitím metod digitálního zpracování obrazu v oblasti ochrany kulturního dědictví. Budou představeny hlavní problémy, které je potřeba řešit, spolu s ukázkami řešení.

V průběhu přednášky budou popsány následující kategorie úloh: pořizování dat, kdy současný vývoj snímacích sensorů nabízí možnost pořízení hyperspektrální reprezentace uměleckého díla a vzniká tak potřeba metod pro analýzu těchto dat; předzpracování dat, kdy se aplikují metody pro objektivní i subjektivní zvýšení kvality pořízených dat pomocí metod pro odstranění šumu, rozmazání, či na odstranění složitějších degradací. Detekce změn, kdy pomocí hyperspektrální sady dat jsou odhalovány skryté změny, posouzení autorství, kde texturální a vysokofrekvenční příznaky slouží k popření možnosti falzifikátů a analýza geometrie scény, kdy je vytvořen počítačový model scény z obrazu a pomocí něho jsou ověřovány hypotézy, se řadí mezi tzv. „higher level“ analýzy. Poslední téma se bude zabývat analýzou neviditelného, myšleno mikroskopických dat používaných během materiálových analýz a fúzi dat z více modalit, kdy informace z jiných modalit než viditelného spektra mohou odhalit informace o skrytých vrstvách malby a tak umožnit nahlédnout do malířovy kuchyně.

Klíčová slova:

Aplikace digitálního zpracování obrazu, kulturní dědictví, analýza obrazu, detekce změn, hyperspektrální analýza

Keywords:

Application of image processing, cultural heritage, image analysis, change detection, hyperspectral analysis

Content

1. Introduction

Today, exploitation of digital image processing (DIP) methods can be seen even in very distant areas such as art restoration applications. The ability to provide flexible analysing tools and to improve the quality and interpretability of input data obtained from processed artworks can make the DIP algorithms very useful and valuable for art restorers. Initially, DIP methods often originally developed for other application areas such as medical research, or industrial quality control have been applied. However, recently new innovative approaches are developed particularly for cultural heritage purposes, reflecting their special [1]. The growing number, variety, and affordability of sensors, the increasing awareness of the power of computer imaging and, indeed, the omnipresent influence of Internet caused increasing interest in digital image processing methods. There have been many international project oriented on this topic - 3D MURALE [2], ARTISTE [3], CHIRON [4], EPOCH [5], to name a few. Very complex work in this area was realized in Ghent during the conservation and analysis of the van Eyck altarpiece [6].

The ability of computer analysis to tackle art can be demonstrated for example on following cases. Firstly, D. Andrzejewski et al. [7] analysed painting style of Mondrian P. and automated his approach to be able to recreate paintings in this style by means of computer. Resulting paintings are often very difficult to differentiate from the originals. Scientists in Delft University of Technology went even further [8]. They extracted the essence from the H. R. Rembrandt style and created brand new painting with strong resemblance to the Rembrandt’s originals.

In this lecture various goals appearing in cultural heritage applications will be mentioned and examples of possible solutions will be demonstrated. Firstly, data acquisition and pre-processing and corresponding issues will be described. Then higher level analysis trying to understand the painting itself while identifying an author, looking for changes and verifying geometry of the painting scene will be introduced. The last chapter is devoted to the analysis of an unseen – of different modalities (infrared, X – ray, to name a few) and/or of microscopic data.

2. Data acquisition and preprocessing

2.1 Multimodal data acquisition

Hyperspectral imaging is nowadays an established technology for an acquisition of cultural heritage data, including paintings [9], [10], large-sized pictorial surfaces such as frescoed halls [11], or even 3D structures like walls or monuments [12]. It is a non-destructive technique for analysis of paintings and other art objects. It provides spectral and colorimetric characterization of the artifact, which helps to document the current state of an artwork, its creation, and the restoration interventions, too. Often the technology of color-accurate reproduction using spectral imaging [13] comes to question.

