

Characteristics of main research directions investigated at the institute and the achievements 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
-----------	---

The Institute of Information Theory and Automation (UTIA) is a public non-university research institution which administratively falls under the Czech Academy of Sciences.

UTIA conducts fundamental and applied research in computer science, signal and image processing, pattern recognition, artificial intelligence, system science, control theory, and econometrics. In the areas closely linked to applications (such as Signal and Image Processing) we focus, besides basic research, on implementations and providing end users with final results. The above-mentioned research areas were established in the Institute thanks to the gradual development in the 1990s, while at the same time directions showing less promise were attenuated or discontinued altogether.

In addition to its research activities, UTIA is engaged in undergraduate, graduate, and postgraduate education through jointly accredited study programs with four universities. It publishes the journal *Kybernetika* and acts as a certified forensic expert institution. UTIA is a mid-sized institute with about 200 employees. It consists of eight research departments, computer centre, library, facility maintenance department and business administration department. UTIA is managed by the Director and the Board.

Research structure.

UTIA has a flat organizational structure. The research is conducted in eight research departments, which are identical with the teams involved in this evaluation. The departments are elementary formal units, led by a Head of Department. Some departments are informally divided into several research groups, which are typically formed to work on a project. A few project groups are spread across two departments. Thanks to the flat structure, the research coordination is very operative. Currently, all departments are high-quality well-balanced groups of individuals, namely experienced scientists, post-doctoral researchers, and doctoral students. This composition is a result of a long-term cooperation with students, teaching at universities and advising doctoral students. The top managements of the Institute have placed significant emphasis on teaching and supervising both master as well as doctoral students and consider it the key factor of attracting promising young scientists to work in the Institute.

The list of the research departments along with a brief characterization of their main areas follows.

Adaptive Systems (AS)

Adaptive Control, Bayesian estimation and prediction, dynamic decision making under uncertainty (concepts, theory, algorithms, software and applications).

Control Theory (TR)

Analysis and design of linear systems including robust control. Numerical methods for control systems analysis and design including chaotic systems. Analysis and design of nonlinear control systems. Topological dynamics and dynamical systems on surfaces and manifolds.

Decision Making Theory (MTR)

Probabilistic Methods in Artificial Intelligence, Bayesian Networks, Conditional Independence Structures, Imprecise Probabilities, Variational Methods, Optimization, Mathematical Methods in Materials Science, Partial Differential Equations

Econometrics (E)

Stochastic models in economics and econometrics, Financial econometrics, Energy economics. Real and monetary macrodynamics. Stochastic and dynamic optimization.

Image processing(ZOI)

Image registration, multichannel blind deconvolution, superresolution, and image compositing. Invariant descriptors for distorted object recognition, namely theory of moment invariants and local descriptors. Forensic image analysis. Content based image retrieval. Major applications in biomedicine, remote sensing, astronomy, security, and art conservation.

Pattern Recognition (RO)

Statistical pattern recognition with emphasis on model-based pattern recognition and application of finite mixtures, modelling of random fields for scene interpretation, probabilistic neural networks, statistical feature selection and applications in economics, car industry, architecture, medicine, and text document classification and processing.

Signal Processing (ZS)

Recursive system identification algorithms, adaptive control and audio processing, advanced digital signal processing algorithms, parallel algorithms and architectures, reconfigurable systems, field-programmable gate arrays (FPGA), novel FPGA architectures, dynamic reconfiguration in FPGA, embedded systems, hardware software co-design

Stochastic Informatics (SI)

Information in statistical experiments and optimal statistical decisions, Robust statistical procedures and their applications in various statistical environments, Statistical inference in random processes and random fields, Stochastic analysis and partial differential equations. Interacting particle systems.

In the sequel, we are not going to repeat the facts which are in detail described in the material provided by the teams. So, we do not mention individual results, projects and publications; we kindly refer to the teams' material. We focus on the activities on the Institute level, which typically go across several teams.

Research results

The wide variety of research topics, which are spread from pure theoretical research to applications, implies also the variety of the outcomes. Since our main focus is on fundamental research, the most important outcome are research papers. In 2010-2014, our researchers authored/coauthored **324 papers in impacted journals** and several hundreds of conference papers. For the detailed list of publications sorted according to the teams and publication categories see the material of individual teams.

Typical outcome of applied research, which is usually funded by application-oriented grant agencies or directly paid by the companies, are patents and software solutions.

Research projects

The current institutional funding (i.e. the budget part provided by the Academy) is about 63 M CZK, while the total annual budget is about 145 M CZK. The difference is covered by various research projects funded by EU, the Czech Science Foundation, the Technology Agency, the Ministry of Education, and by other public sources. A small part of the budget (about 4 M CZK) comes from commercial research. As can be seen from these numbers, UTIA is very successful in attracting external funding. We are currently participating in 8 EU projects and 36 national projects. In the evaluation period, we were involved in 116 projects and 14 industrial contracts altogether.

The projects we have been particularly proud of in 2010-2014:

- Research Center DAR. The largest UTIA project of the period with a total budget over 100 M CZK. The Center, headed originally by prof. Mares and then by prof. Flusser, was a joint structure with three universities and several companies. It was focused on applied research in data analysis, signal/image processing, adaptive systems and artificial intelligence.
- Apple-CORE - Architecture Paradigms and Programming Languages for Efficient programming of multiple CORES. An FP7 ICT project, which lead, in addition to many applied results, to a monograph Daněk M. et al.: UTLEON3: Exploring Fine-Grain Multi-Threading in FPGAs, Springer, 2013.
- PIZZARO - a very successful applied research project funded by the Ministry of Interior. The goal was to develop methods and software solutions for forensic image and video analysis. Currently in use in 50 police departments.
- XXX - the contracted work for XXX A.G., a world-leading producer of thermal and infrared cameras. UTIA developed the method and the software for superresolution of thermal video. The solution is patented in Germany. The best paid short-term project (XXX) from a private source.
- XXX - this long-term collaboration with the major car producer offers a unique opportunity to implement and test our original control algorithms and parameter estimation methods in real car prototypes. It has led to numerous results in developing advanced car systems for the driver support.

Participation in the AV21 Strategy

In 2013, the president of the Academy announced a new initiative of the Academy, called "Strategy AV21" which aims to focus on challenging research topics which are of great practical importance for the Czech institutions, companies and citizens. 10 key areas were identified and the institutes of the Academy were invited to propose research programs. In 2014, after a long discussion, 14 research programs were accepted. UTIA successfully proposed (jointly with the Institute of Mathematics and the Institute of Computer Science) the program "Hopes and Threats of Digital Era", coordinated by prof. Flusser. It is the only accepted program in Mathematics and Computer Science.

Forensic expert activities

Providing expert opinion on various levels is an important role of the Institute. Thanks to its top reputation in research, UTIA is a certified forensic expert institution in Cybernetics

(formally certified by the Ministry of Justice in 2008), with a particular focus on analysis and authentication of digital photographs and video. In 2010-2014 we completed 8 expert opinions for courts and police. We have been also frequently asked for opinion by other organizations.

Scientific awards

Numerous researchers were awarded by various awards/prizes for their excellent achievements. The most prestigious are:

2010 - "SCOPUS 1000 Award" in recognition of more than 1000 SCOPUS citations of a single paper (B. Zitová J. Flusser)

2010 - Fulbright Scholarship (F. Sroubek)

2010 - Werner von Siemens Excellence Award (O. Tichy for his diploma thesis "Integral Models of Dynamic Scintigraphic Studies").

2011 - The Award of the Academy of Sciences of the Czech Republic for outstanding results of major scientific importance for the scientific outcome: Mathematical modelling of visual properties of surface materials (M. Haindl et al.)

2011 - *Outstanding Statistical Application Award of American Statistical Association* and *Frank Wilcoxon Prize* (M. Karny for "Online prediction under model uncertainty via dynamic model averaging: application to a cold rolling mill").

2012 - R. Hofman was awarded by Czech Radiation Protection Society by prize for the best work of young authors in the field of protection against ionizing radiation

2012 - Czech Econometric Society Award (L. Kristoufek for "Tests for long-range cross-correlated processes")

2012 - The Award of the Academy of Sciences of the Czech Republic for outstanding young scientists (T. Kroupa)

2012 - Innovation Award of the The International Institute for Advanced Studies in Systems Research and Cybernetics (C. Hoschl)

2012 - Antonin Svoboda Award for the best Ph.D Thesis in Computer Science (P. Vacha for „Query by Pictorial Example“)

2012 - The Award for the best Ph.D Thesis in Nuclear Science (R. Hofman for „Application of Advanced Data Assimilation Methods in Off-site Consequence Assessment“)

In addition to the above list, four young researchers received the Otto Wichterle Premium and many others received various "Best paper awards" at conferences and student competitions.

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of Adaptive Systems

Department of Adaptive Systems

The Adaptive Systems (AS) department has a long tradition of fundamental research devoted to Bayesian Dynamic Decision Making under uncertainty and incomplete knowledge. Starting in 60s from adaptive control, the research topics significantly evolved over time while preserving the departmental traditions.

The research results are reflected in book chapters, journal and conference papers as well as transfers of theoretical results to diverse applications, which inspire us towards further theoretical advances.

MAIN SCIENTIFIC RESULTS ACHIEVED BY THE AS TEAM

The results are grouped according to the main research topics covered by AS department. Every topic may contain several directions. Samples of the relevant papers are provided.

R1: Fully probabilistic design of decision-making strategies

Fully probabilistic design (FPD) is a non-trivial extension of Bayesian decision making (DM) proposed by M. Karny in the 90s. FPD quantifies DM preferences via so-called ideal distribution and selects the strategy, which minimises Kullback-Leibler divergence of distribution describing the *resulting* closed-loop behaviour on distribution representing *preferred* DM closed loop.

- 1.1. The fundamental result is an axiomatic basis of FPD, which delimits assumptions leading to the FPD and proves the strict inclusion of Bayesian DM into FPD [1]. The AS team, provided basic ideas and techniques.
- 1.2. The power of the FPD framework was shown by formulating a design of tools supporting decision making as a higher-level FPD task [2]. It provides a novel justification of the optimal Bayesian approximation, re-derives and generalises minimum-cross entropy principle. The results open new ways for FPD enhancing and serve as a basis for new research concerning imperfect decision makers. The results were achieved solely in AS.
- 1.3. For the first time, FPD has been used for a design of non-linear controllers with neural networks [3]. The author from AS team, supplied expertise on FPD and proposed the way of tailoring of Neural Network art to FPD.

R2: Decentralised dynamic decision making under uncertainty

A distributed cooperation of imperfect decision makers having multiple DM goals has been further developed. This allowed an *automatic harmonisation* of *knowledge* and *DM goals* within a flat cooperation scheme. The particular results are:

- 2.1. An automatic knowledge elicitation has been proposed. The knowledge elicitation is still a bottleneck of theoretically preferable Bayesian DM. This result [4] provides a widely applicable and practically important methodology. The member from AS team contributed with methodology and algorithms.
- 2.2. Construction of a DM preferences description that exploits FPD has been proposed. This has *no counterpart in a classical DM* and removes the gap between single and multiple-aims DM [8]. The results achieved solely in AS.
- 2.3. The use Kullback-Leibler divergence for combining probability distributions in decentralised settings was justified [5]. The result provides a deep theoretical insight into properties of an iterative search for the optimal combination. The results are of high importance for any application requiring an optimal combination of experts' opinions. The results were achieved solely in AS.

R3: Advances in Bayesian estimation

The traditional AS domain brought a range of results:

- 3.1. A novel, theoretically grounded, design of estimators counteracting an accumulation of approximation errors was proposed [6]. It enhances usability of the Bayesian estimation, provides a new view on stabilisation techniques used in Monte Carlo and extends a use of forgetting beyond imprecisions caused by parameter changes. The results were published in the high-impacted journal (IF 3.89) and are of importance for the information science community. The results were achieved solely in AS.
- 3.2. A Bayesian method how to describe and adaptively learn a model of a system with strict bounds was proposed [7]. Compare to the existing methods, the initial setting of proposed algorithm is very simple, which makes the results of practical importance for engineering community. The results were achieved solely in AS.
- 3.3. A novel method for tracking of slowly varying multivariate parameter elements was proposed [9]. The results belong to rare algorithms allowing different variability of estimated elements. Unlike other algorithms, the method is rather versatile. At the same time, it is system-model independent, which makes it universally applicable. The results were achieved solely in AS.
- 3.4. Recursive version of Bayesian model comparison and model averaging were proposed and tested on a non-trivial application to cold-rolling data [10]. The author from AS team formulated the problem and brought in the expertise on recursive Bayesian estimation. The co-authors provided data and compiled the paper in statistical style.
- 3.5. A semi-analytical method of adaptive filtering for systems with unknown noise parameters was proposed [11]. The method, published in the high-impacted journal (IF 3.13), is of high practical importance as it outperforms the current standards with respect to computational efficiency, and can handle both sensor and actuator offsets. Swedish colleagues provided the original idea, simulations, and experimental evaluation. Our team contributed with mathematical part related to the analytical solution of the involved equations. This is the key contribution that allowed the achieved computational savings.

R4: Estimation in spatially distributed networks

Diffusion estimation is a theoretical framework for collaborative inference of parameter of interest using a spatially distributed network, where each node can exchange information with its adjacent neighbours. This is a recently established research direction, but even the first results are worth of mentioning.

- 4.1. A theoretically-founded method for combination of measurements and parameter estimates within a network of collaborating nodes was proposed. The paper [12] is the first Bayesian contribution to the diffusion estimation theory. The method is universally applicable to a wide class of models and under certain conditions leads to analytically tractable solutions. Based on the result, [13] proposed a novel method for system monitoring with spatially distributed sensors. It guarantees reliable estimation in large networks with communication constraints, e.g. in computer networks. The results were achieved solely in AS.
- 4.2. The work [14] solved the problem of sequential estimation of mixture models in diffusion networks. It is probably the first non-Monte Carlo distributed sequential algorithm, suitable to a rich class of the component models. Under certain conditions, like normality of components (usually assumed by alternative non-sequential algorithms) it admits analytical solution. Our team provided the original idea and elaborated it; the external co-author raised theoretical comments and proposed the experimental setting.

R5: Complex modelling for decision support

This research direction is strongly application-motivated but brings important, widely applicable theoretical conclusions. The modelling for decision support includes two research directions. The first one deals with probabilistic consequence assessment of the aerial accidental discharges of harmful substances, and has the following results:

- 5.1. The result [15] provides a fast evaluation of the external irradiation from a radioactive cloud. The proposed algorithm describes the dynamics of the radioactive cloud propagation over the terrain in a real-time mode. The results were published in the high-impacted journal (IF 3.062) and are of importance for the researchers interested in air pollution. The methodology, algorithmic and simulation part have been prepared by AS team so as writing of the paper. The co-author's contribution was extraction and preparation of the necessary nuclear data from the database of radionuclides.
- 5.2. A vital problem of evaluating quality of radiation-monitoring network is solved in [16] as well as practically important problem of data assimilation of atmospheric models and weather forecast [17]. Both results were obtained by AS team.
- 5.3. Ref. [18] shows that an optimised automatic navigation of the unmanned aerial vehicles aircrafts significantly improves quality of assessment of the radiation situation in the case of radiation accidents. The results are published in the high-impacted journal (IF 3.06) and are of high practical importance.

The second research direction focusing on decision support concerns Bayesian blind source separation in *dynamic* medical imaging. The results obtained are:

- 5.4. Assuming that the activity of each source can be modelled as a convolution between common input function and source-specific convolution kernel, a blind source separation model is introduced [19]. Free-form shapes of the convolution kernels allow applying the proposed algorithm to various dynamic data. The reached accuracy of tissue separation with simulated and clinical data from renal scintigraphy outperformed accuracy of other state-of-the-art methods.
- 5.5. The result [20] significantly extends the previously published mathematical model and applies it to a large dataset where estimations of differential renal function and input function are studied. The results serve to analysis of dynamic scintigraphy data. The research is performed in cooperation with the Institute of Nuclear Medicine, Charles University. AS team proposed the model, performed experiments, and wrote the paper.

R6: Advances in linear, nonlinear, and decentralized control

The recent progress within this matured domain concerns the following results:

- 6.1. Study and control of linear systems, in particular the solution of the pole assignment problem by state feedback for the class of implicit non-square linear systems [21]. AS team proposed a conceptual solution, established the necessary conditions and perform analysis of achieved results. The co-author provided valuable comments.
- 6.2. Study of the partial differential equations with discrete state-dependent delay, in particular the existence and uniqueness of the solution as well as an extension of the fundamental invariance principle [22]. The results were achieved solely in AS.
- 6.3. A new method for determining the non-existence of a common quadratic Lyapunov function [23] based on swarm intelligence. This helps to investigate a global asymptotic stability of a switched linear system. A conceptual solution was proposed by Chilean colleagues, the co-author from AS team provided critical comments.
- 6.4. Decentralized control design [24-26] were focused on (i) design of decentralized state feedback controllers for a special class of continuous-time interconnected systems; (ii) deriving a sufficient conditions for the tolerance of local control channel failures in a global closed-loop system; (iii) networked control systems as feedback control systems with network channels in the feedback loop. The author from our team provided the original idea and conceptual solution.

R7: Transfer of our theoretical solutions to industry

Solution of problems frequently occurring in practical applications mainly concern presence of bounded uncertainty and/or missing data. Our contributions consider transferring the theoretical and algorithmic solutions previously developed within AS to real applications. The examples of such a transfer are:

Transportation:

Modelling of traffic flow and control of large urban traffic areas [30-31] (in cooperation with Škoda Auto a.s) were proposed. The results were successfully tested in Prague Smichov and Zlicin regions (in cooperation with Eldoto a.s). Fuel consumption optimization and vehicle-speed tracking were solved in cooperation with Škoda Auto a.s [32] so as vehicle-position estimation using GPS/CAN data [29]. The AS team was responsible for the theoretical part of the solution.

Metal processing industry:

Conditional monitoring and dynamic assessment of system reliability has been developed [33-34] as well as a reliable soft sensor [35] for thickness control in cold rolling mills (in cooperation with COMPUREG Pízen, s.r.o. and Jozef Stefan Institute, Slovenia). The AS team was responsible for the theoretical part of the solution.

Mechatronic:

Sensorless control of permanent-magnet synchronous ac motor drives has been proposed [4, 36] in cooperation with Regional Innovation Centre for Electrical Engineering, University of West Bohemia. The AS team was responsible for the theoretical part of the solution.

Invention of a robotic device based on a parallel kinematic configuration. The device is intended for machining centres with top milling operations. The patent CZ 301 781 was granted by the Czech Industrial Property Office
<http://isdv.upv.cz/portal/pls/portal/portlets.pts.det?xprim=1231396&lan=en>.

PUBLICATION ACTIVITY

Within 2010-2014 there have been published 50 journal papers (cf. 43 papers during 2005-2009), in IF journals 36 (cf. 24 during 2005-2009), including seven papers in journals with IF > 3 (cf. 1 paper during 2005-2009). Three edited books, four book chapters (cf. four books and three monographs chapters within 2005-2009).

PROJECTS SOLVED

AS department got seven grants from Czech Grant Agencies supporting basic research, five from Czech authorities supporting innovations and applications, two projects from European Commission (Eurostars Programme) and one from Czech-Norwegian Research Programme. It worth mentioning that project proposal submitted within Czech-Norwegian Research Programme was ranked as the second best of 389 proposals.

While the amount of AS projects is similar to 2005-2009, a shift to European level is visible (there was none).

INTERNATIONAL COOPERATION

Our long-term collaboration proved by joint publications are CNR, Italy [4], Universidad de Chile [23], Kharkov State University, Ukraine [37], Jozef Stefan Institute, Slovenia [35], University of the Basque Country, Spain, Universite de Nantes, France [21], Washington University [10]. The **newly established collaboration** already confirmed by joint publications: Aston University, UK [3], Stony Brook University, USA [14], Santa Fe Institute, USA [27-28], Linköping University, Sweden [11], Trapeznikov Institute of Control Sciences, Russian Academy of Sciences [38].

In 2010, 2011 and 2013 AS team organised workshops in conjunction with NIPS and ECML/PKDD conferences [27-28]. This helped to advertise the department research to machine learning and neural processing communities and stimulated establishing new collaborations with: Santa Fe Institute, USA; Rey Juan Carlos University, Spain; Oxford University, UK; Lausanne University, Switzerland; The Hebrew University, Israel.

SUMMARY

The above results look like an 'ordinary' scientific report that makes easy to overlook a few results of an exceptional significance and value. They are:

- results mentioned under research topics **R1** and **R2**

Why are they important?

FPD, originally invented in AS department and independently re-discovered in 2006 as KL-control, *has proved to be the most universal normative decision theory*. Among other advantages, it provides a well-grounded framework for modelling interacting imperfect participants with diverse DM objectives and bounded resources.

- results mentioned under research topic **R3**

Why are they important?

The AS team contributions to recursive Bayesian estimation *go well beyond the state-of-the-art*. They allow to counteract accumulating projection errors; cope systematically with ever-present constraints and with vector-rate parameter variations. Their importance is enhanced by the contemporary need for streamed and distributed data processing.

- application-motivated results mentioned under research topic **R5**

Why are they important?

