ÓBUDA UNIVERSITY

Ph.D. Dissertation

-Thesis Book-

Non-Conventional Data Representation and Control

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Abstract

Non-conventional approaches are prime concerns for most design issues in nonlinear adaptive control and signal processing. During the last decade major advances have been made in the theory of Adaptive Systems. Due to the advantageous features of Soft Computing techniques, such as flexibility and robustness, they have become fundamental tools in many areas. These methods are suitable for solving problems that are highly nonlinear or when only partial, uncertain data is available. In such situations, the application of traditional approaches is often complicated and what is more, can not guarantee the expected performance level. Therefore, my primary aim is to reveal new ways to overcome this difficulty by using Soft Computing, non-conventional and novel data representation techniques. In this Thesis I address novel data representation and control methods that are able to adaptively cope with usually imperfect, noisy or even missing information (for instance, wavelet based multiresolution controllers, anytime control, Situational Control, Robust Fixed Point Transformation (RFPT)-based control). The great majority of the adaptive nonlinear control design are based on Lyapunov's 2nd or commonly referred to as the "Direct" method. The major defect of this method that it is mathematically complicated and it works with a large number of arbitrary adaptive control parameters. Moreover, the parameter identification process in certain cases is vulnerable if unknown external perturbations can disturb the system under control, etc. In the recent years the RFPT has been introduced for replacing

the Lyapunov technique. Since, in this Thesis my first intention was to deal with the possibilities of the combination of classical model identification and the RFPT-based design in depth. I have proposed a new method that utilize the geometric interpretation provided by the Lyapunov-technique that can be directly used for parameter tuning. I have shown that these useful information can be obtained on the actual parameter estimation error by using the same feedback terms and equations of motion as the original methods. In order to improve the parameter tuning process, I have suggested the application of the Modified Gram-Schmidt Algoritm for the possible combination of the RFPT-based method with the Modified Adaptive Inverse Dynamic Robot Controller (MAIDRC) and the Modified Adaptive Slotine-Li Robot Controller (MADSLRC). Besides, I have presented an even simpler tuning technique in the case of the Modified Adaptive Inverse Dynamics Robot Controller that also applies fixed point transformation-based tuning rule for parameter identification. Afterwards, I have presented a systematic method for the generation of a new family of the Fixed Point Transformations, the so-called „Sigmoid Generated Fixed Point Transformation (SGFPT)" for the purpose of „Adaptive Dynamic Control" for nonlinear systems. At first, I have outlined the idea for the „Single Input - Single Output (SISO)" systems, then I have shown that it can be extended to „Multiple Input – Multiple Output (MIMO)" systems. Additionally, I have replaced the tuning method by a simple calculation in order to further simplify and improve the method. I have proposed new advances regarding the SGFPT. Also, I have described a new control strategy based on the combination of the “adaptive” and “optimal” control by applying time-sharing strategy in the SGFPT method, that supports error containment by cyclic control of the different variables. Further, I have introduced new improvements on the SGFPT technique by introducing “Stretched Sigmoid Functions”. The efficiency of the presented control solution has been confirmed by the adaptive control of an underactuated mechanical system. I have investigated the applicability of fuzzy approximation in the SGFPT-type control design and demonstrated the usability via simulation investigations. Furthermore, I have shown a new type of function for the adaptive deformation in the SGFPT. The other important issue that includes the maintenance of unwanted sensor noises that are mainly introduced by feedback into the system under control. Therefore, in the development of a control system the signals of noisy measurements has to be addressed first so that more sophisticated signal pre-processing methods are required. Since, I have concerned the issue of well-adapted techniques for smoothing problems in the time domain and fitting data to parametric models. In a wider sense this means, that research is also needed to determine novel approximations that can be used for smoothing the operation of the adaptive controller. After, I have investigated the Savitzky-Golay (SG) smoothing and differentiation filter. It has been proven that the performance of the classical SG-filter depends on the appropriate setting of the windowlength and the polynomial degree. The main limitations of the performance of this filter are the most conspicuous in processing of signals with high rate of change. In order to overcome this limitation I have developed a new adaptive method to smooth signals based on the Savitzky-Golay algorithm. The provided method ensures high precision noise removal by iterative multi-round smoothing. The signal approximated by linear regression lines and corrections are made in each step. Also, in each round the parameters are dynamically change due to the results of the previous smoothing. For supporting high precision reconstruction I have introduced a new parametric weighting function. Thesis applications and proof of operation have been confirmed by numerical simulations.