The scanning systems produce datasets representing the studied artifacts in various wavelengths. The multispectral scans provide information about the art composition, it helps to achieve faithful color reproduction, it can effectively reveal the artwork creation. Such information can create valuable insight into the painting. It could bring near the history of the painting, demonstrate the painter's original intentions and show the tracks of the restoration interventions. We proposed multispectral acquisition framework [14] (see Fig. 1), which is mobile and adjustable. We believe that such solution could spread even among the individual specialists and thus the multispectral acquisition could become available for general interested public. It is composed of commercial off-the-shelf products and it has low purchase price. It is mobile so it could be used for the data acquisition "in situ", without any limitations.

Figure 1: (left) Constructed LED panel with filters and M3art mockup example (right).

Moreover, we have created M3art database [15] contains data about colors behavior in visible (VIS) and near infrared (NIR) spectral bands. The database is open, publicly available and should serve as the knowledge base for further study of optical properties of pigments, drawing materials and canvases. The content of database consists of fiber optics reflectance spectra (FORS) and digital camera data collected in range 400-1050nm. Measurements were made on up to three layer samples composed of canvas, underdrawings and color layers. The colorants were selected to represent historical painting techniques in Gothic and Renaissance According to underdrawings acquisition ability four material categories were established. We conclude that transmission measurement is more universal than more common reflection measurement for underdrawings detection and should be used when.

2.2 Preprocessing

The collected data from previous step are often damaged by unwanted artefacts. Data can be blurry, noisy and even with some more complex degradations, which can be created along the data acquisition pipeline. In the case of blur, a deconvolution technique [16] can be used, quality of images corrupted by omnipresent noise can be increased by appropriate denoising method. Complex artefacts have to be handled using some custom developed methodology, an example of such is introduced later. Moreover, defects caused by aging can be here included, too. Their removal is often referred as virtual restoration [17], [18], [19]. The goal can be for example removal of the changes due to the aging, as in the project of rejuvenating the appearance of Seurat's A Sunday on La Grande Jatte [20].

2.2.1 Noise

Infrared radiation - oscillating electromagnetic field bounded by 750μm and 5mm analysis has long been used in the fields of art history and restoration. It is used to determine the authenticity of artwork or establish the period of an anonymous work. However, the most commonly used application of infrared radiation in regard to painting analysis is the unmasking of underdrawings, a preparatory drawing for a painting sketched typically using charcoal. These underdrawings are later covered with the artist's medium. Infrared analysis provides an easy non-destructive mean of eliminating the obstacle formed by overlying paint on the underdrawings of many artworks. However, large amount of noise is often present in acquired images. We proposed new denoising method based on the thin-plate spline (TPS) approximation [21]. The new weighting function has been introduced to the classical method, which diversifies the influence of individual pixels for computation of approximating surfaces based on the spatial as well as colour distance. This approach enables to decrease unwanted smoothing effect of TPS denoising on edges and small image details while achieving even bigger noise removal than the original method. In Fig. 2, the denoised example of an old artworks are presented.

2.2.2 Artefacts

One example of unwanted artefacts which can be present during the painting analysis are traces of scanning device [22] or of the canvas itself [23]. For the latter we have successfully applied method originally developed for the image enhancement of microscopy samples used during art restoration. In processing of NIR images of old paintings thanks to the

NIR light hidden underdrawings can be seen. Unfortunately, IR backlighting captures also the canvas structure and its inhomogeneity. The algorithm helps to remove them and simplifies further analysis (see figure 3). The method is based on filtering in the Fourier domain where such regular patterns can be easily removed.

Figure 2: Infrared image of old painting: (left) original, (middle) close-up of the original, (right) denoised close-up.

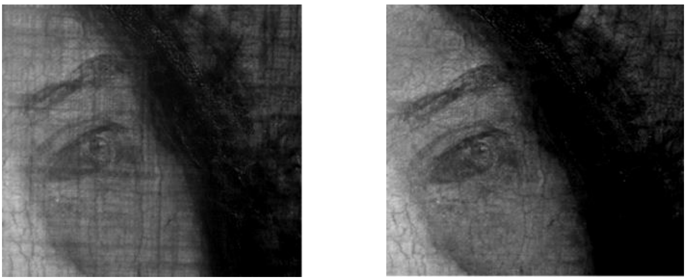


Figure 3: An example of canvas structure visible in the IR data (left) and enhanced output with removed artefact (right). Changes in the eye sketch started to be more perceivable.