The evaluation of dynamic renal studies as well as the probabilistic approach to decision support in radiation protection *have no competitors* in efficient solving these significant real-life problems. The developed methodologies are directly transferrable to other application domains (PET, NMR, other organs, other types of pollution, etc.)

Another important point is a “**personal progress**” of the AS team. Researchers are the main departmental value and thus the “personal progress” of the department decides on the future efficiency and perspectives. During 2010-2014:

- several research groups led by young creative members of AS department have arisen;
- an overall research activity incl. quantity and quality of outcomes is increased compare to the previous evaluation period (see PUBLICATION ACTIVITY);
- strengthening existing and establishing new international collaborations, which enabled the new strongly interdisciplinary research topics and opened new perspectives of future research (see Research plan of the team for 2015-2019).

AWARD-WINNING RESULTS:

- *The 2011 Outstanding Statistical Application Award of American Statistical Association and 2011 Frank Wilcoxon Prize* got M. Kárný from AS team together with A.Raftery and, P.Ettler for the results presented in the paper “Online prediction under model uncertainty via dynamic model averaging: application to a cold rolling mill” [10].
- L. Bakule's article [24] is recognized as one of the Top 25 papers published in Annual Reviews in Control in 2012.
- O.Tichý got “Werner von Siemens Excellence Award 2010” for his diploma thesis “Integral Models of Dynamic Scintigraphic Studies”.
- O.Tichý was awarded the 1st place in the 7th annual Rektorys competition in applied mathematics organized by Department of mathematics, FSv ČVUT, for the work “On Sparsity in Bayesian Blind Source Separation for Dynamic Medical Imaging”.
- R. Hofman was awarded by Czech Radiation Protection Society by prize for the best work of young authors in the field of protection against ionizing radiation.
- R. Hofman got the prize for his thesis “Application of Advanced Data Assimilation Methods in Off-Site Consequence Assessment, in competition of PhD theses in nuclear engineering branches awarded by Institute of Nuclear Research, Řež a.s. and Czech Nuclear Society.

REFERENCES:

- [1] Kárný M., Kroupa T.: *Axiomatisation of fully probabilistic design*, Information Sciences, vol.186, 1 (2012) 105-113.
- [2] Kárný M., Guy T.V.: *On Support of Imperfect Bayesian Participants*, Chapter in: Decision Making with Imperfect Decision Makers, Intelligent Systems Reference Library, vol. 28, (2012) 29-56.

- [3] Herzallah R., Kárný M.: *Fully probabilistic control design in an adaptive critic framework*, Neural Networks, vol. 24, 10 (2011) 1128-1135.
- [4] Kárný M., Guy, TV, Kracík J., Nedoma P., Bodini A., Ruggeri F.: *Fully Probabilistic Knowledge Expression and Incorporation*, Statistics and its interface, vol. 7 (2014) 503–515.
- [5] Kracík J.: *Combining Marginal Probability Distributions via Minimization of Weighted Sum of Kullback-Leibler Divergences*, International Journal of Approximate Reasoning, vol. 52, 6, (2011) 659-671.
- [6] Kárný M.: *Approximate Bayesian recursive estimation*, Information Sciences, vol. 285, 1 (2014) 100-111.
- [7] Pavelková L., Kárný M.: *State and parameter estimation of state-space model with entry-wise correlated uniform noise*, International Journal of Adaptive Control and Signal Processing, vol. 28, 11 (2014) 1189-1205.
- [8] Kárný M.: *Automated Preference Elicitation for Decision Making*, Chapter in: Decision Making and Imperfection, Studies in Computational Intelligence, vol. 474, (2013) 65-99.
- [9] Dedecius K., Nagy I., Kárný M.: *Parameter tracking with partial forgetting method*, International Journal of Adaptive Control and Signal Processing, vol. 26, 1 (2012) 1-12.
- [10] Raftery A. E., Kárný M., Ettler P.: *Online Prediction under Model Uncertainty Via Dynamic Model Averaging: Application to a Cold Rolling Mill*, Technometrics, vol. 52, 1 (2010) 52-66.
- [11] Ökzan E., Šmídl V., Saha S., Lundquist C., Gustafsson F.: *Marginalized adaptive particle filtering for nonlinear models with unknown time-varying noise parameters*, Automatica, vol. 49, 6 (2013) 1566-1575.
- [12] Dedecius K., Sečkárová V.: *Dynamic Diffusion Estimation in Exponential Family Models*, IEEE Signal Processing Letters, vol. 20, 11 (2013), 1114-1117.
- [13] Dedecius K., Sečkárová V.: *Centralized Bayesian reliability modelling with sensor networks*, Mathematical and Computer Modelling of Dynamical Systems, vol. 19, 5 (2013) 471-482.
- [14] Dedecius K., Reichl J., Djuric J.P.: *Sequential Estimation of Mixtures in Diffusion Networks*, IEEE Signal Process. Lett., vol. 22, 2 (2015) 197-201 /available online 2014/.
- [15] Pecha P., Pechová E.: *An unconventional adaptation of a classical Gaussian plume dispersion scheme for the fast assessment of external irradiation from a radioactive cloud*, Atmospheric Environment, vol. 89, 6 (2014), 298-308.
- [16] Hofman R., Pecha P., Šmídl V.: *Evaluation of detection abilities of monitoring networks using multiple assessment criteria*, International Journal of Environment and Pollution, vol. 55, (2014) Nos. 1/2/3/4.
- [17] Šmídl V., Hofman R.: *Marginalized Particle Filtering Framework for Tuning of Ensemble Filters*, Monthly Weather Review, vol. 139, 11 (2011), 3589-3599.
- [18] Šmídl V., Hofman R.: *Tracking of atmospheric release of pollution using unmanned aerial vehicles*, Atmospheric Environment, vol. 67, 1 (2013), 425-436.
- [19] Tichý O., Šmídl V.: *Bayesian Blind Separation and Deconvolution of Dynamic Image Sequences Using Sparsity Priors*, IEEE Transactions on Medical Imaging, vol. 34, 1 (2014) 258-266.
- [20] Tichý O., Šmídl V., Šámal M.: *Model-based extraction of input and organ functions in dynamic scintigraphic imaging*, Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization, (2014) DOI: 10.1080/21681163.2014.916229.
- [21] Korotka T., Loiseau J. J., Zagalak P.: *Weak regularizability and pole assignment for non-square linear systems*, Kybernetika, vol. 48, 6 (2012), 1065-1088.

- [22] Rezunenkenko O., Zagalak P.: *Non-local PDEs with discrete state-dependent delays: Well-posedness in a metric space*, Discrete and Continuous Dynamical Systems, vol. 33, 2 (2013) 819-835.
 - [23] Duarte-Mermoud M.A., Ordonez-Hurtado R.H., Zagalak P.: *A method for determining the non-existence of a common quadratic Lyapunov function for switched linear systems based on particle swarm optimisation*, International Journal of Systems Science, 43, 11 (2012) 2015-2029.
 - [24] Bakule L., Papík M.: *Decentralized control and communication*, Annual Reviews in Control, vol. 36, 1 (2012) 1-10.
 - [25] Bakule L., Papík M., Rehák B.: *Decentralized stabilization of large-scale civil structures*, Proceedings of the 19th IFAC World Congress, (2014) 10427-10432.
 - [26] Bakule L.: *Decentralized control: Status and outlook*, Annual Reviews in Control, vol. 38, 1 (2014) 71-80.
 - [27] Guy T.V., Kárný M., Wolpert D. H. (Eds): *Decision Making and Imperfection*, Springer, Berlin, Studies in Computational Intelligence, vol. 474, (2013).
 - [28] Guy T.V., Kárný M., Wolpert D. H. (Eds): *Decision Making with Imperfect Decision Makers*, Springer-Verlag, Berlin, Intelligent Systems Reference Library, vol. 28, (2012).
 - [29] Pavelková L.: *Nonlinear bayesian state filtering with missing measurements and bounded noise and its application to vehicle position estimation*, Kybernetika, vol. 47, 3 (2011) 370-384.
 - [30] Přikryl J., Tichý T., Bělinová Z., Kapitán J.: *Comparison by Simulation of Different Approaches to the Urban Traffic Control*, Archives of Transport System Telematics, vol. 5, 4 (2012) 26-30.
 - [31] Přikryl J., Kocijan. J.: *Stochastic Analysis of a Queue Length Model Using a Graphics Processing Unit*, Transactions on Transport Sciences, vol. 5, 2 (2012) 55-62.
 - [32] Suzdaleva E., Nagy I.: *Data-based Speed-limit-respecting Eco-driving System*, Transportation Research. Part C: Emerging Technologies, vol. 44, 1 (2014) 253-264.
 - [33] Ettler P., Dedecius K.: *Quantification of Information Uncertainty for the Purpose of Condition Monitoring*, Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO), (2014) 127-132.
 - [34] Ettler P., Dedecius K.: *Probabilistic reasoning in service of condition monitoring*, Proceedings of the 11th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies CM2014/MFPT2014, (2014).
 - [35] Ettler P., Dedecius K., Juričič D., Preglej A.: *Advanced Soft Sensor Technology to be Used for Cold Rolling Mills*, Proceedings of the 16th IEEE International Conference on Emerging Technologies and Factory Automation, (2011) 1-4.
 - [36] Šmídl V., Janouš Š., Peroutka Z.: *Extending Horizon of Finite Control Set MPC of PMSM Drive with Input LC Filter using LQ Lookahead*, Proceedings of IECON: 40th Annual Conference of the IEEE Industrial Electronics Society, (2014) 581-586.
 - [37] Rezunenkenko O.: *Local Properties of Solutions to Non-Autonomous Parabolic PDEs with State-Dependent Delays*, Journal of Abstract Differential Equations and Applications, vol. 2, 2 (2012) 56-71.
- Kurdyukov A., Kustov A., Tchaikovsky M., Kárný M.: *The Concept of Mean Anisotropy of Signals with Nonzero Mean*, Proceedings of the 19th International Conference on Process Control 2013, Eds: Fikar Miroslav, Kvasnica Michael, (Strbske Pleso, SK, 18.06.2013-21.06.2013) (2013).

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of Control Theory

Department of Control Theory

The research in the field of control theory has a long tradition both in the Institute and in the Department of Control Theory. During the 1960s, the researchers there made considerable developments in both transfer-function and state-space methods. During the 1970s and the 1980s, the members of the Department of Control Theory achieved significant results, which launched an entirely new area of research worldwide. Among these are the parametrization of all controllers stabilizing a given plant (known as the Youla-Kučera parametrization) and the design of control systems via polynomial equations. Starting the 1990s, the research activities of the department ranged from robust control to nonlinear systems. Applied research in the department focuses on numerical methods for control-system simulation and design, which yields various original software packages for control and simulation. Furthermore, Department investigates the problems in robotic walking, including their software and hardware implementations. Nevertheless, the theoretical research currently prevails in the Department of Control Theory and it is focused on the control systems analysis, feedback control design and general dynamical systems theory.

The most important research areas during the period 2010-2014 were as follows:

- Analysis and control design for large scale and spatially distributed systems.
- Analysis, control design and synchronization of nonlinear chaotic systems.
- Invariant manifolds in control systems, immersion and invariance design.
- Topological dynamics and general dynamical systems theory.
- Optimal control and its applications.

2.2 Description of the particular achievements during 2010-2014

Structured by above general scientific characteristics and topics of the **Department of Control Theory (DCT)**, the basic achievements are as follows.

2.2.1 Analysis and design for large scale and spatially distributed systems

The research in this area was concentrated on modelling, analysis and control of large scale systems, spatially distributed systems and developing algorithms for multivariate polynomials. Several results were achieved here, namely:

- *The theory and algorithms for stabilization of spatially invariant systems with multiple inputs and multiple outputs.* This theory uses the relationship between stability of a bivariate polynomial and positiveness of a related polynomial matrix

on the unit circle. Note that structural stability implies bounded-input-bounded-output stability. Analysis of structural stability is based on generating polynomials, i.e., polynomials computed from the matrix transfer function of a plant by the procedure given in the literature. The original result consists in the proof that a plant is structurally stable if and only if the Schur-Cohn matrix corresponding to the generating polynomial is positive definite on the unit circle. Since the obtaining generating polynomials is computationally hard (it requires computing set of determinants of matrices), new condition of stability is proposed. This condition is based on the positivity of the Schur-Cohn matrix corresponding directly to the denominator polynomial matrix of the matrix transfer function of a plant which is no longer necessary, however, it is not so computationally hard. This result was obtained by joint work of Petr Augusta and Petra Augustová, both full members of the DCT, [2].

- *Solving algebraic Riccati equations with polynomials and its applications.* These equations arise in, for example, optimal control of spatially distributed systems. It is shown that a solution to an algebraic Riccati equation with polynomials is generally not a finite-order polynomial. Conditions for existence of the finite-order solution are derived. The numerical algorithm for solving algebraic Riccati equations with polynomials is based on so-called spectral method. Versions for both continuous-time and discrete-time systems are developed. Algorithm is based on the use of the fast Fourier transform and it finds all solutions from the set of polynomials if they exist, or truncate non-finite-order solutions and returns them in the form of polynomial of an arbitrary high finite order. This result was obtained by joint work of Petr Augusta and Petra Augustová, both full members of the DCT, [3].
- *Fast algorithm for checking positiveness of a symmetric polynomial matrix on the unit circle.* It is based on the effective sampling of polynomial matrices. The sampling is performed by the fast Fourier transform. The positiveness is checked directly by substituting points from the unit circle into a polynomial. For every numerical value of the polynomial matrix variable the matrix becomes a constant matrix whose positiveness is checked easily by known tools for constant matrices. Surprisingly, this approach is dramatically faster than commonly used semi-definite programming expression. The number of variables of the polynomial matrix can be arbitrary, since the multidimensional FFT is available for checking positiveness of multivariate polynomial matrices. The proposed method gives necessary conditions only, but it can be used, for instance, in stability analysis of spatially distributed systems with an arbitrary number of spatial variables. This result was achieved fully by P. Augusta, the member of DCT team, [4].
- *Technique for stabilisation of spatially invariant systems with one temporal variable and no limits on number of spatial variables.* This approach is based on the iterative use of the technique for stabilization of systems with one temporal and one spatial variables developed and published by P. Augusta, full member of the DCT before. It is based on an equivalence of stability of a multivariate polynomial and positiveness of a certain symmetric polynomial matrix (Schur-Cohn matrix) on the unit circle. Schur-Cohn matrix is constructed iteratively. Each iteration eliminates one spatial variable in the criterion of

stability. This method is sufficient only, but it is computationally effective. This is the joint research with the Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague. P. Augusta, who is the only one of the authors being a member of evaluated Department of Control Theory, contributed to these result by theoretical analysis and solution design, both theoretical and its numerical implementation. His contribution was a key one. Estimate of the evaluated DCT team contribution share is 70%, [5].

- Large-scale systems and their remote control. The control of large systems uses communication networks which induces further issues. The control over a network is discrete since the data are transmitted in so-called packets. Moreover, the transmission channel cannot be considered 100% reliable, so the control must be robust enough to overcome a certain number of losses of these data packets. A benchmark example - a model of a 20-story building where a system for prevention against damage caused by the earthquake is to be designed - is used for evaluation of the results. Time delays in the networked control stimulated interest for investigation of general classes of time delay systems. The results are developed with a future use for large systems in mind. This still fresh and ongoing research is performed by the DCE member B. Rehak in collaboration with L. Bakule from Department of Adaptive Control. B. Rehak contributed significantly as the expert on numerical algorithms, developed corresponding computational algorithms and tuned their codes, performed majority of numerical experiments, provided deeper mathematical insight and participated in the engineering interpretation of results, [7].
- Control of discrete linear repetitive processes using strong practical stability and H_∞ disturbance attenuation. This result presents a new approach to stability analysis and stabilisation of linear repetitive processes – a distinct class of bi-dimensional systems. The concept of the so-called strong practical stability is applied. A new stability test is developed, it is simpler and computationally more efficient than all known previously developed tests. Moreover, this new test makes possible a control law design. That was not possible before. The result was achieved jointly with University of Southampton, Wuppertal University, University of Hong Kong and other partners. P. Dabkowski who was the only one of the authors being a member of evaluated Department of Control Theory, contributed to these result by problem analysis and solution design, most importantly, in the field of strong stability and H_∞ design with application to repetitive processes control. Other co-authors provided motivation, participated in the analysis and helped to interpret results. Estimate of the DCT team contribution share is 40%, [15].

2.2.2 Analysis, control design and synchronization of chaotic systems

This area deals with chaotic systems, but in a less abstract way, namely, with active control of chaotic systems, synchronization and other potential applicable concepts, based on methodology of nonlinear control theory.

- Chaos by switching between different types of simpler systems. Chaos is here consequence of the complicated interactions on the switching boundaries

between simpler systems. Some results on chaos generated by systems switching and applications to secure encryption were obtained. This is the joint collaboration with Centro de Investigacion y Estudios Avanzados, Guadalajara, Mexico. The only DCT team member participating in this research was S. Celikovsky, who prepared some convergence proofs, discussed chaotic behaviour analysis, application for encryption and partly motivated the idea of chaos in switched linear systems historically. His estimated share in this research is 40%. The paper presenting these results just appeared in March 2015 in the recognized impacted Journal of the Franklin Institute, [17].

- *Bimodal quadratic map and its electronic circuit realization.* This result introduces and studies chaotic map and based on these properties provides some outlooks for the application in chaos based secure encryption. More importantly, electronic circuit realization of the mentioned chaotic system is constructed and thoroughly investigated. This makes the possible application in secure encryption especially challenging. This result was achieved in collaboration with El Instituto Potosino de Investigación Científica y Tecnológica, San Luis Potosi, Mexico. S. Čelikovský, who is the only one of the authors being a member of the evaluated Department of Control Theory, contributed to these result by theoretical analysis of the difference map chaotic system properties that were crucial to construct its circuit realization and application to secure encryption. Other co-authors prepared circuit realization and experiments. Estimate of evaluated team contribution share is 40%, [16].
- *Desynchronization Chaos Shift Keying Method Based on the Error Second Derivative and Its Security Analysis.* The desynchronization effect causes by the mismatch between parameters in the systems being synchronized is studied to detect this mismatch as quickly as possible. Detection is very fast due to the use of the second order derivative of its error and its novel efficient estimation method. This result enable to improve performance of the known chaos shift keying secure encryption scheme based on continuous time chaotic systems, providing thereby further encryption options. Result was fully achieved by DCT members S. Celikovsky and V. Lynnyk, [12].
- *Robust synchronization of a class of chaotic networks.* Synchronization of the network with chaotic nodes is analysed when some new network connections in node are added or old ones removed. Some partial results are formulated and proved by rigorous mathematical treatment, more complex networks synchronization is studied numerically. Possible application in network chaos encrypted communication is briefly discussed as well. The research was performed jointly with the Centre for Chaos and Complex Networks, City University of Honk Kong, Prof. Guanrong Chen. S. Celikovsky and V. Lynnyk, members of the Department of Control Theory, derived conditions and mathematical proof for bi-directional synchronization based on the observers theory. They also carried numerical experiments establishing synchronizability of networks with higher number of nodes. G. Chen and S. Celikovsky jointly provided model of the generalized Lorenz systems used in the network nodes. Contribution of Department of Control Theory is estimated as 80%, [13].

2.2.3 Invariant manifolds in control systems, immersion and invariance design

Research in these areas concentrated on the computational methods to determine invariant manifold, both using the direct PDE solvers and using other methods, e.g. iterative ones. Invariant manifolds enable efficient controller design e.g. in the output regulation problem and for observers. They can be viewed also as part of the more general immerse and invariance methodology for the control design. Invariant immersed manifolds can be also determined in analytical closed form for some special classes of systems, especially the mechanical ones, with broad application in robotics, closely related with virtual constraints methodology used there. The following results were achieved in this area.

- Computational methods for center, center-stable and center-unstable manifolds with applications to control and observer design. The methods are based on a simpler characterization of the invariant manifolds and can be therefore easier algorithmized. Another advantage over the previously known methods is the more precise description of the system on a given neighborhood of the origin, enabling to compute the manifold even for systems described by functions without convergent Taylor expansion. This case is often met in case of barrier functions. Suitability of the developed method for problems of nonlinear optimal control theory is straightforward. This method was also adapted to provide the observer design for nonlinear systems. The main idea is to find certain nonlinear mapping linking the states of the observed system with another system which has the same eigenvalues as the observer. This mapping is computed in a way analogous to the computation of the center manifold as described above. This idea is closely related with the well-known immersion and invariance principle. This research was carried out in cooperation with the Department of Aerospace Engineering at Nagoya University in Japan and within DCT group by B. Rehak and S. Celikovsky who contributed to the formulation of the problem, computational design and numerical experiments, [23].
- Immersion and invariance based design for walking robots. Here, the decomposition technique was developed for the continuous time (swing) phase and also for the the so-called embedded impact mapping, to achieve invariance of the decomposition under the impact map. Impact map is an impulsive stage occurring when the swing leg during walking hits the ground and legs are interchanged. Furthermore, methods for estimation of walking robot model were developed as well. Finally, we proceed in building and testing the experimental laboratory platform for the robotic walking. The main idea of decomposition is again basically generalization of the well-known immersion and invariance design. This result was performed by DCT team members S. Celikovsky, M. Anderle with a smaller contribution of Prof. C. Moog, IRCCyN Nantes, France, [14].
- Submersivity and nonlinear control systems on homogeneous time scales. Time scales are an increasingly important tool in the control theory as they allow to unify description of discrete and continuous processes. Submersivity of a system defined on time scales which is described by input-output equations only is of a special importance as it simplifies analysis of systems with delta-derivative operator. The result proves the equivalence of submersivity and full

rank of the matrix defined using the input-output equations thereby providing an easy submersivity test. This result was achieved in collaboration with the Estonian Academy of Sciences, the DCT member B. Rehak contributed to all type of research efforts, his share can be approximated by 50%, [20].