I. Introduction

Among the different approaches of modern engineering applications model-integrated computing plays an exceptional role. Modeling is a fundamental and difficult problem in all the sciences; to design a controller one needs a model. *Soft Computing techniques*, such as fuzzy and neural network-based models, *are found to be highly efficient* due to their flexibility, robustness and easy interpretability. Especially in cases where the problem to be solved is highly nonlinear or when only partial, uncertain and/or inaccurate data is available. At the same time, though their usage can be so advantageous, it is still limited by their exponentially increasing computational complexity. *Combining soft computing, non-conventional and novel data representation techniques* is a possible way to overcome this difficulty. The performance of a controller depends on the available form of the model, therefore my research concentrates on novel data representation and control methods that are able to adaptively cope with usually imperfect, noisy or even missing information, the dynamically changing, possibly insufficient amount of resources and reaction time (for instance, wavelet based multiresolution controllers [*Kratmüller, 2010*], anytime control [*Várkonyi-Kóczy, 2008*][*Várkonyi-Kóczy, 2009/1-2*] [*Várkonyi-Kóczy, 2010/1-2*], Situational Control [*Madarász et al., 2009*], Robust Fixed Point Transformation-based control [*Tar, 2012*], etc.

II. Research Aims and Their Relevance in the Context of the State of the Art

The field of *Adaptive Systems*, that includes for instance recursive identification, adaptive control, filtering, and signal processing, has been one of the most active research areas of the past decade. Since adaptive controllers are *fundamentally nonlinear*, their theoretical analysis is usually very difficult. Therefore, modern approaches of control design and signal processing include a various class of mathematical tools. For example, the idea of *wavelet based controllers* (see, [*Kratmüller, 2010*], [*Dhiraj, 2013*], [*Soumelidis, 2011*], [*Bernard, 1997*]) originates from the facilities of series expansion with wavelets. In paper [*Kratmüller, 2010*] the authors investigate wavelet network and fuzzy approximation in controlling a class of continuous time unknown nonlinear systems. The described method applies variable wavelet bases, where the adjustable parameters enable constructing suitable control laws. An effective way dealing with potentially infinite number of unknown parameters with the help of wavelet basis functions has been introduced in [*Dhiraj et al, 2013*]. The proposed method is based on constructing an ideal infinite controller and approximating its behaviour with a finite controller. The authors highlight the advantages of the 'Mexican hat' type wavelet frames from multiresolution analysis' point of view. Paper [*Soumelidis et al, 2011*] shows a new frequency-domain approach to identify poles in discrete-time linear systems. The discrete rational transfer function is represented in a rational Laguerre-basis, where the basis elements are expressed by powers of the Blaschke-function. This function can be interpreted as a congruence transform on the Poincaré unit disc model of the hyperbolic geometry. The identification of a pole is given as a hyperbolic transform of the limit of a quotient-sequence formed from the Laguerre-Fourier coefficients. Paper [*Soumelidis et al, 2011*] extends this approach for using discrete time-domain data directly. Another interesting new adaptive fuzzy wavelet network controller is shown in [*Bernard, 1997*], for control of nonlinear affine systems, inspired by the theory of *multiresolution analysis* (MRA) of wavelet transforms and fuzzy concepts. The proposed adaptive gain controller, which results from the direct adaptive approach, has the ability to tune the adaptation parameter in each fuzzy rule during real-time operation. Further interesting foundings can be read in [*Várkonyi-Kóczy, 2011*] for supporting real –time design.