3. Higher level analysis

Thanks to the progress in the feature and classification method development DIP algorithms are successfully applied in the area of painting understanding. In most cases the goal is to find out more details about the creation process of an artwork. In the following sections more detailed goals are described together with possible solutions.

3.1 Change detection & comparison

An illustrative example of change detection is the analysis of the evolution of the Last Judgment mosaic [24], situated on the outer wall of the St. Vitus cathedral in the premise of Prague Castle in Prague, Czech Republic (see Fig. 4 (left)). This splendid art piece sized 84-square-meter made of almost 1 000 000 glass cubes was finished in 1371, under the ruling of the King Charles IV.

Figure 4: The Last Judgment mosaic in Prague (left). The fused registration of the current state and the photograph from 1879 (middle) after registration. An example of identified difference (right) – the wave in the hair dress.

The goal of the analysis was to check the quality of the restoration process using the photograph by J. Eckert from 1879, which was found later. The geometrical correspondence of images was ensured using semi-automatic image registration based on affine model, where the exact location of feature points was improved using mutual information (MI) similarity measure [25]. MI method is designed especially for such multimodal case – old and new photograph. After the data fusion, when the both data source were combined using modified colormap (see Fig. 4 middle) individual changes (Fig. 4 right) were identified. The process was realized by operator due to the extreme complexity of the data.

In the case of painting comparison, the goal is to find mutual dependencies between several paintings on the same theme. The dating, the originality as well as the authorship can be questioned here. We have unique chance to analyse four instances of the same theme (the 'Boy with the bird' painting). The key issues in these tasks are image registration and visualisation of the achieved results. We have developed new method for the difference visualisation [26]. Compared images are combined into one fused image without losing important image context. Dissimilar regions are highlighted by colour, which encodes localized differences. The method is based on diverging colour maps. The colour representation of the difference is comprehensible, naturally ordered, and has maximal displayable resolution.

3.2 Author classification

The dating, the provenance and originality of the art piece, revealing of used painting techniques and applied materials as well as finding the inimitability of the author - all these issues of art restoration and art administration can be facilitated by means of proper DIP methods and can lead to the author identification. There are attemps to analyze brush strokes [27], similarly the ArtSpy project tries to find the author by means of several features for given artwork [28]. The authenticity of the artwork can be verified by means of wavelet transformation analysis, where small patches of studied paintings are transformed and energy distribution into individual bands is studied. This approach was used in the big project studying van Gogh's masterpieces [29], [30]. Several laboratories tried different wavelet families and following classification criteria on the same dataset. One of the conclusion was the when applicability of energy of the finest details as identifier of the forgery (the higher, the highest possibility of forgery). Another example how the authorship verification as well as art piece dating can be tackled is the usage of the canvas structure, the individual canvases were described by means of the canvas densities and then paintings were clustered based on this feature [31].

3.3 Scene geometry

The last approach how to understand a painting is based on the recreation of the geometry captured by a painter. This can be beneficial for the author style description. D. Stork has published several papers on this topic. He disproved the theory of pinhole camera used during the painting process by means of the chandelier geometry verification [32], addressed the question where are the persons mirroring in the artwork mirror [33], and proposed improvement in the way how the artwork should be displayed [34], to name a few. His approach is very interesting on the border with computer graphics but he does not have many followers.

4. Unseen data

Using different modalities such as X-ray or infrared reflectography hidden layers of the painting can be seen and underdrawings can be evaluated. Depending on the modality and on used pigments we can analyse original author's intentions, see changes which were realized later, and even discover new painting. Once again, the key issue here is precise registration of multimodal data set and an appropriate visualisation method. Expectations should be adjusted with respect to the present pigments due to their different characteristics and thus behaviour in various wavelengths [35, 36]. An example of such underdrawing analysis is demonstrated in Fig. 5. Another category of seeing unseen is usage of microscope images for analysis of used pigments and of stratigraphy of the painting. The Nephele [37] expert database is based on such dataset and offers archiving of material reports, analysis of microscopic data and context based image retrieval of archived reports, using image similarities.

Figure 5: Mary Magdalene. The input images for image fusion: (left) visual spectra image; (right) infrared spectra image. The fused image (middle).