- Alternative Method of Solution of the Regulator Equation: L_2 -Space Approach. New efficient numerical method to solve the regulator equations (RE) is developed. RE consists of partial differential equations (PDE) and algebraic ones, moreover, the PDE part is of rather peculiar type. RE solution is basic ingredient in many automatic controllers. In fact, the solution of RE is the output zeroing submanifold of the system controlled-invariant manifold, therefore, methods for its computation can be adapted to the more general invariant manifold computations. New method proves the existence of bounded domains where the PDE has a unique solution. RE is then solved via iterations of these solutions. This original idea is then compared with previously known methods to show its efficiency. This result was fully achieved by B. Rehak, the member of DCT team, [22].

2.2.4 Topological dynamics and general dynamical systems theory

Research in this area concentrated on the general theory of dynamical systems, precisely concerning more general chaos theory, problems like defining chaos for set-valued maps, and, further, studying dynamics of smooth systems described by generalized flows and semiflows, or using general abstract tools, like functional derivatives. Main results can be specified in a more detail as follows.

- Generalized Semiflows and Chaos in Multivalued Dynamical Systems. This result provides an important description of the chaotic behavior in multi-valued dynamical system. For the multi-valued system formulated via differential inclusion the practical conditions on the right-hand side were derived to guarantee existence of a solution, which leads to the chaotic behavior. This approach uses the notion of the generalized semi-flow but, importantly, it does not require construction of a selector on the set of solutions. The results were obtained by the DCT team members S. Celikovsky and Z. Beran, [8].
- Unified language and techniques for discrete and continuous dynamical systems including higher order ordinary differential equations based on generalized flows. The term flow is a common term used across many fields of mathematics including theory of dynamical systems, differential geometry, differential equations, functional equations. We have defined a new generalized flow called as the flow with limited intersection of its worldlines. This allows to unify the language of the above mentioned areas of mathematics and to use a new formalism based surprisingly on set theory, precisely a special kind of set embedding. The known cases as for example the Dirichlet problem, Harmonic oscillator or Lagrange interpolating polynomials have been discussed using this new theory. Research was completely done in DCT by its member P. Augustova, [6].

- Chaos on hyperspace. This result addresses the chaotic behavior of a set-valued mapping on a compact space. The existence of the generalized shadowing property in the hyperspace is proved. Based on the generalized shadowing property of the set-valued mappings and the assumption of the existence of an unstable chain recurrent point of the mapping, it was shown that the Bernoulli system of bi-directional shifts is embedded in the sense of semi-conjugacy into the image of set-valued mapping. The result was fully achieved by S. Celikovsky and Z. Beran, the members of DCT team, [9].
- Application of the functional derivatives to the mathematical modeling of dynamical systems. The application of the functional derivatives to the mathematical modeling of complex systems is studied and the connection of functional derivatives with total differentials in Banach spaces is demonstrated. Local and global existence theorems for the linear equations in total differentials is provided and proved. Consequently, a total integrability conditions are provided for the case of linear equations with the functional derivatives. Possible applications of these results are discussed. The results were obtained by S. Celikovsky and Z. Beran, the DCT team members, [10].

2.2.5 Optimal control and its applications

The following results were achieved in this area.

- Optimization of the penicilin production. Important problem of optimizing production of peniciline is addressed based on its nonlinear model described by ordinary differential equations with controlled inputs. Application of the optimal control theory and originally adapted numerical methods enabled to increase in theoretical simulations significantly the previously known production amounts. Results were appreciated not only by control engineering but also by biosystems community resulting in publication of the well impacted journal. This is the joint research with the Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague. S. Čelikovský, who is the only one of the authors being a member of the evaluated Department of Control Theory team, contributed to these result by providing theoretical analysis of the peniciline production model and suggesting numerical algorithms to find optimal solutions for peniciline production. He also helped to prepare numerical experiments and their interpretation. Estimate of the DCT team contribution share is 60%, [21].
- Optimal and suboptimal decoupling a linear system by dynamic compensation. The systems in implicit form and parametrized the set of all controllers that decouple the system and render it regular, proper and stable were studied.. Then it was shown how to obtain optimal and suboptimal decoupling controllers by an appropriate selection of the parameters. The result was fully achieved by V. Kucera, the member of DCT team, [19].
- Optimal microalgal growth problem and its infinite time horizon analysis. This result addresses important problem of optimal process control applied in the model of biomass growth control using the light irradiance. It provides analytical solution based on the singular perturbation reduction and then applying

Pontryagin maximum principle to obtain optimal solution which is interesting due to the nonlinear character of the model. Results give increase to previously known performance and justify some heuristics previously adopted by biotechnological research community. S. Čelikovský, being the only one of the authors from the Department of Control Theory, contributed to these results by mathematical results analyzing the model properties, analysis of velocity of the convergence to the singular perturbation based reduction, solved analytically the resulting optimal control problem and significantly helped to design alternative numerical solution to be compared with that analytical one. Estimate of the DCT team contribution share is 70%, [11].

- LMI optimization based design of robotic walking. This result provides novel approach to the design of walking-like trajectory and it exponentially stable tracking in the model of the underactuated walking robot. The new idea is based on the exploring the intrinsic physical feature of walking when the variable of the Lagrangian kinetic symmetry coincides generalized coordinate coincides with the unactuated one. It is then combined with tracking error analysis via modern methods of control theory and linear matrix inequality based design. S. Celikovsky, M. Anderle and J. Zikmund, members of the Department of Control Theory, provided problem statement, derived condition for walking trajectory design and tracking and designed such a trajectory and tracking using numerical LMI optimization. The only co-author outside the evaluated team, D. Henrion, participated in preparing and realizing LMI optimization code. Estimate of evaluated team contribution share is 80%, [1].
- Complete Fast Analytical Solution of the Optimal Odd Single-Phase Multilevel Problem. This result provides the novel and efficient way to compute optimal switching angles for general multilevel odd symmetry waveforms. This problem is shown to be more general than the optimal pulsewidth modulation (PWM) problem, which is an established method of generating PWM waveforms with low baseband distortion. The optimal switching sequence is obtained by computing zeros of two FOP polynomials in on variable or, alternatively, by a special recurrence formula and eigenvalues computation. The research was fully performed by members of the DCT team M. Sebek, P. Kujan and M. Hromcik, [18].

List of publications containing presented DCT team results

- [1] Anderle M, Čelikovský S., Henrion D., Zikmund J. Advanced LMI based analysis and design for Acrobot walking, Int. Journal of Control vol.83, 8 (2010), p. 1641-1652.
- [2] Augusta P., Augustová P. On stabilisability of 2-D MIMO shift-invariant systems. Journal of the Franklin Institute, vol.350, no. 10, 2013.
- [3] Augusta P., Augustová P. Algorithm for solving polynomial algebraic Riccati equations and its application. Cybernetics and Physics, vol.1, no. 4, 2012.
- [4] Augusta P. A numerical test of positiveness on the unit circle based on the fast Fourier transform. Proc. of the 21st Med. Conf. on Control and Automation, 2013.
- [5] Augusta P., Hurák Z. Distributed stabilisation of spatially invariant systems: positive polynomial approach. Multidim. Systems and Signal Proc., vol.24, 2013.
- [6] Augustová P. On some generalizations of flows. Abstracts of Talks of the 20th European Conference on Iteration Theory 2014. Lagow, PL, 14.09.2014-20.09.2014.

- [7] Bakule L., Papík M., Rehák B. : Decentralized stabilization of large-scale civil structures, Proceedings of the 19th IFAC World Congress, 2014, p. 10427-10432.
- [8] Beran Z., Čelikovský S. Generalized semiflows and chaos in multivalued dynamical systems, 2012, <http://dx.doi.org/10.1142/S0217979212460162>.
- [9] Beran Z., Čelikovský S. Chaos on hyperspace, 2013, <http://dx.doi.org/10.1142/S0218127413500843>.
- [10] Beran Z., Čelikovský S. Application of functional derivatives to analysis of complex systems, 2013, <http://dx.doi.org/10.1016/j.jfranklin.2013.04.007>.
- [11] Čelikovský S., Papáček Š., Cervantes-Herrera A., Ruiz-León J. Singular Perturbation Based Solution to Optimal Microalgal Growth Problem and Its Infinite Time Horizon Analysis, IEEE Trans. on Aut. Control vol.55, 3 (2010), p. 767-772.
- [12] Čelikovský S. and Lynnyk V. Desynchronization Chaos Shift Keying Method Based on the Error Second Derivative and Its Security Analysis, International Journal of Bifurcation and Chaos vol.22, 9 (2012).
- [13] Čelikovský S., Lynnyk V. and Chen G. Robust synchronization of a class of chaotic networks, Journal of the Franklin Institute, vol.350, 10 (2013), p. 2936-2948.
- [14] Čelikovský S., Anderle and M., Moog C. H. Embedding the generalized Acrobot into the n-link with an unactuated cyclic variable and its application to walking design, Proceedings of the European Control Conference 2013 (ECC), p. 682-689.
- [15] Dabkowski, Galkowski K., Bachelier O. and Rogers E.: Control of discrete linear repetitive processes using strong practical stability and H_∞ disturbance attenuation, Systems and Control Letters vol.61, 12 (2012), p. 1138-1144.
- [16] García-Martínez M., Campos-Cantón I., Campos-Cantón E., Čelikovský S. Difference map and its electronic circuit realization, Nonl. Dyn..74 (2013), p. 819-830.
- [17] Gómez-Gutiérrez D., Čelikovský S., Ramírez-Trevino A., Castillo-Toledo B. On the observer design problem for continuous-time switched linear systems with unknown switchings, Journal of the Franklin Institute, vol.352, 4 (2015).
- [18] Kujan P., Hromčík and Šebek M. Complete Fast Analytical Solution of the Optimal Odd Single-Phase Multilevel Problem, IEEE Trans. on Industrial Electronics vol.57, 7 (2010), p. 2382-2397.
- [19] Kučera V. Optimal decoupling controllers revisited, Control and Cybernetics vol.42, 1 (2013), p. 1-16.
- [20] Kotta U., Rehák B., Wyrwas M.: On submersivity assumption for nonlinear control systems on homogeneous time scales, Proc. of the Estonian Acad. of Sci., vol. 60, 1 (2011), p. 25-37.
- [21] Pčolka M., Čelikovský S.: Numerical aspects of optimal control of penicillin production, Bioprocess and Biosystems Engineering vol.37, 1 (2014), p. 71-81.
- [22] Rehák B.: Alternative Method of Solution of the Regulator Equation: L2 -Space Approach Asian Journal of Control vol.14, 4 (2012), p. 1150-1154.
- [23] Sakamoto N., Rehák B., Ueno K.: Nonlinear Luenberger observer design via invariant manifold computation, Proc. 19th IFAC World Congress, 2014, p. 37-42.

2.3 Selected achievements during 2010-2014 in brief

Finally, let us give a brief selection from the extensive exposition above, including some impact of the related earlier research and external funding achievements.

- Optimization results for biosystem published in highly impacted journals, both in automatic control and in bioengineering area journals, namely, in IEEE Trans. Aut. Contr. and in Biosystems and Bioengineering.
- The development of the new and efficient algorithm for stability analysis and stabilisation of spatially invariant systems with multiple inputs and multiple outputs. In contrast to this algorithm, other existing methods require computing the set of determinants of polynomial matrices, which can be lengthy and numerically ill behaved.
- The new and efficient numerical methods for the invariant manifold computations with application to various design tasks.
- Series of results on chaos control and synchronization, including study of chaotic networks.
- Highly cited papers from early 2000's co-authored by S. Celikovsky continued to acquire even more citations during the period 2010-2014 as well, currently two most cited of these papers have 477 and 150 citations in total, correspondingly, autocitations excluded, registered by Web of Science SCI.
- DCT team has achieved during 2010-2014 in total several theoretical research grants covering some of the above theoretical research areas. The total amount obtained by the DCT team during the evaluated period 2010-2014 was over 11 milion of CZK (approx. over 400 thousand EUR).

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of Decision Making Theory

Department of Decision Making Theory

The research of the department is motivated by the question how systems studied in sciences and social sciences develop and which equilibria and in which way they reach. This inevitably involves development of suitable mathematical models. The main research areas of the team in the selected time frame are optimization, nonsmooth analysis, mathematical methods in mechanics of solids, computational mechanics and numerical analysis, Bayesian networks, conditional independence structures, game theory, information theory, evidence theory, and mathematical logics. Members of the department have been maintaining rich international scientific contacts which help them to follow (and also to initiate and to create) up-to-date research trends in the areas of their expertise. As most of the team members are involved in lecturing of advanced courses at universities, these current directions of research are immediately reflected in bachelor, master, and doctoral theses topics offered by our department. Consequently, some results described in the sequel were obtained jointly with Ph.D. students at our department, namely with L. Adam, V. Lín, M. Pištěk, and G. Pathó. Below we mention main scientific achievements of the department during 2010-14 in the selected themes.

Optimization and nonsmooth analysis (J.V. Outrata, M. Červinka). The research has been conducted essentially in the following three areas:

(i) Mathematical programs with equilibrium constraints (MPECs). We derived sharp necessary optimality conditions for a class of infinite-dimensional MPECs related to unilateral contact problems in mechanics. Then we obtained new strong stationarity conditions in MPECs with strongly regular equilibria. Finally, we performed a deep sensitivity analysis of discretized shape optimization problems with various friction models and used it in their numerical solution.

(ii) Stability analysis of parametrized equilibria with conic constraints. This research was focused on deriving workable conditions ensuring some basic stability properties of solution maps to these equilibria. In particular, we studied the so-called Aubin property, isolated calmness property and tilt stability of conic programs. Particularly deep results were achieved in case of Lorentz cones. The results were applied to stability of electronic circuits.

(iii) Calmness and error bounds. These properties have been fully characterized in terms of primal and dual derivative-like objects. Further, new constraint qualifications have been constructed and their relationships to calmness of the respective perturbation mappings have been established. For the isolated calmness of equilibria with inequality constraints an efficient criterion has been found.

Mathematical methods in mechanics of solids, computational mechanics, and numerical analysis (M. Kružík, J. Valdman, T. Roubíček, M. Kočvara).

Numerous mathematical models in continuum mechanics and thermomechanics of solids described by systems of nonlinear partial differential equations or inequalities were formulated in a thermodynamically consistent way and mathematically analysed with the aim to prove existence of their solutions and devise efficient numerical strategies for their approximation implementable on computers. Examples are models in geophysics or in phase transformations in ferromagnetic materials and shape memory alloys. Other instances include plasticity, damage, or adhesive contacts formulated either in small or in large strains. The attention has been also paid to various activated, primarily rate-independent processes and to combination of different phenomena.. Our long-standing cooperation with physicists from the Czech Technical University resulted in a series of papers on gradient crystal plasticity with specific forms of surface energy density.

Mentioned applications motivated theoretical research in the calculus of variations. Our research resulted in various fine weak lower semicontinuity statements for integral functionals. These can be used to show existence of minimizers for variational problems with differential constraints. Significant effort has been devoted to problems of non-interpenetration of matter and orientation-preservation in models of mathematical elasticity. A precise answer was given in two-dimensional models among bi-Lipschitz deformations and our results motivated other groups to attack this difficult open problem.

As to nonlinear computational mechanics, in the last years, we developed a-posteriori error estimates which are tools to measure approximation errors in computations of problems. In particular, we concentrated on obstacle problems, problems with nonlinear boundary conditions and poroelastic problems.

We showed, for the first time, a rigorous way how to add the most important constraint to the topology optimization problem. This, in effect, makes from an academic approach a practical tool for mechanical and civil engineering. Although topology optimization has been used for several years by now, the stresses in the resulting structure were always computed a-posteriori and this required another computational loop. With the invented method, this loop is no longer needed. This may lead to a significant reduction in time and effort in the design process.

Bayesian networks (J. Vomlel). The research has been conducted essentially in the following areas:

Efficient inference in Bayesian networks. We proposed new methods of efficient inference in Bayesian networks (BNs). We achieved several results that allow significant computational speedup during inference in BNs containing conditional probability tables (CPTs) of special types. Namely, we presented constructive proofs about the rank and the symmetric rank of tensors corresponding to the threshold and l-out-of-k functions and their noisy counterparts. Analytical and experimental comparison with the parent-divorcing method showed superiority of the proposed CP tensor decomposition method. We also proposed an approximate probabilistic inference method based on the CP tensor decomposition and applied it to a prototype application where standard methods are not tractable. In order to be able to exploit not only the local structure of some conditional probability tables but also other structural information potentially present in a Bayesian network, like determinism or context specific independence, we described a method for combining the CP tensor

decomposition of probability tables with probabilistic inference using weighted model counting.

Optimal triangulation problem. To perform efficient inference in Bayesian networks by means of a Junction Tree method, the network graph needs to be triangulated. The quality of this triangulation largely determines the efficiency of the subsequent inference, but the triangulation problem is unfortunately NP-hard. We investigated new methods for depth-first search and best-first search for finding optimal total table size triangulations. The search methods were made faster by efficient dynamic maintenance of the cliques of a graph. This problem was investigated by Stix, and we derived a new simple method based on the Bron-Kerbosch algorithm that compares favorably to Stix' approach. The new approach is generic in the sense that it can be used with other algorithms than just Bron-Kerbosch.

Conditional independence structures, learning of Bayesian networks (M. Studený, V. Kratochvíl, J. Vomlel). There were three areas of research during the observed period. The first topic was the development of methods for (computer) verification of the conditional independence implications. In cooperation with foreign colleagues, the idea of application of methods integer linear programming was followed. Two papers were devoted to this topic, one published in 2010, one submitted in 2014. The second and main topic was the mathematical theory for statistical learning of Bayesian network structures based on the application of methods of combinatorial optimization. This was done in cooperation with foreign colleagues R. Hemmecke, D.C. Haws and recently also with J. Cussens. Five papers on this topic were published and one submitted. The main idea was to take the point of view of polyhedral geometry and re-formulate the problem as the task of integer linear programming. The central idea here was the concept of the *characteristic imset polytope*; most of the papers on this topic were devoted to the geometric description of this polytope, for example attempts at finding and characterizing its facets.

Selected classes of cooperative and strategic games and their applications (T. Kroupa, M. Studený). We showed that the core, which is one of the main solution concepts in cooperative game theory, can be described for large classes of games based on MV-algebras. In case that the core is contained in a space of high dimension, the Cimmino-style algorithm can be used to recover the core elements. Together with O. Majer we have advanced in the study of strategic games represented by continuous and piecewise linear integral payoff functions. We found a sufficient condition enabling us to conclude that each of the players can randomize only over a finite set of equilibria, while acting according to any of Nash equilibrium strategies. We found a criterion for extreme supermodular functions used in game theory and applied in geometric approach to learning Bayesian networks. The condition leads to solving a certain simple linear equation system determined by the combinatorial core structure. Our results also enable us to describe indecomposability in the space of generalized permutohedra.

Information theory (F. Matúš). Main results in this area were reached in the following four aspects.

(i) Integral functionals based on convex normal integrands that are finite on the positive and infinite on the negative numbers, strictly convex but not necessarily differentiable. The functionals were minimized subject to finitely many moment constraints. The effective domain of the value function was described by a conic core. Minimizers and generalized minimizers were explicitly constructed from solutions of modified dual problems, not assuming the primal constraint qualification. The results provide definitive theoretical answers in situations that have been open for decades.

(ii) The entropy region is constructed from vectors of random variables by collecting Shannon entropies of all subvectors. Its shape was studied by means of polymatroidal constructions, notably by convolution. Four-atom conjecture on the minimization of Ingleton score was refuted. The topic is motivated by recent progress in network coding theory and cryptography.

(iii) The standard exponential families of probability measures on Euclidean spaces that have finite supports. In such a family parametrized by means, the mean is supposed to move along a segment inside the convex support towards an endpoint on the boundary of the support. Limit behavior of several quantities related to the exponential family was described explicitly.

(iv) The classes of matroids that are closed to the minors, addition of coloops and principal extensions. To any matroid in such a class another matroid was constructed such that the latter contains the former as a minor, has all proper minors in the class and violates Zhang-Yeung inequality. The result was applied to classes of multilinear, algebraic and almost entropic matroids to conclude that the classes have infinitely many forbidden minors.

Evidential compositional models (J. Vejnarová, V. Kratochvíl, R. Jiroušek). The most widely used models managing uncertainty and multidimensionality are, at present, the so-called *probabilistic graphical Markov models*. The problem of multidimensionality is solved in these models with the help of the concept of conditional independence, which enables factorization of a multidimensional probability distribution into small parts (marginals, conditionals or just factors). Among them, the most popular are Bayesian networks using acyclic directed graphs and conditional probability distributions. Compositional models, on the other hand, present an algebraic approach to multidimensional structured models using, in probabilistic framework, marginal distributions. It was proved several years ago, that these two classes of models are equivalent.

In graphical models, system of independence relations is coded using graphs. Compositional models represent an algebraic alternative to the graphical models. The system of related conditional independencies is not encoded explicitly but it is hidden in a model structure itself. Papers [1,2] provide answers to the question how to recognize whether two different compositional model structures are equivalent - i.e. whether they induce the same system of conditional independencies. Above that, one can find an easy way to convert one structure into an equivalent one in terms of some

elementary operations on structures, closely related ability to generate all structures equivalent with a given one, and a unique representative of a class of equivalent structures.

In the mentioned period, we dealt with compositional models mainly in the framework of evidence theory. We introduced the operator of composition for basic assignments and proved all the necessary properties enabling us to develop compositional models also in this, more general framework. Further, we investigated the relationship between evidential networks and evidential compositional models and found out, that the class of the latter is more general.

We also dealt with a problem of differentiation among compositional models in possibility theory (here the models are parameterized by a continuous t-norm) – we proved that models based on Gödel's and product t-norms have a nice probabilistic interpretation.

- [1] Kratochvíl Václav : [Probabilistic Compositional Models: solution of an equivalence problem](#), International Journal of Approximate Reasoning vol.54, 5 (2013), p. 590-601.
[2] Kratochvíl Václav : [Characteristic Properties of Equivalent Structures in Compositional Models](#), International Journal of Approximate Reasoning vol.52, 5 (2011), p. 599-612.

Mathematical logics (C. Noguera). We wish to mention the following results.

(i) Study of many-valued logics. We devoted a substantial part of the research capacity to the development of logical systems to go beyond the classical two-valued paradigm that forces all statements to be either true or false. Many logical problems and technological applications require more flexible analysis that allow for a graded notion of truth, with many intermediate levels between full truth and full falsity. Fuzzy logics and other many-valued logics provide a powerful mathematical framework to deal with reasoning under vagueness and imprecision. During these years we have contributed to the area by studying fuzzy logics that explicitly include intermediate truth-values as constants in their language, fuzzy logics with truth-stressers and truth-depressers (to analyze linguistic hedges like *it is almost true that* or *it is obvious that*) the interpretation of conjunctions over arbitrary scales of truthvalues, the arithmetical complexity of many-valued logics with universal and existential quantifiers, fuzzy logics able to cope with inconsistent information, and finally the identification of a minimal system of fuzzy logic that underlies all the known ones. The results have been published in seven journal papers and three book chapters.

Moreover, C. Noguera co-edited a two-volume handbook collecting and systematizing the modern research on mathematical fuzzy logic.

(ii) Abstract study of non-classical logics: The need for different logical systems arises in many contexts in which the classical analysis is inadequate or insufficient, not only in the problems requiring a graded notion of truth. Therefore, besides many-valued logics, there is a plethora of other formal systems of non-classical reasoning. Such diversity calls for a uniform systemic treatment. One way to achieve it is by means of an algebraic approach known as *abstract algebraic logic* (AAL). In this paradigm, one associates classes of algebras to each particular logic system, in an analogous way

as Boolean algebras can be associated to classical logic. During the last five years, C. Noguera has been very active in this area as well, in particular by developing an approach to non-classical logics based on the behavior of their implication connective, studying the basic properties of disjunction connectives, and starting the development of a general theory of non-classical logics with universal and existential quantifiers. The results have been published in three journal papers (plus two more accepted papers to appear and one submitted).

Decision-Theoretic Troubleshooting (V. Lín, J. Vomlel). Decision-theoretic troubleshooting is one of the areas to which Bayesian networks were applied. Given a probabilistic model of a malfunctioning man-made device, the task is to construct a repair strategy with minimal expected cost. The problem has received considerable attention over the past two decades. Efficient solution algorithms have been found for simple cases, whereas other variants have been proven NP-complete. We studied several variants of the problem found in literature, and proved that computing approximate troubleshooting strategies is NP-hard. We also showed that several troubleshooting scenarios proposed in the literature are equivalent to well-studied machine scheduling problems. This immediately yields new complexity-theoretic and algorithmic results for troubleshooting. Further, we examine the so-called call service action which is often used in troubleshooting but has no natural counterpart in machine scheduling. We show that adding the call service action to basic troubleshooting models does not make the problem intractable.

Additional information about the team. Results mentioned above were also presented at many international and national conferences and workshops in the form of invited (South Pacific Optimization Meeting, Newcastle, Australia 2013, International Conference on Variational Analysis and Applications, Erice, Italy, 2012 -- both J. Outrata, GaLoP IX 2014, Grenoble, France – T. Kroupa, for instance) or contributed talks as well as at many research seminars at foreign universities and institutions. On the other hand, members of our department regularly (co)organize or are involved in scientific committees of many international meetings (e.g. Prague Stochastics 2014, Modelling 2014, ManyVal 2013, WUPES 2012, Czech-Japan Seminars on Data Analysis and Decision Making 2012 and 2013) and schools (traditional Spring school on variational analysis at Paseky) with distinguished foreign and domestic speakers. Besides regular events, other workshops and schools were (co)organized, too (for example Workshop on relaxation, homogenization, and dimension reduction in hyperelasticity in Paris 2014). This clearly shows that the department is firmly built in worldwide networks in many areas of applied mathematics.

Our research has standing support by many national and international grants (GAČR, GAČR-FWF, Australian Research Council, Academy of Sciences-DAAD, Marie Curie Fellowship, to name a few) The activity of the department is also demonstrated by 154 journal articles or conference proceedings published (some of them with coauthors) in 2010-14; cf. the library of the Institute. Most of them appeared in renowned international journals.

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of the Econometrics

Department of the Econometrics

The research group contributes to three main areas of research: financial econometrics (intersecting finance and statistics), energy economics and macroeconomics.

The main emphasis of the work in the fields of financial econometrics and energy economics is put on the development of new econometric techniques for modelling data from financial and energy markets, and testing beliefs about how prices are being formed in these markets. First area of research generally focuses on management and measurement of financial and energy risk with help of data collected at high frequencies up to milliseconds. This is especially important in the energy markets, as prices are formed with different mechanisms in comparison to financial markets. We contribute to the literature by developing new techniques for modelling price processes, which are then used for improvement of current methodologies for risk measurement. We focus on the time-frequency estimation of realized volatility, link it to the durations between trades at ultra-high frequencies, and further use these techniques to formulate new models for better understanding and forecasting of risk in markets. Second area of research focuses on understanding market dependencies, its connectedness, and information transmission mechanisms. The main focus is on disentangling long-run and short-run connectedness, asymmetric information arrivals, and impact of jumps and co-jumps, which helps us to further improve our understanding of general market behavior. New techniques have direct implications for practitioners. The focus of the third area of research is in development of the new techniques in frequency domain. Whereas mainstream literature is focusing on the time domain estimation, it is natural to study the behavior of economic variables at various business cycles as well. Using new spectral estimators, we are able to uncover the dependencies and dynamics of financial variables at long-run from short-run, which has important implications for various fields, as well as policy making. In the field of macroeconomics, team focuses on the new stream of modeling approaches, which are headed in the direction to explicitly account for potential heterogeneous behavior of economic subjects, possible structural breaks introduced by the emergence of crisis as well as to better understand the uncertainty and links among various (macroeconomic and financial) markets. The development of both new theoretical models and policy-oriented models is the main focus.

Following paragraphs detail the main results of the team in the past five years.

The team contributed with the development of new methodologies for risk management [<http://hdl.handle.net/11104/0238364>] based on quantile regression and recently developed high frequency data-based measures of volatility. The new approach is simple and captures very well the conditional quantiles of stock market returns, which is central topic of study in the financial econometrics literature. Thus the contribution of the work is potentially large for the broad literature studying risk management and measurement. In the field of high frequency financial econometrics,

team contributed with several methodological advances. First notable result is development of new spectral based measures of realized variance, and covariance [<http://hdl.handle.net/11104/0238359>], which are important shift in usage of high frequency data, as they allow to estimate quantities at frequencies, and also allow to quantify the impact of jumps and co-jumps on the return variation. In addition, team members contributed with important theoretical results in the price creation process by analytical study linking properties of financial durations and volatility [<http://hdl.handle.net/11104/0238358>]. Final notable result is formulation of the stochastic cusp catastrophe theory with time-varying volatility together with the methodology of estimation [<http://hdl.handle.net/11104/0238360>]. Using the formulated theory, team provides a framework for estimation of the speculative bubbles in stock markets. These results are of fundamental character. In addition, new measure for capital market efficiency has been constructed [<http://hdl.handle.net/11104/0212200>, <http://hdl.handle.net/11104/0236071>]. The measure takes into consideration the correlation structure of the returns (long-term and short-term) and local herding behavior. During the evaluation period, team also contributed to the connectedness literature in several ways. We defined new measures of connectedness, which are able to quantify asymmetries in the transmission mechanism in financial markets [<http://hdl.handle.net/11104/0244325>]. In addition to the methodological contribution, team also identified strong asymmetries with negative information being the main channel for information transmission at various financial and energy markets [<http://hdl.handle.net/11104/0242965>, <http://hdl.handle.net/11104/0237770>]. Important contributions in this area of research is also new methodology based on the spectral estimator for bivariate long memory models, which are able to uncover a frequency dependent dynamics in the connectedness [<http://hdl.handle.net/11104/0241889>, <http://hdl.handle.net/11104/0237764>, <http://hdl.handle.net/11104/0237765>]. Using wavelet techniques, team uncovered strong time-frequency dynamics in the connectedness of various markets, which has strong implications for practitioners [<http://hdl.handle.net/11104/0222067>, <http://hdl.handle.net/11104/0201831>]. In macroeconomic modeling, team shown that deterministic models are able to capture the realistic movements of the macroeconomic variables. It was shown that nonlinear time series can successfully detect and quantify the presence of deterministic chaos in time series generated by a dynamic economic system as well as generated by the real economic process [<http://hdl.handle.net/11104/0223563>]. The evolution of monetary policy in a group of inflation targeting countries through the lens of estimated time-varying monetary policy rule was analyzed. The issues of endogeneity and short samples applying a moment-based estimator of time-varying parameter model with endogenous regressors were used. Our finding that inflation persistence typically decreased after the adoption of inflation targeting. These findings stimulated our ongoing research on inflation dynamics in low-inflation environment with anchored inflation expectations and muted response of inflation to changes in economic activity [<http://hdl.handle.net/11104/0238372>, <http://hdl.handle.net/11104/0223469>].

In addition, team participates on research within number of successful grant projects. Supported by the European Union's Seventh Framework Programme for research, team contributes to the collaborative project of seven respected institutions within the "Financial Distortions and Macroeconomic Performance: Expectations, Constraints and Interaction of Agents" project. Team is particularly responsible for identification and modeling of speculative bubbles, and methodologically contributes to deeper understanding of the complex relationships between financial distortions and macroeconomic performance. An important collaborative project of the leading Czech

institutions team participates in, is the GA ĆR Excellence project “Dynamical models in Economics”. Team contributes mainly by development of the methodologies in several fields discussed in detail above. In addition, team members actively participate at GA ĆR standard projects focusing on specific issues in financial econometrics and macroeconomic, with notable project “New Nonlinear Capital Markets Theories: Fractal, Bifurcation and Behavioral Approach”, which resulted in many important concepts, and received an excellent evaluation.

In conclusion the research team contributed to the literature with many important methodological concepts, which open new research questions. Notably, the work devoted to the time-frequency dynamics of dependence between economic variables, and new spectral based estimators using high frequency data are of fundamental value. The following table demonstrates the publication activity of the team members. An evolution of published research results in the period 2010 - 2014

Impact Factor	2010	2011	2012	2013	2014	Total
(0,1>	8	6	12	9	11	46
(1,3>	8	3	7	8	14	40
(3,5>	0	2	4	3	4	13
(5, ∞)	0	0	0	3	1	4
	16	11	23	23	30	103

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of Image Processing

Department of Image Processing

The Image Processing team (ZOI team) was working in the 2010 – 2014 time period in many research directions, both theoretical and application-oriented, where the moment theory, image restoration, image forensics, cultural heritage applications and medical imaging form the representative set of the covered research topics. The research was done in tight cooperation with both Master and PhD students, the publications as well as created software applications attracted mentionable interest of the international scientific community. Many of published papers in 2010-2014 were written together with international colleagues – we have more than [40 co-authors](#) from abroad. As well there are many publications realized together with people from other UTIA departments (AS, RO, ZS) and other Academia institutes ([Astronomical Institute](#), [Institute of Computer Science](#), [Institute of Physics](#), [Institute of Inorganic Chemistry](#), [Institute of Photonics and Electronics](#)). In 2010-2014, six software tools were implemented, based on the developed new algorithms – PIZZARO, Nephele, Fresco, GenEx, BSR Toolbox, and LEAF – all are described later in the text.

Members of the ZOI team were awarded many scientific prizes in 2010-2014. For the outstanding research activity Babak Mahdian got The Otto Wichterle Award to promising young scientists given by The President of the Academy of Sciences of the CR in 2013. B. Zitova and J. Flusser were awarded in 2010 by the prestigious "SCOPUS 1000 Award" in recognition of more than 1000 SCOPUS citations of their paper " [Image registration methods: A survey](#)". Awards for outstanding contribution at the conferences were granted to Jan Kotera, Ph.D. student (15th International Conference on Computer Analysis of Images and Patterns CAIP 2013, co-authored by Filip Šroubek and Peyman Milanfar), to Cyril Höschl, a Ph.D. (Innovation Award, given by The International Institute for Advanced Studies in Systems Research and Cybernetics, 24th International Conference on Systems Research, Informatics and Cybernetics, 2012), Jan Schier and Bohumil Kovar (The Best paper award, the International Conference on Bioinformatics Models, Methods and Algorithms, 2011), and to Filip Šroubek a Barbara Zitová (The Best paper award, EUROMED conference 2010). We were awarded in the Best publications competition in UTIA (2010, 2012, 2014). In 2013, Honorary Bernard Bolzano Medal for Merit in the Mathematical Sciences was awarded to Dr. Jaroslav Kautsky, PhD (Flinders University of South Australia, Australia), who is regularly visiting ZOI department for 3 month stays and co-authored many ZOI papers. Finally, Filip Šroubek received a Fulbright Visiting Scholarship at the University of California, Santa Cruz for 2010/2011. Major achievement of the scientific and pedagogical activity of our department is successful accreditation of new PhD program [Computer Graphics and Image Analysis](#) at the Faculty of Mathematics and Physics, Charles University in Prague, where three ZOI researchers are members of the committee and one of them is its chairman.

The ZOI team participate in many Czech projects, theoretical as well as industry-oriented, funded by Czech Science Foundation (7), Technology Agency CR (3), GA UK (2), Ministry of Industry and Trade (1), Ministry of Interior (2), and Academy of Sciences CR (1). There are two international projects running in this time period, one funded by [ARTEMIS](#) and another by Malaysian Government. We had commercial projects in the 2010 – 2014 time period. In 2010, we provided image massive-data searching tools for detection of stolen and possibly modified images from the databank to Profimedia (832,800 Kč). At the same year new original methods for superresolution and blind deconvolution developed by ZOI team were provided to fIR camera producer, German company Testo AG (1 480 200 Kč) and Matlab toolbox BSR for blind superresolution was installed at the Ministry of Interior (62 500 Kč). In

2012, the image-video based software solution for evaluation of geological situation of a locality was realized for Control Systems Int. (150 000 Kč). Finally, in 2014 the PIZZARO SW was installed in the Ministry of Defense (60 000 Kč) and a research in the area of deep belief networks was realized for Cisco Systems (304 245 Kč). In total, the commercial projects brought to the ZOI team 2 888 945 Kč in the evaluated time period.

The main research achievements of ZOI research team, categorized with respect to their topic:

- Theory of moment invariants
- Image restoration, deconvolution & superresolution
- Image forensics
- Cultural heritage
- Medical applications

Moment theory

The topic of moment theory and derived invariants with respect to both geometric and radiometric image degradations is well established in ZOI team and it has been still gaining significant attention. In October 2009 the key book ([Moments and Moment Invariants in Pattern Recognition](#)) was published by three members of the team in Wiley & sons. It appeared as an e-book in Wiley digital library in 2010. The topic remained active and in mid-2014 the preparation of the sequel, once again for Wiley & sons publishing house, started. Recently, Jan Flusser authored the [Moment Invariants for Object Recognition](#) entry in the Wiley Encyclopedia of Electrical and Electronics Engineering.

The major achievements on the area of moment invariants are the theory of implicit moment invariants, new classes of invariants, more efficient ways of their generation and computation and new areas of their application. The publications, describing our research published in the given time period got already more than 50 citations (WoS). The [generation of affine moment invariants by means of graphs](#) created biggest interest – 24 citations.

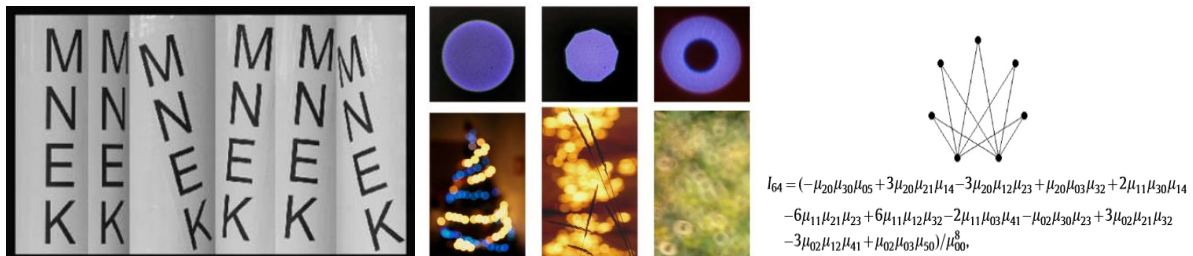


Figure: From the left: An example of polynomially transformed images; Examples of the real out-of-focus blur PSF at circular aperture, polygonal aperture formed by the lamellas, and the ring-shaped PSF of a catadioptric objective; An example of irreducible invariant along with its generating graph.

[Theory of implicit moment invariants](#) –The new so-called implicit moment invariants measure the similarity between two images factorized by admissible image deformations. The implicit invariants can be used as features for object recognition when the polynomial spatial transform is present.

Flusser Jan, Kautský J., Šroubek Filip : [Implicit Moment Invariants](#), *International Journal of Computer Vision* vol.86, 1 (2010), p. 72-86

[Projection Operators and Moment Invariants to Image Blurring](#) - We present the invariants to convolution with an arbitrary N-fold symmetric PSF, both in Fourier and image domain. We introduce a notion of a primordial image as a canonical form of all blur-equivalent images. It is defined in spectral domain by means of projection operators. We prove that the moments of the primordial image are invariant to blur and we derive recursive formulae for their direct computation without actually constructing the primordial image.

Flusser Jan, Suk Tomáš, Boldýš Jiří, Zitová Barbara : [Projection Operators and Moment Invariants to Image Blurring](#), *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, appeared on-line in 2014

[Graph Method for Affine Moment Invariants Generation](#) – We published new general method for an automatic deriving of affine moment invariants of any weights and orders. The method is based on representation of the invariants by graphs. We proposed an algorithm for eliminating reducible and dependent invariants. This method represents a systematic approach to the generation of all relevant moment features for recognition of affinely distorted objects.

Suk Tomáš, Flusser Jan : [Affine Moment Invariants Generated by Graph Method](#) , *Pattern Recognition* vol.44, 9 (2011), pages 2047–2056

[Blur Invariants Constructed From Arbitrary Moments](#) - We present a general method on how to construct blur invariants from arbitrary moments and show that it is no longer necessary to separately derive the invariants for each polynomial basis. An example for Legendre moments is given.

Kautsky J., Flusser Jan : *Blur Invariants Constructed From Arbitrary Moments* , *IEEE Transactions on Image Processing* vol.20, 12 (2011), p. 3606-3611

[Decomposition methods](#) - We did thorough research of decomposition methods of binary images in order to be able efficiently compute image moments. We compared their performance and gave advice how to select an appropriate method in particular cases. We proposed a new method for an object decomposition.

Suk Tomáš, Höschl Cyril, Flusser Jan: [Decomposition of Binary images - A Survey and Comparison](#) , *Pattern Recognition* vol.45, 12 (2012), p. 4279-4291

[Calculation of the Krawtchouk Moments](#) (KM) - We developed two methods for KM calculation based on the outputs of cascaded digital filters. The first approach uses the digital filter outputs to form geometric moments for KMs computation. The second method uses a direct relationship to obtain KMs from the digital filter outputs. Krawtchouk polynomials are here defined in terms of binomial functions, which are equivalent to the digital filter outputs. The experimental study shows that the first and the second proposed techniques perform 57% and 87% faster than the recurrence method for a real image of a size 128 x 128 pixels, which performs a significant improvement.

Honarvar Shakibaei Asli B., Flusser Jan : [Fast computation of Krawtchouk moments](#) , *Information Sciences* vol.288, 1 (2014), p. 73-86

[Symmetric 3D objects recognition](#) - We provide a complete list of all existing combinations of rotation and reflection symmetries in 3D. We defined 3D complex moments by means of spherical harmonics, and studied the influence of individual symmetry groups on their values.