4.1 Hidden layers

4.1.1 Van Gogh masterpiece

An excellent example [38] what can be achieved purely thanks to the digital image processing and hyperspectral data acquisition is virtual reconstruction of hidden portrait by van Gogh, which was later repainted by him resulting in "Patch of Grass", displayed in Kröller-Müller Museum, Otterlo, the Netherlands. They analysed the painting using X-ray fluorescence microanalysis (XRF) and X-ray absorption near edge spectroscopy (XANES). Collected data were preprocessed, individual chemical elements interpreted by their corresponding colour, resulting in a woman face hidden underneath.

4.1.2 Visualisation of concealed features

An innovative digital processing methodology for accentuating information contained in the infrared reflectograms was proposed in [39]. NIR reflectography, coupled to VIS one, is a spectrophotometric imaging technique employed to probe both the inner and the outer layers of artworks. However, NIR reflectograms may partially contain information pertinent to the visible spectrum (due to the poor pigment transparency in NIR) and this decreases their comprehensibility. The proposed method consists of inducing minor changes in pixel intensity by suppressing VIS information content from NIR information content. The method creates such enhanced NIR reflectogram by extrapolating VIS reflectogram to a reflectogram recorded in NIR range and by subtracting it from the measured values in the near infrared spectral sub-band (see Fig. 6). As an extrapolator a feed forward artificial neural network (ANN) was suggested.

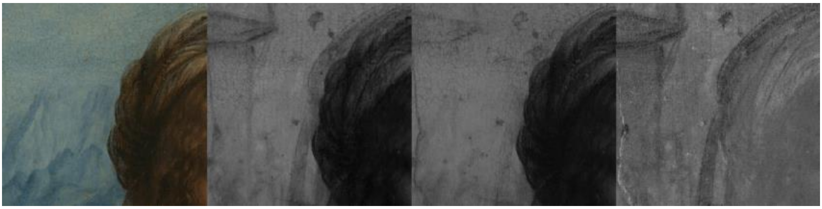


Figure 6: Experiment with the 16th century wooden desk painting attributed to Leonardo da Vinci. (left) RGB image, (middle left) a reflectogram centered at wavelength $\lambda = 1050$ nm, (middle right) output of ANN extrapolation, (right) difference between the measured and the extrapolated outputs the information gain.

A relevant estimation of the visible cover contribution in NIR reflectogram based on the visible spectral response is possible if and only if the set of materials is separable. Therefore existence of a transfer function $f : I(VIS) \rightarrow I(NIR)$, where I denotes the reflectance intensity, is assumed. To construct the best approximation f_T of this function f according to the collected pixels and their spectral responses, the pixels containing only the visible cover with no information gain were employed. Only in this way extrapolated values containing minimum of information gain and maximum information pertinent to visible cover are obtained. Being $f_T \sim f$, by using f_T spectral responses in the NIR spectral windows for all the pixels in the image can be extrapolated, creating a hypothetical image in the NIR spectral window, $\hat{I}_{NIR}$, containing only visible cover, which can be subtracted from the measured data:

$$f_T(I_{VIS}) = \hat{I}_{NIR},$$

$$\Delta = \left| I_{NIR} - \hat{I}_{NIR} \right|.$$

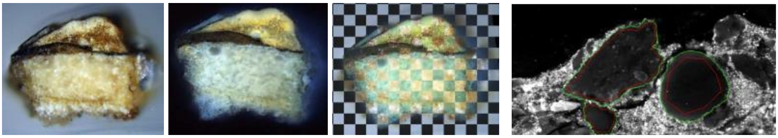
With suitable scaling of information gain Δ, an enhancement of hidden details is obtained. For purpose of method demonstration, feed forward artificial neural network (ANN) for fT construction was selected.

4.2 Microscopic analysis

The aim of the material analyzes of artwork painting layers is to identify inorganic and organic compounds using microanalytical methods, and to describe stratigraphy (learning about layers) and morphology of layers. Here, the layer is defined as consistent and distinguishable part of a painting profile. Such classification gives 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. The material analyzes work with minute surface samples 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.