Suk Tomáš, Flusser Jan : [Recognition of Symmetric 3D Bodies](#) , *Symmetry*, vol.6, 3 (2014), p. 722-757

[Image deconvolution from the geometric moments](#) - We propose a novel algorithm for image deconvolution from the image geometric moments when the point-spread function (PSF) is circular or elliptical and Gaussian. The proposed inverted formula paves the way to reconstruct the original image using the Stirling numbers of the first kind.

Honarvar B., Flusser Jan : [Image Deconvolution in the Moment Domain](#) , *Moments and Moment Invariants: Theory and Applications*, p. 111-125 , Eds: Papakostas G. A., 2014

The moment theory was applied for example for [solar flares temporal-evolution diagnostics](#), [for wood slices recognition](#) and for [near infrared face recognition](#) (Zernike moments). One international PhD student (Iranian student from Malaysia) graduated with this topic and now he is successfully continuing his research in ZOI team at the postdoc position, another student (Chinese student from France) held one year postdoc position funded by ERCIM grant.

Image Reconstruction Tools - Blind deconvolution and Superresolution

These two areas of image processing were crucial for ZOI team during the evaluated time period. 12 book chapters and journal papers complemented with 16 conference papers describe related recent achievements of our research group. One of the publications was awarded for [outstanding contribution](#) at the 15th International Conference on Computer Analysis of Images and Patterns [CAIP 2013](#). F. Šroubek did some of this research during his Fulbright fellowship in USA in the P. Milanfar laboratory.

Šroubek's deep knowledge of the topic led to the establishment of the new course for MFF UK and FJFI CVUT "[Variational methods in image processing](#)".

[Methods for blind deconvolution](#) - We proposed several approaches to the blind deconvolution problem. We presented a method using alternating maximum a posteriori estimation with heavy-tailed priors for blur estimation from a single image and sharp image recovery. It uses ultra-sparse gradient priors and augmented Lagrangian method. Further, we demonstrated a superior performance of the variational Bayesian estimator and discussed suitability of automatic relevance determination distributions as image priors.

Kotera Jan, Šroubek Filip, Milanfar P. : [Blind Deconvolution Using Alternating Maximum a Posteriori Estimation with Heavy-Tailed Priors](#), Computer Analysis of Images and Patterns, p. 59-66 , Eds: Wilson Richard, Bors Adrian, Hancock Edwin, Smith William, Computer Analysis of Images and Patterns, (York, GB, 27.08.2013-29.08.2013)

Šroubek Filip, Šmídl Václav, Kotera Jan: [Understanding image priors in blind deconvolution](#), 2014 IEEE International Conference on Image Processing, p. 4492-4496, 2014 IEEE International Conference on Image Processing

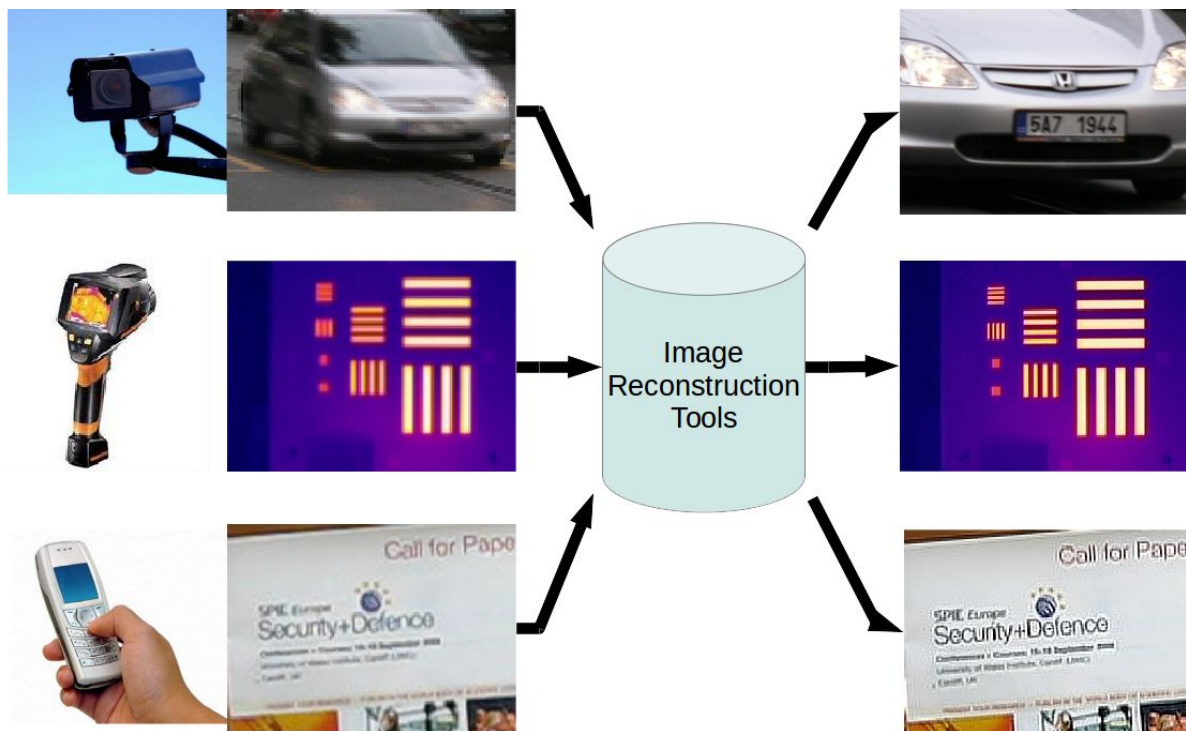


Figure: Examples of the achievable increase of image quality by means of Image Reconstruction Tools. The variability of the platform is demonstrated, too.

[Multichannel Blind Deconvolution](#) If multiple images of the same scene are acquired, this multichannel blind deconvolution problem is better posed and allows blur estimation directly from the degraded images. The first approach was formulated as [energy minimization](#) problems with specific regularization terms on images and blurs. Then we added robustness to noise and stability in the case of large blurs or if the blur size is vastly overestimated using alternating minimization. We formulated blind deconvolution as a regularized optimization problem and looked for a solution by alternately optimizing with respect to the image and with respect to blurs. The rapid convergence of the proposed method was illustrated on synthetically blurred data. In the last approach instead of estimating the PSFs directly and only once from the observed images, we first generated a rough PSFs estimate using a robust multichannel deconvolution algorithm, and then deconvolved the PSFs to refine the outputs.

Šroubek Filip, Milanfar P. : [Robust Multichannel Blind Deconvolution via Fast Alternating Minimization](#) , IEEE Transactions on Image Processing vol.21, 4 (2012), p. 1687-1700 (21 citations in WoS)

Zhu X., Šroubek Filip, Milanfar P. : [Deconvolving PSFs for a Better Motion Deblurring Using Multiple Images](#) , Computer Vision – ECCV 2012, p. 636-647, ECCV12 - 12th European Conference on Computer Vision, (Florence, IT, 07.10.2012-13.10.2012)

[Patch-based blind deconvolution](#) – This proposed method is based on parametric interpolation of convolution kernels. The space-variant blur is here present in images predominantly degraded by camera shake without any knowledge of camera trajectory. Blurs are first estimated in a small number of image patches. We derived a novel parametric blur interpolation.

Šroubek Filip, Šorel Michal, Horáčková Irena, Flusser Jan : [Patch-based blind deconvolution with parametric interpolation of convolution kernels](#) , Proceedings of the 2013 IEEE International Conference on Image Processing ICIP 2013, p. 577-581, International conference on image processing, ICIP 2013

[Space-variant restoration](#) – We created mathematical models for spatially varying blur and proposed basic restoration approaches connected with these models. We addressed a new approach to space-variant super-resolution for images blurred by camera motion or any other blur changing slowly enough so that it can be locally modelled by convolution. It is one of the first attempts to apply true super-resolution to data with space-variant blur.

Šorel Michal, Šroubek Filip, Flusser Jan : [Towards super-resolution in the presence of spatially varying blur](#) , Super-resolution imaging, p. 1-38 , Eds: Milanfar Peyman

Šorel Michal, Šroubek Filip : [Restoration in the presence of unknown spatially varying blur](#) , Image Restoration: Fundamentals and Advances, p. 63-88 , Eds: Gunturk Bahadir, Li Xin, 2012

[Superfast superresolution](#), done together with P. Milanfar from University of California at Santa Cruz, USA (consultations) - We proposed a fast algorithm solving the inverse problem of resolution enhancement (superresolution) with edge-preserving regularization. We demonstrated that the additive form of half-quadratic linearization is superior as all operations can be implemented in the frequency domain using the FFT. The super-resolution was successfully applied on far infrared images.

Šroubek Filip, Kamenický Jan, Milanfar P. : [Superfast superresolution](#) , 18th IEEE International Conference on Image Processing, p. 1177-1180, 18th IEEE International Conference on Image Processing

[Mobile platform deconvolution](#) - We have developed an application on smartphones for space-variant image deblurring. Low-light hand-held photography requires long exposures and leads to space-variant blur degradation. Removing blur without any information about the camera motion is a computationally demanding and unstable process. We used rotational inertial sensors (gyroscopes) to detect the motion trajectory of the camera during exposure and then applied it as a base for removing blur from the acquired photographs. The demo is a close-to-real-time deblurring technology, implemented on an Android smartphone.

Šindelář O., Šroubek Filip : [Image deblurring in smartphone devices using built-in inertial measurement sensors](#) , Journal of Electronic Imaging vol.22, 1 (2013)

Šroubek Filip, Flusser Jan : [Removing camera shake in smartphones without hardware stabilization](#) , Motion Deblurring: Algorithms and Systems, p. 100-122 , Eds: Rajagopalan A. N., Chellappa Rama

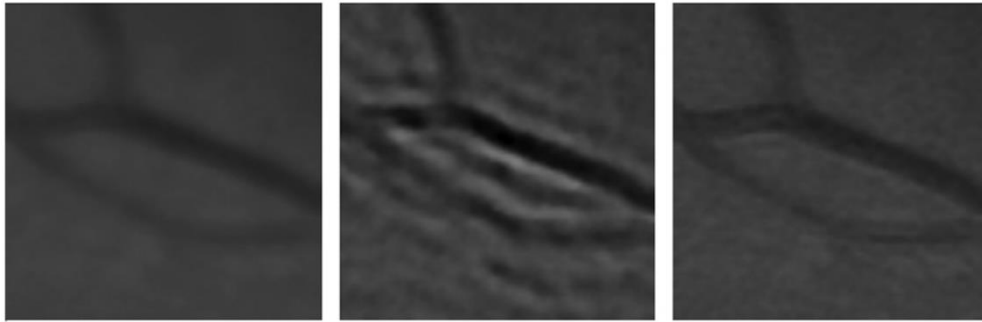


Figure: Details of eye fundus image restoration. From left to right: the original degraded image, the restoration without correction of PSFs and the restoration with the correction.

[*Multichannel Deconvolution in Eye Fundus Imaging*](#) - Retinal images are often degraded with a blur that varies across the field of view. Because traditional deblurring algorithms assume the blur to be space-invariant they typically fail in the presence of space-variant blur. In this work we considered the blur to be both unknown and space-variant. We assumed that in small regions the space-variant blur can be approximated by a space-invariant point-spread function (PSF) and then we extend individual PSFs by linear interpolation and perform a global restoration. This research was conducted together with Marrugo A. and Millán M. S. from Columbia and Spain, respectively. They are experts in ophthalmology image processing and they helped to define the problem and did testing.

Marrugo A., Šorel Michal, Šroubek Filip, Millan M. : [Retinal image restoration by means of blind deconvolution](#) , Journal of Biomedical Optics vol.16, 11 (2011)

Marrugo A., Millán M. S., Šorel Michal, Šroubek Filip : [Restoration of retinal images with space-variant blur](#) , Journal of Biomedical Optics vol.19, 1 (2014)

[*Platform Motion Blur Image Restoration System*](#) - Platform motion blur is a common problem for airborne and space-based imagers. Photographs taken by hand or from moving vehicles in low-light conditions are also typically blurred. We proposed a computational imaging system that incorporates an optical position sensing detector array, a conventional camera and a method to reconstruct images degraded by spatially variant platform motion blur. The research was done together with researchers from Univ. of California, San Diego, USA. Our colleague Šorel brought the space varying deconvolution idea into the solution.

Olivas S. J., Šorel Michal, Ford J. : [Platform motion blur image restoration system](#) , Applied Optics vol.51, 34 (2012), p. 8246-8256

[*Removing Boundary Artifacts for Real-Time Iterated Shrinkage Deconvolution*](#). We proposed a solution to the problem of boundary artifacts appearing in several recently published fast deblurring algorithms based on iterated shrinkage thresholding in a sparse domain and Fourier domain deconvolution. Our approach adapts an idea proposed by Reeves for deconvolution by the Wiener filter. The time of computation less than doubles.

Šorel Michal: [Removing Boundary Artifacts for Real-Time Iterated Shrinkage Deconvolution](#) , IEEE Transactions on Image Processing vol.21, 4 (2012), p. 2329-2334

Image registration

The problem of geometrical alignment of images is still active in ZOI team. B. Zitova and J. Flusser were awarded by the prestigious "[SCOPUS 1000 Award](#)" in recognition of more than 1000 SCOPUS citations of the paper (Zitová, B. & Flusser, J. (2003), [Image registration methods: a survey.](#), *Image*

Vision Comput. **21** (11) , 977-1000). Recently, this publication has got more than 2294 citations WoS (Google Scholar 5146) and is one of [the most downloaded paper](#) of Image and Vision Computing.

[Registration for N-fold Symmetric Blurs](#)

In the evaluated time period we published new registration methods for blurred images with N-fold symmetric and dihedral blurs. The method is inspired by traditional phase correlation, which is now applied to certain blur-invariant descriptors instead of the original images. It does not require any landmarks. This approach is extended in the [current publication](#) (2015).

Pedone M., Flusser Jan, Heikkilä J. : [Blur Invariant Translational Image Registration for N-fold Symmetric Blurs](#) , IEEE Transactions on Image Processing vol.22, 9 (2013), p. 3676-3689

Image forensics

The trustworthiness of photographs has an essential role in many areas like forensic investigation, surveillance systems, intelligence services, or medical imaging. Verifying the integrity of digital images and detecting the traces of tampering have become an important research field. The ZOI team addressed this area of research from image processing point of view. All theoretical results were successfully implemented in the [PIZZARO](#), software solution for identification of imaging devices and data and for reconstruction of acquired images and video. The SW has recently more than 50 installations in different units of Czech Police and the tool was presented to Europol (Analytical Prague 2014, international police conference). The ZOI team provides often consultation services to the Czech Police.

We have published two overview publications covering the topic of blind verification which verifies the integrity of digital images and detect the traces of tampering without using any protecting pre-extracted or pre-embedded information.

Saïc Stanislav, Mahdian Babak : [A bibliography on blind methods for identifying image forgery](#) , Signal Processing-Image Communication vol.25, 6 (2010), p. 389-399

Mahdian Babak, Saïc Stanislav : [Blind Methods for Detecting Image Fakeness](#) , IEEE Aerospace and Electronic Systems Magazine vol.25, 4 (2010), p. 18-24



Figure: An original image (left), an example of a copy-move forgery, and the map of the duplicated regions.

[Digital image ballistics](#) - We proposed analysis and new description of the multiplicative deterministic noise component of imaging sensors. We exploited the multiplicative nature of this component for deriving a method enabling its estimation. Since this noise component is unique per sensor, consequently, the derived method is used to pinpoint the exact device that created a specific digital photo. The method is resistant to optical zoom and JPEG compression.

Mahdian Babak, Saïc Stanislav : [A Novel Method for Identifying Exact Sensor Using Multiplicative Noise Component](#) , Proceedings of the IEEE International Symposium on Multimedia (ISM), 2013, p. 241-247, IEEE International Symposium on Multimedia (ISM), 2013

Similarly, we introduced a statistical approach to image metadata analysis of images from “unguaranteed” sources, based on [JPEG quantization tables](#) and on [JPEG compression artifacts](#). The latter was tested on real-life experiment with a quantitative study and the results supported the conclusion that combining various image forensic methods is a must.

Mahdian Babak, Saic Stanislav, Nedbal Radim : [JPEG Quantization Tables Forensics: A Statistical Approach](#) , Computational Forensics : Proceedings of the 4th International Workshop, IWCF 2010, p. 150-159 , Eds: Sako Hiroshi, Franke Katrin Y., Saitoh Shuji, IWCF 2010

Mahdian Babak, Saic Stanislav : [Image Tampering Detection Using Methods Based on JPEG Compression Artifacts: A Real-Life Experiment](#) , Proceedings of ISABEL'11, ISABEL '11 Proceedings of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies, 2011

Given a database consisting of “unguaranteed” images, we introduced [a statistical approach to blind verification](#) - assessing image originality by using the image file’s header information (e.g., JPEG compression parameters). The proposed framework is applied to several fingerprint types selected for image integrity verification.

Mahdian Babak, Nedbal R., Saic Stanislav : [Blind Verification of Digital Image Originality: A Statistical Approach](#) , IEEE Transactions on Information Forensics and Security vol.8, 9 (2013), p. 1531-1540

Cultural Heritage Applications

The area of cultural heritage can make a use of the modern image processing algorithms nowadays. The ZOI team participated in several applications, where image processing methods were used during the art conservation process or for its evaluation. All work is done in cooperation with XXX laboratory (joint workplace of XXX).

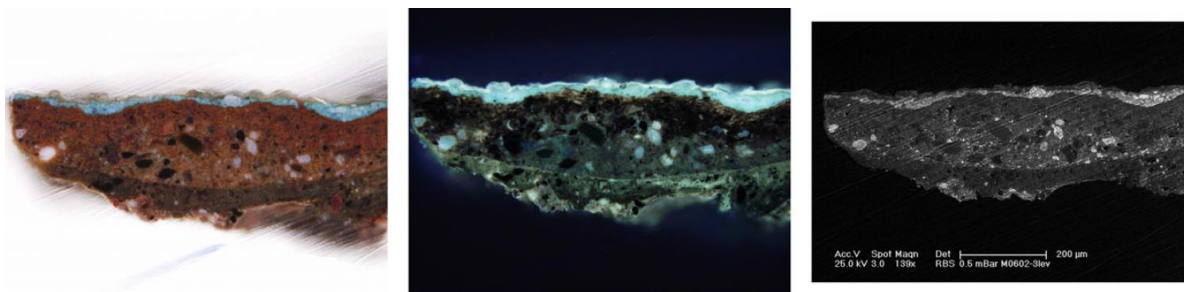


Figure: The images of the cross-section samples from material research of artworks are acquired in three modalities – visible spectrum (VIS), ultraviolet spectrum (UV) and scanning electron microscope (SEM). Image courtesy of ALMA, Prague.

[Microscopic samples for material research](#)

The key issue of the art restoration is the material research (MR). Its aim is the location and the classification of inorganic and organic compounds using microanalytical methods, and description of painting layers and their morphology, where the layer is defined as consistent and distinguishable part of the painting profile. We realized a performance evaluation of image segmentation algorithms for microscopic image data, used in MR, however the results are applicable in general microscopic imaging. We carried out a large number of experiments with a variety of segmentation methods to evaluate the behavior of individual approaches on the testing set of microscopic images (cross-section images taken in three different modalities from the field of art restoration). The segmentation results were assessed by several indices used for measuring the output quality of image segmentation algorithms.

Beneš Miroslav, Zitová Barbara : [Performance evaluation of image segmentation algorithms on microscopic image data](#) , Journal of Microscopy, p. 1-21, appeared on-line in 2014

The image based tools for processing of microscopis samples can be found in [Nephele](#), a comprehensive information software system for processing and archiving data produced in the process of art conservation. The Nephele addresses the key issue of the art conservation - identification of the painting materials used. While working on the Nephele SW, we had to face several issues like grinding [artifact removal](#) and image segmentation and [retrieval](#) in order to be able to [analyze cross-section images](#).

Zitová Barbara, Beneš Miroslav, Hradilová J. : [Nephele – Smart Digital Memory of Artwork Conservation](#) , ERCIM News vol.86, p. 47-48

Beneš Miroslav, Zitová Barbara, Blažek Jan, Hradilová J., Hradil David : [Removing the Artifacts from Artwork Cross-section Images](#) , Proceedings of the 18th IEEE International Conference on Image Processing, p. 3598-3601, ICIP 18th IEEE International Conference on Image Processing, 2011

Zitová Barbara, Beneš Miroslav, Hradilová J., Hradil David : [Analysis of painting materials on multimodal microscopic level](#) , Proceedings of SPIE IS&T/SPIE Electronic Imaging 2010 , Eds: Stork D. G., Coddington J., Bentkowsk-Kafel A., IS&T/SPIE Electronic Imaging 2010

Our work on cross-section images brought us to the international team working with ancient documents. The main aim of the team was proposal of an efficient way for multispectral data acquisition. The framework for virtual restoration of ancient documents is based on a combination of multispectral acquisition, 3D imaging and digital image analysis. For each document its multispectral representation and 3D surface maps are created. Statistical techniques of decorrelation are applied to extract individual context parts of the document patterns (stamp, text, etc.) and to attenuate interferences.

Bianco G., Bruno F., Tonazzini A., Salerno E., Savino P., Zitová Barbara, Šroubek Filip, Console E. : [A framework for virtual restoration of ancient documents by combination of multispectral and 3D imaging](#) , Eurographics Italian Chapter Conference, p. 1-7 , Eds: Puppo E., Brogni A., de Floriani L., Eurographics Italian Chapter Conference, 2010

Bianco G., Bruno F., Salerno E., Tonazzini A., Zitová Barbara, Šroubek Filip : [Quality Improvement of Multispectral Images for Ancient Document Analysis](#) , EUROMED 2010, 3rd International Conference dedicated on Digital Heritage, p. 29-34 , Eds: Ioannides M., Fellner D., Georgopoulos A., Hadjimitsis D., 3rd International Conference dedicated on Digital Heritage, 2010

[Multi-modal measurement for artwork analysis](#)

Latest cooperation with art restorers was done under [m3art](#) project, which aim was to collect and analyze multimodal data sets from samples of dyes and creating the [database](#) of digitalized snapshots and measured values. Then we developed image based fusion algorithms for [artwork analysis](#). Finally we have developer an open-source software ([Fresco](#)) using results of our research. The output of m3art project got big attention among international scientists and we have already started cooperation with XXX, public institute of the Italian Ministry for Cultural Heritage based in Florence. It is a global leader in the field of art restoration.

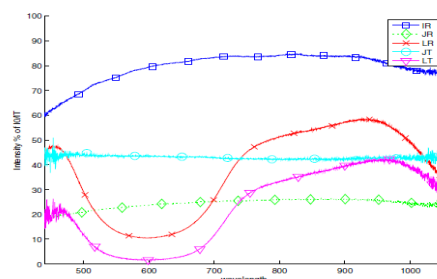


Figure: The canvas with model samples imitating Gothic/Renaissance painting. Transmittance and reflectance of azurite (IR – the canvas, LR, LT - the canvas with azurite layer, JR, JT- the drawing on the canvas).

Blažek Jan, Zitová Barbara, Tichý T., Vašutová V. : [Optical properties of historical paint pigments under near infrared \(NIR\) radiation](#) , ACTA ARTIS ACADEMICA 2014, p. 35-41 , Eds: Hradil David, Hradilová Janka, mezioborová konference ALMA 2014

Blažek Jan, Soukup Jindřich, Zitová Barbara, Flusser Jan, Hradilová J., Hradil David, Tichý T. : [M3art: A Database of Models of Canvas Paintings](#) , Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2014, p. 176-185

Blažek Jan, Zitová Barbara, Flusser Jan : [Image Fusion for Difference Visualization in Art Analysis](#) , Digital Heritage International Congress, p. 653-656, Digital Heritage 2013

Kamenický Jan, Zitová Barbara : [Contrast preserving color fusion](#) , Color Imaging XVI: Displaying, Processing, Hardcopy, and Applications - Proceedings of the SPIE 2011, IS&T/SPIE Electronic Imaging 2011

Medical and biological image processing

The major application area of image processing methods in ZOI is medical/biological imaging. Next to smaller projects like evaluation of perfusion parameters in [DCE-MRI](#), segmentation of CT images by means of [statistical region merging](#), or [segmentation of cells](#) on microscopic images which were both realized outside the ZOI department during the visits of our members, there were several key projects running directly in ZOI department.

[Monte Carlo simulation of PET images for injection dose optimization](#)

The radiotracer dose amount is set with respect to the average weight of the patient according to regulations. However this relation does not correspond to the experience of the specialists (the hospital Na Homolce). We have performed Monte Carlo simulations of PET imaging. The new proposed dependence qualitatively differs from the rules used in clinical practice nowadays and the results indicate potential for improvement. The image quality within the broad spectrum of patients can be equalized and radiation risk to slim patients, with special importance for children, can be diminished.

Boldyš Jiří, Dvořák Jiří, Skopalová M., Bělohávek O. : [Monte Carlo simulation of PET images for injection dose optimization](#) , International Journal for Numerical Methods in Biomedical Engineering vol.29, 9 (2013), p. 988-999

[Videokymography](#)

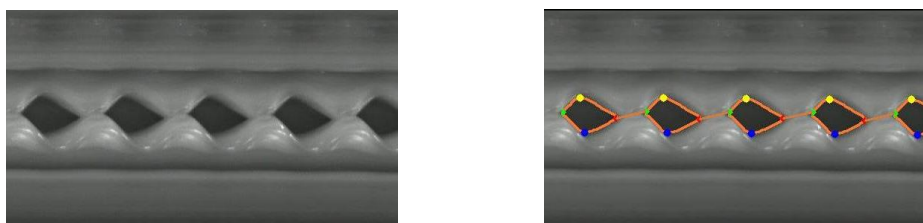


Figure: An example of videokymographic data and corresponding set of detected features.

We are involved in development of computer-aided diagnosis tools for the enhancement of videokymographic data and the extraction of typical characteristics of vocal folds vibrations, such as, e.g., the time-varying extent of rima glottidis and the progression of mucosal waves, and corresponding vibration parameters (e.g. frequency, symmetries, and amplitude). The set of evaluated features was designed by experts. This cooperation resulted into the new project, which started in 2014 and is funded by the Technology Agency of the Czech Republic.

Novozámský Adam, Sedlák Jiří, Zita Aleš, Herbst Ch., Švec J. G., Zitová Barbara, Flusser Jan : [VKFD: Computerized Analysis of Videokymographic Data](#) , PEVOC, p. 293-294 , Eds: Domagalský T., PEVOC - Pan European Voice Conference, 2013

We had tight cooperation with the [Yeast Colony Group](#) of the [Department of Genetics and Microbiology](#) at the Faculty of Sciences, Charles University. The conference paper "[Automated counting of yeast colonies using the Fast Radial Transform algorithm](#)" has been awarded the Best paper award at the BIOINFORMATICS 2011 conference. There was successful project funded by the Technology Agency of the Czech Republic, targeted as [computer-aided diagnostics of the Turner syndrome](#) using digital image processing methods on the fluorescence in-situ hybridization (FISH) microscopy images. Moreover, Jan Schier has been program co-chair for [BIOIMAGING](#) conference in 2012, 2014 and 2015. Jan Schier was involved in the investigation of [Huntington's Disease](#), too.

Schier Jan, Kovář B., Kočárek E., Kuneš M. : [Image Processing for Automated Analysis of the Fluorescence In-Situ Hybridization \(FISH\) Microscopic Images](#) , Convergence and Hybrid Information Technology, p. 622-633, 5th International Conference, ICHIT 2011

Biologically motivated research was realized in ZOI in cooperation with Charles University in Prague, Faculty of Education. A system for recognition of woody species in Central Europe according to the images of their leaves was proposed, together with own data set, which includes 151 species at this moment. The method is based on Fourier descriptors normalised to translation, rotation, scaling and starting point. The application is available through a [web application](#).

Novotný P., Suk Tomáš : [Leaf Recognition of Woody Species in Central Europe](#), Biosystems Engineering vol.115, 4 (2013), p. 444-452

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of Pattern Recognition

Department of Pattern Recognition

The scope of the Pattern Recognition department activities covers statistical pattern recognition and visual data modelling. The emphasis is being put on finite mixtures, modelling of Markov random fields for scene interpretation, physically correct visualization, and visual data restoration. The model-based pattern recognition makes use of new theoretical results from probabilistic neural networks, statistical feature selection, unsupervised segmentation, and the illumination invariants theory.

In all these areas, the group members enjoy an international reputation manifested by scientific awards and memberships in the governing bodies of international organizations. The team of department authors received in 2011 the Award of the Academy of Sciences of the Czech Republic for outstanding results of major scientific importance for the scientific outcome: Mathematical modelling of visual properties of surface materials.

The department produces mainly basic theoretical research, with applications in various branches (particularly medicine and economics) often in cooperation with university research workplaces. Visual appearance models of shape and surface material are mainly applied in the car industry, architecture, and virtual reconstruction of cultural heritage objects. Image synthesis methods are applied in multispectral image restoration (astronomy, remote sensing), colour film and range map restoration. Recognition methods are utilized in medicine (skin and breast cancer detection), security (iris and banknotes detection), industry (wood species and ceramics tiles recognition), environmental protection, text-document classification, and remote sensing.

The department has introduced two new university courses Pattern Recognition and Advanced Pattern Recognition which are parts of the standard curriculum at two faculties (Faculty of Information Technology, Faculty of Transportation Sciences) of the Czech Technical University in Prague both in Czech as well as in English mutations. The department supervised several PhD and MSc thesis.

The department extensively participates in the international research cooperation in the ERCIM MUSCLE working group, IAPR committees, numerous conference programme committees, and editorial boards and took part in several EU project proposals.

Major research results

Department theoretical results can be categorized into the following seven thematic groups:

1. visual appearance of surface material modelling,
2. visual appearance precise measuring,
3. supervised and unsupervised classification,
4. feature selection,
5. illumination invariants,
6. Markov random fields and mixture models,
7. classifier and modelling quality benchmarking.

These categories are partly interrelated because visual surface appearance modelling, supervised and unsupervised classifications as well as illumination invariants are developed from the underlying multidimensional probabilistic models of the Markovian or mixture types.

1 Visual appearance of surface material modelling

Real surface material visual appearance is a highly complex physical phenomenon which intricately depends on incident and reflected spherical angles, time, light spectrum and other physical variables. Physically correct visual appearance of surface materials is one of the major research topics of the department. In our book [Visual Texture](#), Accurate Material Appearance Measurement, Representation and Modeling printed by Springer-Verlag London we provided the first comprehensive state-of-the-art survey of the newly emerging area of physically correct visual texture modeling, which is the appropriate paradigm for representation of material visual properties. This book covers recent state-of-the-art of texture synthesis area and the entire pipeline from material appearance representation, measurement, analysis, and compression, to modeling, editing, visualization, and perceptual evaluation. The book covers all known aspects of the most advanced visual surface representation which can be recently applied—the seven dimensional Bidirectional Texture Function (BTF) including all published mathematical BTF models which were developed in the department. Parts of this book are also available in the form of [ACM SIGGRAPH Courses](#).

A [BTF model](#) based on estimating the joint probability density of the included nine spatial, directional, and spectral variables in the form of a Gaussian mixture of product components was developed. The reflectance prediction formula can be expressed analytically as a simple continuous function of input variables and allows fast analytic evaluation for arbitrary spatial and directional values without need for a lengthy interpolation from a finite grid of angular measurements. This method achieves high compression ratio increasing linearly with texture spatial resolution. Another [BTF-MA model](#) based on a set of underlying mono-spectral two-dimensional moving average factors or Markovian [BTF-SAR model](#) based on a set of underlying simultaneous autoregressive models were proposed.

A novel high visual quality [compound Markov random field](#) multispectral bidirectional texture function model combines a non-parametric control random field with analytically solvable wide-sense Markov representation for single regions and thus allows very efficient non-iterative parameters estimation as well as the compound random field synthesis. The model is utilized for realistic texture compression, enlargement, and powerful automatic texture editing. Edited textures maintain their original layout but adopt anticipated local characteristics from one or several parent target textures. Another [Potts Markov compound random field model](#) was developed and applied on BTF data modeling.

A method for seamless enlargement and editing of intricate [near-regular type of bidirectional texture](#) function (BTF) which contains simultaneously both regular periodic and stochastic components was developed. The method is based on automatic separation of periodic and random components from one or more input textures

A [dynamic texture synthesis method](#) that matches given multispectral texture appearance and respects its original optic flow was developed. The analytical part of the method, which is completely separated from the synthesis part, is based on optimal toroid-shaped dynamic texture patches which are created in each spatial and time dimension, respectively. The method is extremely fast and capable to enlarge a learned natural dynamic texture spatially and temporally in real-time.



Fig. Synthesized dynamic textures.

Additional [multispectral dynamic texture model](#) is based on a combination of input data eigen analysis and subsequent processing of temporal mixing coefficients. This method exhibits overall good performance, offers extremely fast synthesis which is not restricted in temporal dimension and simultaneously enables to compress significantly the original measured visual data.

The BTF visual appearance dependency on viewing and illumination conditions significantly complicates not only its acquisition, representation, and modelling but also makes its rendering noticeably more demanding. There was not any graphical environment allowing BTF texture rendering. We developed a unique [Blender BTF texture plugin](#) for the purpose of BTF texture mapping and rendering. The plugin benefits from our previously developed BTF Roller texture enlargement method which is the integral part of its implementation. The plugin allows creating realistic computer animations with additional BTF textures of any required size mapped onto an object surfaces while the other functionality of Blender retains.

2 Visual appearance precise measuring

The best current measurable representation of a material appearance (BTF) requires tens of thousands of images using a sophisticated high precision automatic measuring device. Within the Pattern Recognition department, we have built a unique high precision robotic gonioreflectometer. The setup consists of independently controlled arms with camera and light. Its parameters such as angular precision (to 0.03 degrees), spatial resolution (1000 DPI), and selective spatial measurement qualify this [gonioreflectometer](#) as a state-of-the-art device.

We have proposed also an approximate [portable acquisition setup](#) based on a simple, affordable mechanical gantry containing a consumer camera and two LED lights. It captures a very limited predefined subset of material surface images. Our acquisition setup shows a promising visual quality. It combines a photorealistic reproduction of material appearance with low building costs and extremely fast measurement times.

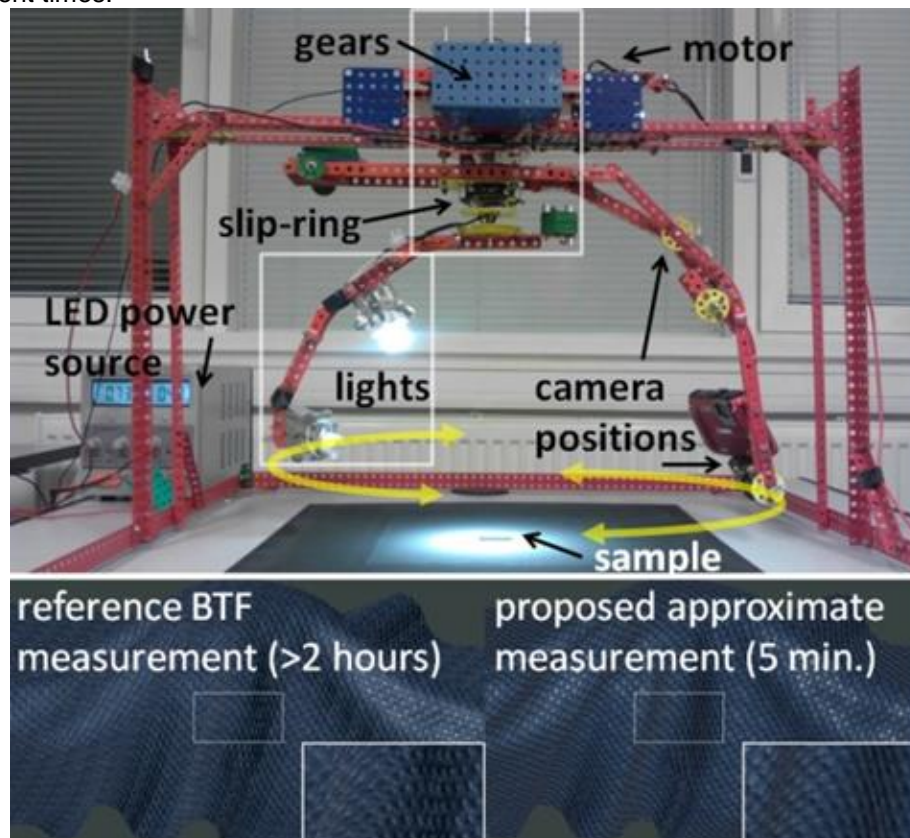


Fig. Portable setup for fast material appearance measurement

Some of our unique BTF / BRDF sample measurements are available for the research community on our server <http://btf.utia.cas.cz>. BRDF represents material's reflectance dependently on illumination and viewing directions. We present a novel [public database of 150 BRDFs](#), novel method of anisotropic highlights alignment, and an adaptive template-based sampling method based on reusing of the precomputed sampling patterns of the measured BRDFs. Our method enables a more efficient measurement of BRDFs of unknown materials.



Fig. BRDF Slices: Accurate Adaptive Anisotropic Appearance Acquisition

Another efficient measurement [method is based on sampling of BRDF](#) subspaces at fixed elevations by means of several adaptively-represented, uniformly distributed, perpendicular slices. This method requires only a sparse sampling of material; the interpolation provides a very accurate reconstruction, visually and computationally comparable to densely measured reference. An alternative possibility is to [approximate reconstruction](#) of the BRDF data from a very sparse dataset.

An image-based [registration method](#) for high-resolution multi-view images of a planar material surface which does not require registration marks is exploited in our gonireflectometer.

A [BTF compression model](#) allowing decomposition of individual view and illumination dependent texels into a set of multi-dimensional conditional probability density functions was developed. These functions are compressed in turn using a novel multi-level vector quantization algorithm. The result of this algorithm is a set of index and scale code-books for individual dimensions.

3 Supervised and unsupervised classification

The problem of [sequential pattern recognition](#) is the on-line optimal feature selection according to the previous measurements. We have shown that the problem of sequential recognition has an exact analytical solution when using mixtures of product components. Recognition based on product mixtures provides a unique possibility to evaluate the conditional informativity of unobserved variables and thus, e.g. in any phase of medical diagnostics, the physician can choose the most informative examination.

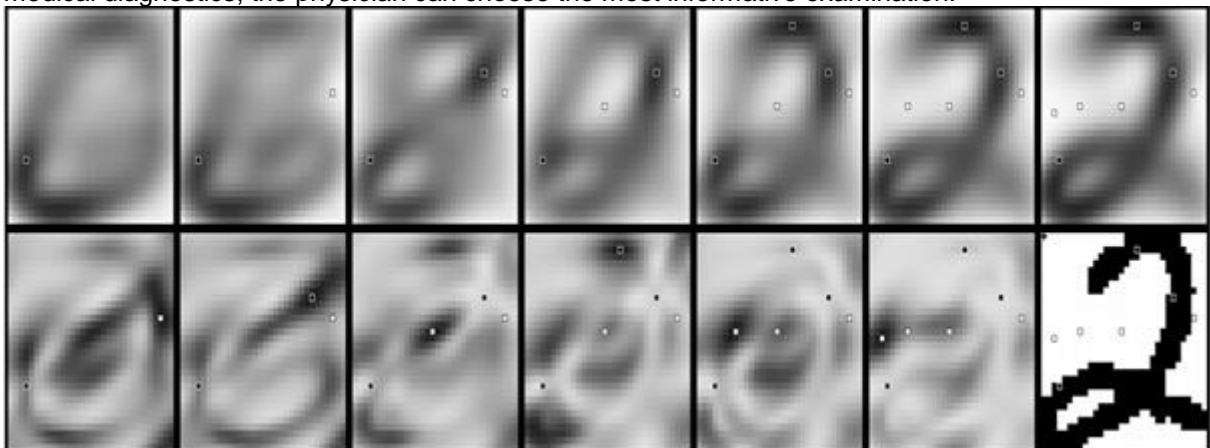


Fig. Example: sequential recognition of numerals on the binary 32x32 raster. The upper row shows the changing expectation of the classifier according to the uncovered (white or black) raster fields. The lower row shows the informativity of raster points corresponding to the known raster fields and finally the input image. It can be seen that the expected image may strongly change in case of unexpected raster field value.

A fast multispectral unsupervised [iris occlusions detection method](#) based on the underlying multispectral spatial probabilistic iris textural model and adaptive thresholding was proposed. The model adaptively learns its parameters on the iris texture part and subsequently checks for iris reflections, eyelashes, and eyelids using the recursive prediction analysis. Our method obtained the best accuracy and ranked first from the 97+2 alternative methods in the Noisy Iris Challenge Evaluation contest run on a large colour iris database.

Five fully automatic methods for [X-ray digital mammogram enhancement](#) based on a fast analytical textural model were developed. These efficient single and double view enhancement methods are based on the underlying two-dimensional adaptive causal autoregressive texture model. The methods locally predict breast tissue texture from single or double view mammograms and enhance breast tissue abnormalities, such as the sign of a developing cancer, using the estimated model prediction statistics. The double-view mammogram enhancement is based on the cross-prediction of two mutually registered left and right breasts mammograms or alternatively a temporal sequence of mammograms.

We proposed [enhancement of screening mammograms](#) by estimating the local statistical models of grey levels of a suitably chosen search window - in the form of a mixture of Gaussian densities. Having estimated the mixture parameters we calculate at all window positions the corresponding log-likelihood values which can be displayed as grey levels at the respective window centers. The resulting log-likelihood image closely correlates with the original mammogram and emphasizes unusual details.

A similar locally estimated Gaussian mixture model was considered to [detect image forgery](#). An [unsupervised dynamic colour texture segmentation](#) method with unknown and variable number of texture classes. Single regions with dynamic textures can furthermore dynamically change their location as well as their shape. Individual dynamic multispectral texture mosaic frames are locally represented by Markovian features derived from four directional multispectral Markovian models recursively evaluated for each pixel site. Estimated frame-based Markovian parametric spaces are segmented using an unsupervised segmenter derived from the Gaussian mixture model. The method was objectively numerically evaluated on the dynamic textural test set from the Prague Segmentation Benchmark.