Stratigraphy of color layers is usually studied in visible spectrum (VIS), in ultraviolet spectrum (UV), and by means of the scanning electron microscopy (SEM). These free types of input 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 - for example, the UV analysis works with luminescence, which can help distinguish materials not resolvable otherwise. Similarly, SEM images are bringing very precise info about the layer content and structure.

Working with image data - VIS, UV, SEM - has three phases from digital image processing point of view [37]. Firstly, the images have to be put into geometrical alignment. The data acquisition can be done in different times and possibly at different places so VIS, UV, and SEM images of one sample are often geometrically misaligned due to the manipulation errors etc. They can be mutually shifted, rotated, scaled, to name the most possible spatial differences. To be able to carry out further analyzes, an image registration has to be accomplished. This is realized using mutual information (MI), originating in the information theory and introduce to image processing by Viola and Wells [25].



(a) (b) (c) (d)

Figure 7: The microscopic images of the artwork specimen in visible VIS (a) and UV (b). (c) chessboard mosaic of registered VIS and UV images. (d) an example of grain segmentation.

The second phase of image data usage can be called data analysis. Combining all three modalities the notion of the layers' order, their structure and mutual relations can be done. Individual layers of different materials and even their structure (material seeds location) can be now distinguished by means of the image segmentation techniques. The last phase refers to the effective future usage of achieved results. 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. A database of materials reports could serve as a knowledge database for further restoration cases.

To create really useful tool a big attention has to be paid to the efficient data retrieval algorithms. 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 can increase the helpfulness of the system. The content-based image retrieval methods can be the solution (see Fig. 8). The retrieval is based on color features, energy of wavelet coefficients in different bands and co-occurrence matrices, reflecting the joint probability of the occurrence of grey level pairs.

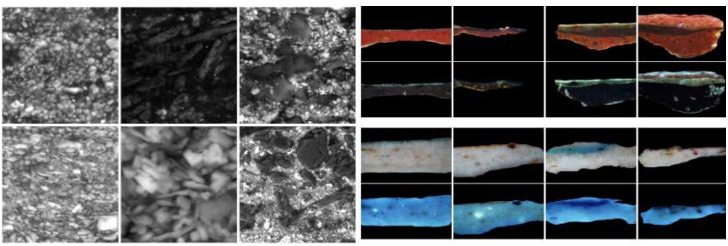


Figure 8: (left) Examples of layer cut-offs from SEM images, rated as similar by the content based image retrieval. The corresponding pairs form columns. (right) Results of image retrieval. Left column contains the query specimens, next columns in corresponding rows are results of the retrieval in order of the sample similarity.

Proposed Nephele [37] system is the extended database system for material analyzes reports with image preprocessing modules and image retrieval facility. This system rises from 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.

5. Conclusion

The lecture presented a review of categories of digital image processing methods, which play important role in the cultural heritage applications. Recently, during the art restoration, masterpieces are often analyzed using scanners working in different modalities and producing thousands of Mbytes about each painting. Without automation it would be difficult to handle such amount of information.

In the lecture several main goals and issues were identified and solutions presented: data acquisition and preprocessing, higher level analysis - change detection, authorship verification and geometry analysis; and finally unseen data processing, where the microscopy data and multimodal data fusion are typical examples.

The examples were chosen based on the expertise of the Department of Image Processing in UTIA, AV ČR and related publications are listed in References section. All results were achieved in cooperation with both Czech (Academy of Fine Arts, Prague) as well as international (Opificio delle Pietre Dure, Florence, University of Florence, Art-Test, Florence, Italy) laboratories. Achieved progress was presented in international journals, conferences and in the museums (Museum of Modern Art, New York, USA). Experience from the cases was included into the lectures thought at FJFI ČVUT and MFF UK and several Master theses, one finished and one almost finished Doctoral thesis were realized.

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Education:
Mgr. – computer science, Faculty of Mathematics and Physics,Charles University, Prague, 1995, „Textures and their computation by reaction diffusion “
RNDr. – computer science, Faculty of Mathematics and Physics, Charles University, Prague, 2000
Ph.D – software systems, Faculty of Mathematics and Physics, Charles University, Prague, 2000, "Registration of Radiometrically Deformed Images by Invariant Descriptors"

Affiliation:
Since 1995 - Institute of Information Theory and Automation, The Academy of Sciences, CR
since 2006 - head of the Image Processing Department

Teaching: Undergraduate and Graduate courses

- University of Veracruz, Mexiko, „Image processing and pattern recognition“, 3+0, Zk, LS, 1999, 2001, 2005
- FJFI Czech Technical University in Prague, „Digital image processing I“, 3+1, since 1999 assistant, since 2010 principal teacher
- FJFI Czech Technical University in Prague, „ Digital image processing II“, 3+1, since 1999 assistant
- FJFI Czech Technical University in Prague, Faculty of Mathematics and Physics, Charles University, Prague, „Special functions in the image processing “, (wavelets), 2+0, since 2002, established by Zitova, Flusser
- Faculty of Mathematics and Physics, Charles University, Prague, „Special seminar on digital image processing“, 0+1, since 2010
- Faculty of Mathematics and Physics, Charles University, Prague, „Digital image processing in practice “, 0+2, since 2013

Students

Finished diploma theses **11**, diploma theses running **1**, finished doctoral theses **1**, doctoral theses running **2** (one to be defended this year)

Publications

Co-author of **3** monographies on image, published in Wiley Publishing House, **21** papers in journals, **42** conference papers, **3013** citations in WoS, co-author/author of four software packages (VKG Analyzer, PIZZARO, NEPHELE, IMARE), tutorials ICIP 2005, 2007, 2009; EUSIPCO 2007; CVPR 2008; ICPR 2016; h-index **7**

Stays abroad:
- 1996/1997,1999, 2000: Flinders University of South Australia, 8 months
- 1998: Ruhr University, Bochum, Germany, 2 months
- 1999, 2001, 2005: University of Veracruz, Jalapa, Mexico, 6 months

Grants

- 2017 – 2018: Ministry of the Interior, System for image processing analysis for Czech Police, principal co-investigator
- 2014 – 2017: grant TA TA04011392 – Early ultrasound detection of breast cancer, principal co-investigator
- 2014 – 2017: international - ARTEMIS; ALMARVI Algorithms, Design Methods, and Many-Core Execution Platform for Low-Power Massive Data-Rate Video and Image Processing, co-investigator
- 2014 – 2017: grant TA TA04010877 – Automatic evaluation of videokymographic recordings for early diagnosis and prevention of vocal fold tumors, principal co-investigator
- 2010 – 2013: Ministry of the Interior, VG20102013064 - PIZZARO - Tools for imaging device identification, authentication, and image reconstruction, project manager
- 2009 – 2010: Internal promotion of international cooperation AVČR - AV ČR M100750901, Image analysis and automatic analysis of artwork material layers, co-investigator
- 2000 – 2002: Postdoctoral grant GA ČR No. 102/01/P065 – Geometric registration of degraded images, principal investigator
- Team member of 9 GA CR grants

Awards

- National Hlávka prize for yound reserachers, **2003**
- First prize in The best publication in UTIA **2003, 2014**, **2016**
- Wichterle premium of the Academy of Sciences of the Czech Republic, **2006**
- The Award of the Chairman of the Czech Science Foundation, **2007**
- Price of the Academy of Sciences of the Czech Republic for the scientific achievement "Image recognition using fusion", **2007**
- "SCOPUS 1000 Award" **2010** for more than 1000 SCOPUS citations for the paper "Image registration methods: A survey", Image and Vision Computing, vol.21, pp. 977-1000, 2003

Other activities

- Associated editor for Pattern Recognition (Elsevier) journal (IF 3.4)
- Regular reviews for international (for example IEEE PAMI, IEEE TIP, PR)
- Expert courses for European center for medical informatics, statistics and epidemiology of the Charles University, seminars for general public, other Czech universities, and high school students
- Reviewer for the European union projects in Horizont 2020, for master and doctoral theses, for various international organizations
- Member of Doctoral Study Board in Computer Graphics and Image Analysis at MFF UK, of Doctoral Study in biomedicine board

Research Interests

All aspects of digital image processing and pattern recognition; particularly object recognition by invariants, degraded image recognition, geometric invariants, theory of moments, remote sensing and medical imaging applications, security and forensic applications.