Two related problems: [finding regions of dynamic texture](#) in a video and [detecting moving targets](#) in a dynamic texture were solved using efficient and fast methods for both cases. First, we show how the optical flow residual can be used to find dynamic texture in video. Then we apply the singular value decomposition (SVD) to a temporal data window in a video to detect moving targets in dynamic texture via the residual of the largest singular value.

An [unsupervised range video segmentation](#) method based on a spatial probabilistic model for intended vehicle-based safety and warning system applications was verified.

4 Feature selection

Feature selection is one of key pre-processing steps enabling to save time and to improve classification models accuracy. A [survey of modern feature selection](#) approaches was recently published by the department researchers. We studied the dependency-aware [feature ranking stopping rules](#) and [feature selection method](#) for very high dimensionality. Three approaches to [reduce the negative effect of the curse of dimensionality](#) on the feature selection process were proposed. Another [hybrid feature selection algorithm](#) based on standard sequential search was derived.

We investigated the problem of evaluating the [stability of feature selection processes](#) yielding subsets of varying size in the IEEE Transactions on Pattern Analysis and Machine Intelligence article. We introduced several novel feature selection stability measures and adjusted some existing measures in a unifying framework that offers broad insight into the stability problem. The properties of considered measures were studied in detail and demonstrated on various examples what information about the feature selection process can be gained. We also introduced an alternative approach to feature selection evaluation in the form of measures that enable comparing the similarity of two feature selection processes. The introduced framework enables new ways of evaluating the quality of classification systems, capable of revealing wider range of pitfalls that may negatively affect machine learning performance.

The feature selection methods developed in the department were made public in the form of the [Feature Selection Toolbox](#).

5 Illumination invariants

We derived novel colour and rotation invariant [Markovian texture features](#) to solve the difficult problem of material surface recognition under variable in-plane material rotation, illumination spectrum, intensity (cast shadows), and illumination direction changes. No knowledge of illumination conditions is required and realistic visual scene recognition will benefit from these features in numerous medical, security, military, and other applications. Alternative [illumination invariant features](#) extracted from three different Markov random field (MRF) based texture representations were derived as well. The proposed textural features are invariant to illumination spectrum and extremely robust to illumination direction. They require only a single training image per texture and no knowledge of illumination direction, brightness or spectrum.

Our Markovian invariants were thoroughly [evaluated](#) with several state-of-the-art textural features on four representative and extensive image data-bases (ALOT, Bonn BTF, UEA Uncalibrated, and KTH-TIPS2). These features systematically outperform leading Gabor, Opponent Gabor, LBP, and LBP-HF alternatives. Moreover, they even allow successful recognition of arbitrary illuminated samples using a single training image per material and they were successfully applied also for BTF data.

A content-based [tile retrieval system](#) based on the underlying multispectral Markov random field based illumination invariant representation was implemented in a mobile application.

6 Markov random fields and mixture models

A complete treatment of the exceptional [3D wide-sense Markov model](#) which can be completely solved analytically and easily synthesised is presented in this Springer book chapter. The model can be modified to faithfully represent complex local data by adaptive numerically robust recursive estimators of all its statistics. Illumination invariants can be derived from some of its recursive statistics and exploited in content based image retrieval, supervised or unsupervised image recognition. Its modelling efficiency is demonstrated on several analytical and modelling image applications, in particular on unsupervised image or range data segmentation, bidirectional texture function (BTF) synthesis and compression, dynamic texture synthesis and adaptive multispectral and multichannel image and video restoration.

A multidimensional probabilistic [BTF Bernoulli mixture model](#) for representation and synthesis of BTF textures was developed. Texture synthesis is based on easy computation of arbitrary conditional distributions from the model. Additional multivariate [discrete or Gaussian or mixture models](#) for colour and BTF textures were derived as well.

A complex [mixture of dependence-tree densities](#) model was developed for complex data for which the product components simplicity could appear too restrictive. The dependence tree densities can explicitly describe the statistical relationships between pairs of variables at the level of individual components and therefore the approximation power of the resulting mixture may essentially increase. The strength of dependence-tree- and product mixture models is [compared](#) in the framework of the probabilistic neural networks.

A [restoration method](#) based on the Markovian model was applied to the multitemporal solar images. Its goal is to model and remove degradation in a subimage, where a specific event is investigated. Using information of the input (blurred) channels within a short observed sequence a new undegraded image is reconstructed.

7 Classifier and modelling quality benchmarking

The department has developed and maintains the worldwide evaluation standard for image classification - the [Prague texture segmentation data-generator and benchmark](#). This benchmark is a web based (<http://mosaic.utia.cas.cz>) service designed to mutually compare, evaluate their characteristics, and rank different static or dynamic, image or texture, supervised or unsupervised classifiers, and to support new segmentation and classification methods development. A similar [remote sensing benchmark](#) was

developed in the framework of the Prague texture segmentation data-generator and benchmark (PTSDB) to validate hyperspectral satellite image segmenters.

In order to promote evaluation of the unsupervised colour image segmentation algorithms using publicly available extensive data sets, standard performance assessment methodology and online web verification server and database (The Prague Texture Segmentation Data Generator and Benchmark), we have organized a [world-wide competition](#) for the best unsupervised image segmentation algorithms the [Unsupervised Image Segmentation Contest](#) in conjunction with the IAPR 22nd International Conference on Pattern Recognition - ICPR'14 in Stockholm.

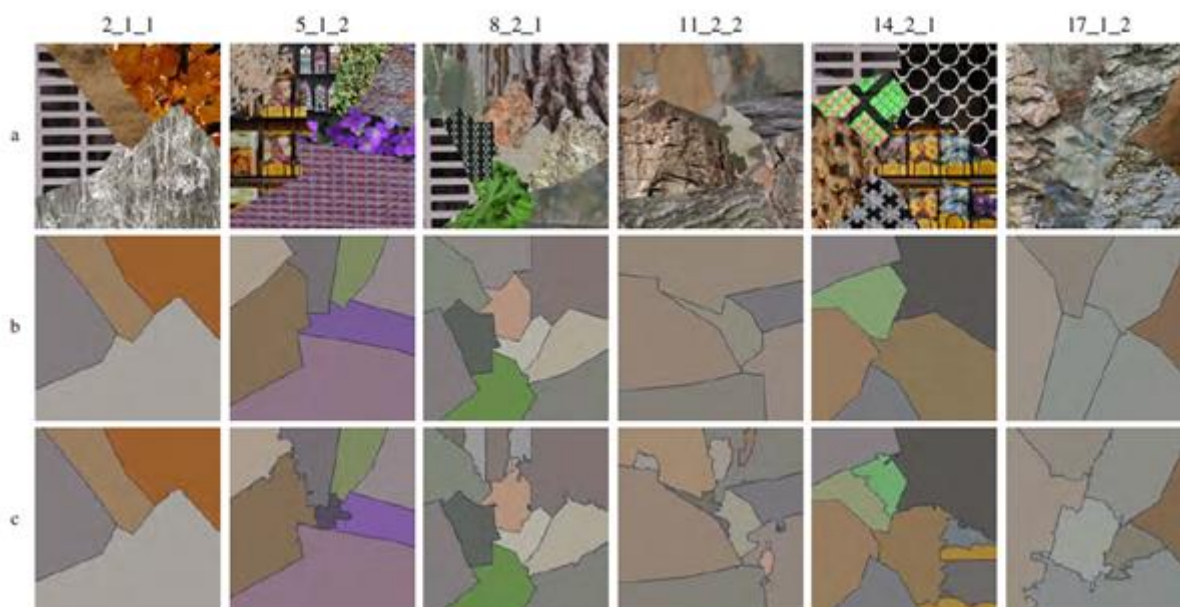


Fig. Several generated test mosaics from the benchmark (upper row), the ground truth (middle row) and the corresponding unsupervised classifier results (bottom row).

Automatic texture quality evaluation is important but still unsolved difficult problem. While several generative mathematical texture models were developed, their reliable qualitative evaluation is for now possible only using impractical and expensive visual psycho-physics which hampers their further progress. We developed the [texture fidelity benchmark](#) created to help the validation of texture fidelity criteria being developed. The benchmark is a web based service (<http://tfa.utia.cas.cz>) designed for performance evaluation, mutual comparison, and ranking of various texture fidelity measures. The benchmark supports rapid verification and development of new fidelity criteria approaches. The benchmark allowed to prove that none of the state-of-the-art image quality measures as well as the only published texture quality measure including all its several variants cannot be used for texture quality evaluation.

We investigated the [effect of shape and texture on subjects' attention](#) in a controlled psychophysical experiment with stimuli featuring different combinations of shape, illumination directions and surface texture. Appearance of five tested materials was represented by measured view and illumination dependent Bidirectional Texture Functions. Our results revealed several interesting aspects of human perception of different textured materials and, surface shapes. In another visual psychophysics studies we identified a [minimal number of point light sources](#) approximating a realistic illumination or observers perception dependence on real materials [orientation and illumination directions](#). We proposed a set of [statistical descriptors](#) motivated by standard textural features, and psychophysically evaluated their performance on three subtle artificial texture visual degradations. We have found that descriptors based on two-dimensional causal auto-regressive model, have the highest correlation with the psychophysical results.

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
-----------	---

Scientific team	Department of Signal Processing
-----------------	---------------------------------

Department of Signal Processing

The department of signal processing has been established in 1999 with the mission to transform the knowledge in the area of signal processing and recursive identification of systems into applicable research results, software libraries and hardware modules suitable for use in integrated circuits.

Main focus of the department of signal processing is research, development and implementation of advanced digital signal and image processing algorithms, mainly in the fields of telecom, audio processing and processing of high resolution video streams in the real time. We build on our experience within the Bayesian approach to recursive identification of linear systems with time variable parameters.

Our target platforms are Field-Programmable Gate Arrays (FPGAs). We use mostly Matlab and Simulink to specify, model and verify algorithms which we subsequently convert and synthesize to FPGAs. These specialized HW solutions are designed for use in embedded systems. That is why we also study architectures, which result in fast execution, small memory footprint, small chip area and low power consumption. This is achieved through designing new DSP algorithms or modifying the existing DSP algorithms and by exploiting advanced architectural properties of FPGA circuits.

Our aim is not only to deal with the theoretical design of algorithms but also to help industrial partners to solve implementation issues in all their complexity.

Our department participated in several RTD projects supported by Framework Programmes of the EU as well as national grant agencies. In March 2015 our group takes part in five projects financed by ARTEMIS and ENIAC Joint Undertakings and three projects financed by the Czech granting agencies (TACR, GACR and EUPRO program of the MEYS).

The scientific profile is complemented with activities which promote cooperation between academia and industry. This work is realized in the frame of the project OKO ICT Branch Contact Organization and the FP7 project Idealist.

The department is headed by Ing. Jiří Kadlec, CSc. with two deputies: Ing. Zdeněk Pohl, PhD. is the deputy head of the department of signal processing and Dr-Ing. Jiří Plíhal is the deputy head of the department with the responsibility for all activities related to the industrial research funded by company Škoda Auto within the frame of cooperation with ÚTIA.

Recursive identification, linear regression and systolic arrays

Foundation of our research is the recursive Bayesian system identification. In case of linear regression model, it leads to the families of recursive least square algorithms (RLS) with different forms of parameter tracking. The recursive updates of the information matrix or recursive updates of its inverse are implementable with numerical robustness in a square root factorised form by application of a sequence of orthogonal rotations. These factorised recursive least square algorithms, known as QR RLS can be mapped into pipelined triangular structures known as systolic arrays. Multiple subsequent time steps of the recursive identification are executable in parallel on the same array of computing cells. Each cell of the array corresponds to a matrix element of the triangular square-root of the information matrix. This brings massive data parallelism at the algorithmic level. This is utilized in our effective implementations of these algorithms in hardware.

In signal processing applications, the system-model is often defined as a finite response regression model (FIR) or the auto-regression model (AR). This brings additional properties to the recursively updated factorised matrices. The pipelined systolic arrays can be in this case simplified to the QR RLS Lattice structures, with the same numerical properties as the QR RLS. Numerical complexity of QR RLS Lattice grows linearly with the system order N . Numerical complexity of QR RLS grows linearly with N^2 . Versions of these recursive signal processing algorithms which eliminate the need of scalar square root operation are known as QRD.

Recursive estimation of probabilities of hypotheses about system structure and nested lower order regression models

The recursive Bayesian framework allows reasoning and guidance for the recursive QRD signal processing algorithms, which are capable to recursively estimate and track the probabilities of a fix set of hypotheses about structure of the regression model. In general, it requires to computation of one QRD model for each hypothesis.

The pipelined QRD systolic arrays and the QRD Lattice arrays contain, under conditions defined in the recursive Bayesian framework, all information needed for the evaluation of all lower-order, nested, regression models in the maximal size systolic array. If the application constrains allows utilising of this nesting property, the estimation of probabilities of the optimal system order can be realised, without the penalty of parallel recursive identification of all QRD or QRD Lattice models.

Numerical properties of nested data in the pipelined systolic QRD and QRD Lattice arrays and the concept of normalized fixed point implementations

The Bayesian framework allows to extend the concept of nested lower order models and to derive theoretically the corresponding probability distributions of all transformed data propagated in the pipelined systolic QRD and QRD Lattice arrays.

Special deterministic transformations of QRD algorithms maintain the nesting properties and the pipelined systolic structure of the array in hardware implementation. Additionally, all data propagated through the pipelined systolic array and all transformed coefficients will get probability distributions with the guaranteed data range $\langle -1, 1 \rangle$. This opens the possibility to implement all computation of the algorithm only in fixed-point arithmetic.

The use of fixed point implementation leads to low power consumption and low latency of operations. Overflows at the boundary range $\langle -1, 1 \rangle$ are purely the consequence of the limited precision of data representation and can be solved by use of the saturation hardware in all performed fixed-point arithmetic operations. The Bayesian framework gives us the guidance and theoretical base for these regularisations.

Design and implementation of signal processing algorithms in programmable hardware chips

We utilize all these properties of signal processing algorithms for the development and implementation of effective hardware computing blocks known as intellectual property cores (IP cores) for field programmable gate arrays (FPGA). FPGAs allow us to develop, design and implement application specific integrated circuits (ASICs) for signal processing. FPGAs contain the programmable logic resources. FPGAs also include optimised configurable fixed point multiply and accumulate (MAC) IP blocks and optimized random access memory (RAM) IP blocks.

Pipelined Floating Point Arithmetic

The recursive QRD RLS and QRD RLS Lattice algorithms are usually implemented in floating point arithmetic. That is why we have developed high level libraries with variable precision floating point arithmetic and the corresponding pipelined IP cores for the FPGA with bit-exact identical properties. Floating point IP cores are pipelined. This means, that the new operation can be started in every system clock cycle. But it takes several clock cycles until the results emerge from the pipelined unit. This can create dependencies, which are complicating the effective implementation of massively pipelined designs.

The theoretical knowledge about the systolic structures of QRD RLS and QRD RLS Lattice algorithms helps us to use the algorithmic level parallelism. We are using it to get higher utilisation of pipelined floating point IP cores and RAM blocks.

Pipelined Logarithmic Arithmetic

The logarithmic numbering system (LNS) and the logarithmic arithmetic is an alternative to the floating point arithmetic. It represents data practically identical range as the floating point representation. It is using the fixed-point representation of the exponent and fixed mantissa equal to

two. The multiply, divide, square root and power operations can be implemented as simple fixed-point operations with minimal hardware cost. These operations have no latency and can be replicated in the dedicated hardware implementation of a signal processing algorithm as often as needed. This leads to novel solutions with low power, low latency and low hardware cost for algorithms which use frequently these operations.

The difficult part of the logarithmic arithmetic is the addition. This operation has been implemented in the department as pipelined hardware module for the 32 bit and 19 bit arithmetic. The realised intellectual property core (IP) integrates 2 pipelined logarithmic adders.

The designs of DSP algorithms in the logarithmic are constructed in the hardware around one or two shared pipelined logarithmic addition IP core modules. Other operations are distributed in the hardware and replicated as often as needed. The problem of mapping of the algorithm to the hardware is therefore simplified to the effective scheduling of addition operations. Large proportion of variables of DSP algorithm can be stored in temporary registers in this case. The registers are storing only a single value. It is used by the next dedicated distributed-logarithmic IP core module. This property of logarithmic arithmetic simplifies the assignment of variables to the shared RAM blocks in the FPGA.

The logarithmic arithmetic has also several disadvantages in comparison to the mainstream floating point arithmetic. It does not scale well beyond the 32 bit precision due to of the exponential growth of complexity of the logarithmic add unit. The input and output data conversions from/to fixed point representation are easier and faster in case of the floating point numbering system. The logarithmic input output conversion requires use of a pipelined logarithmic addition IP module, dedicated just for the iterative conversion from/to the fixed point input/output data. We have developed pipelined input and output conversion IP cores for both systems.

Results reached in 2010-2014

- Book (A. Heřmánek): *Next generation equalisation algorithms*. LAP LAMBERT Academic Publishing GmbH & Co, 2010. 132 s. ISBN 978-3-8433-6457-7.
- FPGA design and implementation of recursive filter parameter identification based on affine projection. The design works with logarithmic arithmetic with 19 bit precision and 32 bit precision. Journal paper publication *ACM Transactions on Embedded Computing Systems*. 2010, Vol.. 9, no. 3, s. 1-31. ISSN 1539-9087. (M. Tichý).
- Conference paper (Z. Pohl, and M. Tichý). A Framework for Self-adaptive Collaborative Computing on Reconfigurable Platforms. In *Advances in Parallel Computing*. Amsterdam : IOS Press BV, 2012, s. 579-586. ISBN 978-1-61499-040-6.
- FPGA design and implementation of QR RLS Lattice algorithm. The design is using logarithmic arithmetic with 19 bit precision and 32 bit precision.

EdkDSP platform

The mapping, design and implementation of signal processing algorithms in form of systolic arrays on the FPGA hardware requires typically reuse of multiple parallel data paths with the pipelined arithmetic units (logarithmic or floating point). This can be realised in a fixed hardware by several identical synchronous finite state machines sharing the arithmetic data paths in different time slots.

The EdkDSP platform has been introduced by the department to replace these parallel finite state machines, by a single reprogrammable synchronous controller, programmable in the Assembly language and in C language.

The EdkDSP platform enables to design relatively complex FPGA IP cores which can be connected to the central processor inside of the FPGA and reprogrammed in the runtime of the application by change of the firmware of the EdkDSP internal controller.

The EdkDSP IP core based hardware implementation is a fixed hardware instance. However it can serve for a family of similar signal processing algorithms.

In the SCALOPES project, the resource management middle layer for the EdkDSP accelerators was prototyped. It allowed making the design process of hardware accelerated applications easier, scalable and composable. Several different variants of the EdkDSP accelerators were used for its benchmarking. These variants have included also the complex floating point arithmetic. The accelerators have used different firmware for individual complex DSP operations. The performance of the resource management middle layer was evaluated on these three demo applications:

- GSM sensing,
- Digital Audio Broadcasting (DAB) physical layer,
- Image Upscaling

Each of these application employed heterogeneous accelerators, executing different firmware.

Results reached in 2010-2014

- Chapter in book (SCALOPES). *Smart Multicore Embedded Systems* Springer, 2011. s. 149-184. ISBN 978-1-4614-0060-8.
- Two chapters in book (SMECY) *Reconfigurable Computing. From FPGAs to Hardware/Software Codesign*. Springer, 2014. s. 45-77 and s. 159-175 ISBN 978-1-4614-8799-9.
- Motion detection demonstrator (SMECY)
 - Motion Detection performed by foreground-background segmentation based on mixture of Gaussians models.
 - Extract features of foreground objects at 6 fps (walking humans).
 - Image processing (640x480x24b).

- Standard digital camera interface for data input and output.
- Bit exact EdkDSP model in Matlab and Simulink with 32bit floating point data paths
- Transaction based co-simulation of Simulink bit-exact model with processor running on the FPGA hardware.
- Methodology for automated generation of EdkDSP FPGA IP core software drivers interfaces for Xilinx FPGA systems with MicroBlaze soft core processor and the IBM PLB bus or Xilinx AXI-lite bus (form of the ARM AMBA bus)
- Evaluation packages and documentation, licensing framework for EdkDSP IP cores for:
 - 90nm Spartan3AN FPGA , PLB bus, 75 MHz clock, 0,15 GFLOP/s peak
 - 45nm Spartan6 FPGA , PLB or AXI bus, 95 MHz clock, 1,52 GFLOP/s peak
 - 28nm ZYNQ, dual ARM Cortex A9, 100 MHz clock, 6,40 GFLOP/s peak
 - 28nm Artix7 FPGA, AXI bus , 125 MHz clock, 12,00 GFLOP/s peak
 - 28nm Kintex7 FPGA, AXI bus , 175 MHz clock, 16,80 GFLOP/s peak

Several big research laboratories are recognising the potential of our approach and cooperate with us in this research. We can name here the most active partners:

Germany: Infineon Technologies AG, Robert Bosch GmbH, Global Foundries (Dresden).

Finland: Nokia TECH, VTT Technical Res, Centre of Finland, Tampere University.

Netherlands: Philips Healthcare, Vector Fabrics BV, TU Delft, Embedded Systems Institute.

France: ST Microelectronic, CEA LETI, CEA LIST, Thales Communication;

The detailed list of partners in these projects and links to the released evaluation packages and application notes produced by our Department can be found at <http://zs.ÚTIA.cas.cz/> .

External public funding to ÚTIA for this research (2010-2014): 31,505 Mil. CZK = 1240 k€. (Projects: CAK2, VLAM, SCALOPES, SMECY, IDEAS, EMC2, THINGS2DO, ALMARVI, PANACHE)

Fine-grain multi-threading in programmable HW

This research work has been focussed on HW and SW implementation of novel processor, capable to implement the fine-grain multithreading in programmable HW. Processor UTLEON3 extends the LEON3 processor.

Results reached in 2010-2014

- Book (AppleCORE) *UTLEON3: Exploring Fine-Grain Multi-Threading in FPGAs*. Springer, 2013. 209 s. ISBN 978-1-4614-2409-3.
- Modular VHDL source code for the UTLEON3 under an open license together with a thorough discussion of the design's internals, motivations and possible applications.
- 27.-29. 8. 2011 - Presentation of UTLEON3 processor at University of Cambridge (Daněk, Kafka, Kohout, Sýkora)

External public funding to ÚTIA for this research (2010): 3,800 Mil. CZK = 150 k€. (Project: AppleCore)

Human machine interface interaction based on vehicle control systems

One of the main factors for energy efficiency enhancement in fully electric vehicles is systems integration. This research is leading to a step change in the control software architecture with particular focus on comprehensive energy management. The main objective has been the energy savings and extended driving range of the fully electric vehicle, with benefits of improved vehicle safety and comfort. This research has been performed in the EU iCOMPOSE project, where ÚTIA has been acting as the sub-contractor to the project partner Škoda Auto.

The development of individual control of the electric motor torques of fully electric vehicles has been performed in the EU E-VECTOORC, where ÚTIA had acted also as the sub-contractor to the project partner Škoda Auto.

In both mentioned projects was main attention devoted to analysis of HMI interaction based on vehicle control systems. This research has been coordinated by Dr-Ing. J. Plíhal. He has joint the department of signal processing in January 2014.

Results reached in 2010-2014

Conference paper: Cost Functions for Assessment of Vehicle Dynamics. In *Proceedings of the 2013 IEEE Symposium Series on Computational Intelligence*, IEEE SSCI 2013. Piscataway : IEEE, 2013, s. 48-55. ISBN 978-1-4673-5851-4.

Coordination of R&D projects with Technical Development of Skoda Auto

This cooperation is based on general contract between UTIA and Skoda Auto. It has resulted in concrete development work performed in Department of signal processing, Department of adaptive systems and the Department of decision making theory. This cooperation is coordinated by Dr-Ing. Jiří Plíhal.

External industrial funding to ÚTIA in 2013: 3,306 Mil CZK.

External industrial funding to ÚTIA in 2014: 4,252 Mil CZK.

Support to the information and communication technology research teams in the Czech Republic

We actively promote and support cooperation between academia and industry. This work is realized in the frame of the project OKO ICT Branch Contact Organization and the FP7 project Idealist.

This activity has been our form of education service provided for the Czech constituency instead of teaching in regular training courses at CZ universities. We believe that this form of education provides maximal impact.

It also serves as mechanism for building of our research collaboration with partners in the Czech Republic.

Results reached in 2010-2014

- Several journal papers describing the participation in EU funded research projects papers and numerous presentations on seminars and information days
- WWW server with actual information for the Czech constituency in the area of ICT (actual funding and cooperation possibilities). See <http://www.oko-ict.cz/> .

External public funding to ÚTIA for this support activity (2010-14): 5,777 Mil CZK = 224 k€. (Projects: Cosine II, Idealist2011, Idealist2014, OKO ICT, OKO ICT II).

Concluding comments about the research period 2010-2014

We have managed to recover from two difficult years 2012 and 2013. Several projects had to be finalised and defended in these two years with very limited external research funding. Several Post. Doc. colleagues have decided to leave our team in these two years. In 2013, we have managed to participate in several winning international project proposals. This helped us to secure the external research funding.

In 2010-2014, members of our team (4 FTE researchers) have worked as

- partners in 11 EU funded (FP6 or FP7) projects,
- subcontractors in another 2 EU funded (FP6 or FP7) projects
- partners in 5 Czech projects

The corresponding external funding for ÚTIA from these external public funding sources (without subcontracts and without SA industrial contracts) was 41,298 Mil. CZK = 1,622 Mil. € in 2010-2014.

Starting from April 2014, we mainly collaborate with international research teams in two large research projects related to the embedded system and image processing (EMC2 and ALMARVI) and in two strategic microelectronic pilot lines projects THINGS2DO and PANACHE. These four EU projects expect from our team mainly designs of electronic demonstrators and prototypes. We can build on our expertise in the hardware and software co-design, combined with the knowledge of the adaptive signal processing theory and algorithms. These projects are securing the short term perspective of the team.

We have to address the longer perspective of the team by involving of new young researchers and PhD students. In January 2015, we have established new link with the Faculty of Transport of the Czech Technical University in Prague. New members of our team are Doc. I. Nagy, CSc. and Ing. E. Suzdaleva, PhD. Both are conducting research in ÚTIA and also teaching in the Faculty of Transport.

The general outlook of the department is positive with wide range of interesting challenges.

Research Report of the team in the period 2010–2014

Institute	Institute of Information Theory and Automation of the CAS, v. v. i.
Scientific team	Department of Stochastic Informatics

Department of Stochastic Informatics

The team – which coincides with a department of the Institute of Information Theory and Automation (ÚTIA) – has carried out a fundamental research in the field of probability theory, mathematical statistics and statistical signal processing. ÚTIA is essentially the only non-university institution hosting research in this direction.

A. In probability theory, our research concentrates mainly on infinite dimensional systems (stochastic partial differential equations and interacting particle systems).

a) Research in the field of stochastic analysis:

a1) An in-depth study was carried out of the uniqueness problem for stochastic wave equations with polynomial nonlinearities, driven by a spatially homogeneous Wiener process. By extending the Strichartz inequalities to stochastic convolutions it was shown that pathwise uniqueness always holds in the subcritical case. In the critical case, it was shown that solutions with weakly continuous paths in the energy space, if they exist, have necessarily strongly continuous paths and are unique. These results correspond to the state-of-the-art in the deterministic case. See M. Ondreját: Journal of Differential Equations 248 (2010), [1579-1602](#).

a2) Under rather general hypotheses it was shown that there exists a global weak solution to a system of wave equations with critical growth coefficients in local Sobolev spaces. To this end, a new method of constructing weak solutions was developed. The use of local spaces makes it possible to consider a much wider class of initial data and get rid of unnatural restrictions on the nonlinear terms. By allowing systems of equations, general elliptic operators instead of the Laplacian and nonlinear terms depending on the time derivative of the solution, a result was obtained which can be used in the study of stochastic manifold-valued wave maps. See M. Ondreját: Electronic Journal of Probability 15 (2010), [1041-1091](#).

a3) The study of stochastic wave equations in Riemannian manifolds is a fairly new field, where only little is known and results depend heavily on the spatial dimension and the geometry of the target manifold. We proved that there exists a weak solution if either the space dimension is one and the target manifold is arbitrary, or the space dimension is arbitrary but the target space is a Riemannian homogeneous space (e.g. a sphere). All papers on stochastic wave maps are coauthored by Z. Brzeźniak from the University of York, both authors contributed to this research equally. See Z. Brzeźniak, M. Ondreját: Communications in PDEs 36 (2011), [1624-1653](#); Annals of Probability 41 (2013), [1938-1977](#).

a4) Degenerate stochastic parabolic equations were studied. By introducing a new concept of a kinetic solution it was possible to prove the existence and uniqueness of solutions. As a prerequisite, a rather surprising result was established on the existence of smooth solutions to semilinear stochastic equations on the torus. See M. Hofmanová: Stochastic Processes and their Applications 123 (2013), [4294-4336](#); NoDEA 20 (2013), [757-778](#).

a5) In cooperation with M. Veraar from the Technical University of Delft, the Dudley theorem on integral representation of Brownian functionals was extended to Banach space-valued functionals. Standard proofs of Dudley's theorem cease to work in an infinite-dimensional setting, hence a new approach was developed, which may be useful even in the classical situation. Both authors contributed to this research equally. See M. Ondreját, M. Veraar: Journal of Theoretical Probability 27 (2014), [1350-1374](#).

a6) A (one-sided) Burkholder-Davis-Gundy type inequality with sharp constants was established for stochastic integrals in 2-smooth Banach spaces. As a consequence, exponential tail estimates for

stochastic convolutions were easily obtained via Zygmund's extrapolation theorem. See J. Seidler, *Electronic Journal in Probability* 15 (2010), [1556-1573](#).

a7) By employing procedures developed in infinite dimensional stochastic analysis, a new, fairly elementary proof was obtained of the existence of solutions to stochastic differential equations whose coefficients are continuous and either have linear growth or satisfy a suitable Lyapunov condition. The proof avoids both theorems on integral representation of martingales and the Skorokhod representation of random variables converging in law. See M. Hofmanová, J. Seidler: *Stochastic Analysis and Applications* 30 (2012), [100-121](#); 31 (2013), [663-670](#).

a8) A simple proof was found of the existence of a progressively measurable modification of a measurable adapted process. This is a well known basic result in stochastic analysis, but no elementary proof seems to have been available previously. See M. Ondreját, J. Seidler: *Electronic Communications in Probability* 18 (2013), no. 20, [1-6](#).

b) Research in the field of interacting particle systems:

b1) The Brownian web is a collection of coalescing one-dimensional Brownian motions, starting from each point in space and time, the Brownian net (introduced by Sun and Swart in 2008) is an extension of the Brownian web that arises as the scaling limit of coalescing random walks that also branch with a small rate. In a long paper, that appeared in the prestigious journal *Memoirs of the AMS*, the Brownian web and net were used to study a class of measure valued processes which arise as the continuum limit of random walks in a random space-time environment. It was shown that the idea of a random walk in a random environment can be made rigorous even in the continuum limit, with the Brownian web and net playing the role of the random environment. See E. Schertzer, R. Sun, J. Swart: *Memoirs of the AMS* 227 (2014), no. 1065, [1-160](#).

b2) The contact process was studied with the usual integer lattice replaced by the hierarchical group, which better models the spatial structure of some biological populations. It was shown that this leads to new behaviour; the proofs use an interesting new renormalization technique. See S. Athreya, J. Swart: *Probability Theory and Related Fields* 147 (2010), [529-563](#).

b3) The exponential extinction rate of subcritical contact processes on very general lattices was studied as a function the birth rate and a new formula for the derivative of this function was proved in terms of a quasi-invariant law describing the process conditioned on survival. See A. Sturm, J. Swart: *Electronic Journal of Probability* 19 (2014), no. 53, [1-46](#).

b4) Systems of particles with branching, coalescence and annihilation were studied. Although these systems are not monotone, earlier results of Athreya and Swart for monotone systems without annihilation were extended almost completely to the non-monotone setting. See S. Athreya, J. Swart: *Electronic Journal of Probability* 17 (2012), no. 80, [1-32](#).

b5) There exists a number of results proving that for certain stochastic models for the distribution of two species, if each species can invade the territory occupied by the other species, then coexistence is possible (there exists an invariant law with both species present). We proved a sort of converse statement for a particular class of one-dimensional systems. See J. Swart: *Electronic Communications in Probability* 18 (2013), no. 38, [1-12](#).

b6) Intertwining relations for birth-and-death processes were studied. It was shown that an arbitrary birth-and-death process can be coupled to a pure birth process in such a way that both processes arrive at a given level at the same time and the latter never exceeds the former. See J. Swart: *Kybernetika* 47 (2011), [1-14](#).

b7) It is believed that the 3-state antiferromagnetic Potts model on the integer lattice is disordered at all temperatures in dimension 2 but ordered for low temperatures in higher dimensions. Surprisingly, by using improved Peierls techniques we proved that even in 2 dimensions there is a class of lattices for which there is long-range order. See R. Kotecký, A.D. Sokal, J. Swart: *Communications in Mathematical Physics* 330 (2014), [1339-1394](#).

Some of these results were obtained in cooperation with S. Athreya from the Indian Statistical Institute in Bangalore, R. Kotecký from the Warwick University, E. Schertzer from Université Pierre et Marie Curie Paris, A.D. Sokal from the New York University, A. Sturm from the University of Göttingen, and R. Sun from the National University of Singapore; the authors contributed equally to the respective papers.

B. In ergodic theory, attention was paid to return times in dynamical systems and extreme value laws. It was previously known that the exponential law for return times to cylinders is the only limiting law in the case of strongly mixing processes with positive entropy, whereas for non-mixing zero entropy processes only discrete laws had been found. We constructed a non-mixing process of zero entropy such that the exponential law appears as the only limiting law for return times to cylinders. It had also previously been known that well mixing systems with positive entropy have extreme value laws which converge to one of the three standard distributions: Gumbel, Fréchet or Weibull. We studied the extreme value law for non-mixing dynamical systems obtaining a different type of the extreme value law, not known before. These results were obtained in cooperation with P. Grzegorek from the Technical University of Wrocław and N. Haydn from the University of Southern California. The authors contributed equally to the respective papers. See P. Grzegorek, M. Kupsa: Communications on Pure and Applied Analysis 11 (2012), [1361-1383](#); N. Haydn, M. Kupsa: Ergodic Theory and Dynamical Systems, [online 2014](#).

C. In mathematical statistics, our research has focused on multiple-output regression methods and statistical survival analysis.

a) Two interrelated concepts were developed of directional multiple-output quantile regression, tailored to regression models with multivariate responses and general unimodal error distributions, starting with the paper by M. Hallin, D. Paindaveine and M. Šíman in Annals of Statistics 38 (2010), 635-669. For example, basic properties and an intuitive geometric interpretation of directional regression were discovered, and new quantile-related statistics for multivariate statistical inference were introduced. These results were applied to the theory of data depth, where the developed algorithms made it possible e.g. to efficiently compute for the first time the Tukey depth contours in the spaces beyond dimension two or three, to find an analytic formula for the halfspace depth of points in a general regression setup, or to study a new concept of projection depth for points in a general regression case. This research was carried out in cooperation with D. Paindaveine from the Université Libre de Bruxelles. The authors contributed equally to the respective papers. See e.g. D. Paindaveine, M. Šíman: Journal of Multivariate Analysis 102 (2011), [193-212](#); Computational Statistics and Data Analysis 56 (2012), [840-853](#).

b) Research has been started on elliptical multiple-output quantiles. New elliptic location quantiles were introduced in a convex optimization framework, their natural properties and links to semi-definite programming were established, and consistency of sample estimators was proved.

This research is carried out together with D. Hlubinka from the Charles University in Prague; both authors contributed equally to the research. See e.g. D. Hlubinka, M. Šíman: Journal of Multivariate Analysis 116 (2013), [163-171](#).

c) Our knowledge of multiple-output quantile regression was used to define an intuitive and target-independent precision capability index for multivariate manufacturing processes under very mild hypotheses and in a very general tool wear setup when all convex tolerance regions are permitted and no limiting distributional assumptions are required. Further, we proposed a unified and natural way for obtaining new multivariate and tool wear extensions of any univariate process capability index by means of projection pursuit. See Communications in Statistics – Theory and Methods 43 (2014), [377-387](#), [1949-1955](#).

d) A study of new nonparametric tests for conditional heteroscedasticity has been started by generalizing Kendall autocorrelations to the weighted case, computing their exact sample moments and proving their asymptotic normality in the sample case. See M. Šíman: Communications in Statistics – Theory and Methods 41 (2012), [1733-1738](#).

e) The existing research in the field of statistical survival analysis with the main focus on the model diagnostics and goodness-of-fit tests, was continued. New theoretical results were achieved for the asymptotic distribution of empirical martingale residuals in the accelerated failure time regression model. Bayesian estimation procedures, together with Markov chain Monte Carlo methods, were developed for Cox, accelerated failure time and Aalen additive models. The problem of stochastic optimization was studied in the case when the stochastic characteristics of the system are estimated from randomly right-censored data, the analysis of precision of obtained solutions being based on corresponding theoretical results of survival analysis. See e.g. P. Novák: Kybernetika 49 (2013), [40-59](#); P. Volf: Kybernetika 50 (2014), [297-309](#).

D. In the field of statistical signal processing, the following problems were addressed:

a) Independent component analysis (ICA) and blind source separation.

a1) ICA is a useful method for artifact extraction and elimination. Concerning on its theoretical foundations, a novel algorithm for joint block-diagonalization of sets of matrices was found, which is applicable to blind subspace estimation, where the received signals are separated into clusters of components so that the components within each cluster may be dependent. Further, two papers and a book chapter were published giving surveys of the state-of-the-art in this field. These papers have multiple coauthors, but the contribution of P. Tichavský is substantial (approximately 50 per cent) in all cases. See e.g. G. Chabriel & al.: IEEE Signal Processing Magazine 31 (2014), [34-43](#).

a2) In the area of applications, a new method of adaptive reconstruction of ICA-processed neonatal EEG data was proposed. The method is designed to cope with the challenging situation of a low number of channels and frequent short-in-time and high amplitude artifacts and has the potential to be applied routinely in neonatal EEG processing. This research was carried out in cooperation with V. Krajča and K. Paul from the Department for Mother and Child Care in Prague, who supplied empirical data and expertise in EEG interpretation. See M. Zima & al.: Physiological Measurement 33 (2012), [39-49](#).

b) Signal processing for acoustic signals.

b1) A new method was developed for the so called cocktail party problem, i.e. blind audio source separation. The proposed solution is a time-domain algorithm, in contrast with the existing algorithms which work in the frequency domain and so lead to nonlinear distortions of the estimated signals. Subsequently, we found several extensions of the algorithm. The Czech patent office granted a patent to this invention. See e.g. Z. Koldovský, P. Tichavský: IEEE Transactions on Audio Speech and Language Processing 19 (2011), [406-416](#).

b2) A study was carried out of the problem of semi-blind noise extraction using a partially known position of the target source. The proposed method has an application to noise reduction in dual-microphone mobile phones using a bank of pre-measured target-cancellation filters and was also granted a patent by the Czech patent office. See e.g. Z. Koldovský & al.: IEEE Transactions on Audio Speech and Language Processing 21 (2013), [2029-2041](#).

c) Tensor decomposition methods. (Where by tensor we mean here a multidimensional linear array of a rectangular shape.)

c1) We studied the canonical polyadic (CP) decomposition of tensors, which serves for storing tensors in a compressed form. A hard theoretical question concerning stability of the CP decomposition was solved by deriving a Cramer-Rao lower bound on the accuracy of the CP decomposition if the tensor is noisy. Further contributions were a new implementation of the damped Gauss-Newton algorithm and an algorithm based on tensor reshaping for the CP decomposition. Moreover, algorithms for other types of tensor decompositions were proposed: tensor deconvolution, which may be more suitable in some applications, and the decomposition of a tensor into a sum of Kronecker products of smaller tensors, which may be used, e.g., for image inpainting. See e.g. A.-H. Phan & al.: SIAM Journal on Matrix Analysis and Applications 34 (2013), [126-147](#); Tichavský & al.: IEEE Transactions on Signal Processing 61 (2013), [1986-1997](#).

c2) It was shown how tensor decompositions can be used for blind separation of underdetermined mixtures of independent speech signals, when the number of microphones is lower than the number of speakers to be separated. See e.g. P. Tichavský, Z. Koldovský: IEEE Transactions on Signal Processing 59 (2011), [1037-1047](#).

The results on tensor decompositions were obtained in cooperation with A. Cichocki and A.-H. Phan from the Riken Brain Science Institute in Wako (Japan); all authors contributed equally to the research.

E. Whilst the research of the team in probability theory continued smoothly, the research in mathematical statistics was heavily affected by several factors. The first of these was the premature death of I. Vajda in 2010; he had a substantial influence on the research of the whole team for many years. As a consequence, some of his collaborators, who had a part-time job in ÚTIA, left the institute. Another factor was the retirement of J. Michálek, who however concentrated on expert activities in the last years. The long-lasting illnesses of J. Šindelář (who already retired) and M. Janžura have prevented them from intensive research work. P. Boček abandoned research and works now in the institute as an IT specialist. P. Volf is still active both in research and even more in teaching, but he has already reached his retirement age. Hence it has been necessary to build the statistical part of the team almost anew. M.

Šiman, who returned to Prague from Belgium, brought to the institute the promising topic of multidimensional nonparametric statistics and has published an impressive number of results in this field recently, however, it is highly desirable to attract to the institute further gifted young statisticians. This task turned out to be difficult, in particular because of budget restrictions on fundamental research in the Czech Republic, excessive dependence on project financing and the critically low number of (capable) students of theoretical probability and statistics at Charles University.

Insecure prospects of getting a permanent job in research also led T. Pazák to leave the institute. He authored two high-quality papers on Boolean algebras and measures on them in the evaluated period; this line of research is now discontinued in the institute. The same reasons forced several promising Ph.D. students to break off their studies and accept a position in financial institutions.

F. To conclude, we would like to emphasize that our intention has been to publish only papers containing new and surprising ideas, not to maximize fashionable quantitative indicators seemingly measuring the quality of research.