The traditional approach in the design of *adaptive controllers for nonlinear dynamic systems normally applies Lyapunov's „Direct" method* [*Lyapunov, 1892*]. Several solutions have been proposed in order to replace this technique by a simpler approach (for example, [*Tar et al., 2010/1*], [*Tar et al., 2001/1*], [*Tar et al., 2001/2*], [*Tar et al., 2001/3*], [*Tar et al., 2002*]. The main characteristics of the Lyapunov-based technique can be summarized as follows: a) it yields satisfactory conditions for the stability; b) instead of focusing on the primary design intent (e.g. the precise prescription of the trajectory tracking error relaxation) it focuses on proving "global stability" that often is too much for common practical applications; c) in the identification of the model parameters of the controlled system it provides a tuning algorithm that contains certain components of the particular Lyapunov function in use, therefore it works with a large number of arbitrary adaptive control parameters; d) the parameter identification process in certain cases is vulnerable if unknown external perturbations can disturb the system under control. Concentrating on the primary design intent the *"Robust Fixed Point Transformation (RFPT)"*-based technique [*Tar, 2010*] was suggested, that – at the cost of sacrificing the need for global stability - applied iteratively deformed control signal sequences that, on the basis of *Banach's Fixed Point Theorem*, converged to the appropriate control signal only within a bounded basin of attraction. This method was found to be *applicable for a wide class of systems to be controlled*, it was robust against the unknown external disturbances. Various tuning methods were suggested for keeping the control signal in the basin of attraction of the fixed point [*Tar, 2010*], later its global properties were investigated in [*Tar et al., 2011*], [*Várkonyi et al., 2012*], [*Kósi et al., 2012/1*] and [*Kósi et al., 2012/2*]. These *investigations resulted in the following conclusion*: for a wide class of physical systems it is always possible to so tune one of the adaptive control parameters, that so called "precursor oscillations" appear when the monotone convergent sequence turns into a non-monotone but still convergent one before turning into bounded chaotic fluctuations. Since it was possible to observe the precursor oscillations with a simple, model-independent observer, it also became possible to maintain the convergence, therefore the lack of guaranteed *global stability was efficiently compensated from the point of view of practical applications*. The RFPT –based control has also been applied in various tasks, for instance in chaos synchronization [*Várkonyi et al., 2010*] and traffic control [*Tar et al., 2012/1*]. As Lyapunov's Direct Method can be applied in the Model Reference Adaptive Control [*Sekaj et al, 2005*], the Robust Fixed Point Transformations can also be used for such purposes [*Tar et. al., 2010/2*]. Further interesting results have been obtained in the control of certain dynamical systems (e.g. [*Tar et al., 2012/2*], [*Tar et al., 2013*]).

The above summarized antecedents and the preliminary results introduced in my *M.Sc. Thesis* [*Dineva, 2013*] provided interesting prospects for further investigations.

III. Research Methodology

The theoretical considerations and their usability are validated by simulation investigations. The great majority of the practical problems results in differential equations that do not have solutions in closed analytical form. Since, in order to build numerical simulations I have applied the INRIA's Scilab programming environment. For obtaining realistic simulations I have also applied the SCILAB's XCOS tool that provides an excellent graphical interface and includes more efficient numerical integrators. Furthermore, a few of the simulations have been carried out by using the package "Julia" with a sequential code using Euler integration method. This dynamic language ensures a very fast evaluation for technical computing. For some investigations I have applied Matlab8 that offers a variety of tools and functions that otherwise are widely used in applied research. The applied scientific methods are ensuring the *precision and thoroughness of the simulation results*.

IV. New Scientific Results and Theses

In this section the *Theses* will be shown and in the sub-sections their detailed description is given.

IV.1. Combination of Classical Model Identification with the RFPT-based Design by the Use of New Tuning Method

Thesis 1: *I have introduced a new method for the combination of the classical model-based adaptive control approaches as the "Modified Adaptive Inverse Dynamics Robot Controller" (MAIDRC) and the "Modified Adaptive Slotine-Li Robot Controller" (MADSLRC) with the Robust Fixed Point Transformation-based design. The proposed new algorithm ensures efficient parameter identification by the use of the modified Gram-Schmidt method. Additionally, I have developed a new, even more simplified strategy that also applies fixed point transformation-based tuning rule in the case of the MAIDRC control design.*

IV.1.1. Detailed explanation of Thesis-1

The key point of this new concept relies on the fact that the original initial equations of motion can be so rearranged, that instead serving the need of creation a quadratic Lyapunov function, direct information can be obtained on a "fragment" of the actual model parameter estimation error. On the basis of a simple geometric interpretation this information can be directly used for parameter tuning. The modified Gram-Schmidt algorithm is proposed in the parameter tuning process on the matrix of the kinematically known dynamic system parameters that yields more efficient tuning and in general requires less number of arbitrary control parameters. This step greatly simplifies the calculations. In contrast to the traditional solutions that normally guarantee global (asymptotic) stability by using Lyapunov functions, the adaptive controllers designed by the use of “Robust Fixed Point Transformations (RFPT)” are only locally stable, cannot learn the system’s analytical model parameters but they are very robust to modeling deficiencies (for instance, abandoned friction effects) and unknown external forces. Utilizing the fact that the mathematical form of the new rearrangement also allows the use of the RFPT-based iterative feedback terms, I have shown that the learning ability of the original controllers can be efficiently combined with the robustness of the RFPT-based feedback in the lack of unknown external disturbances. I have also shown that though the unknown external disturbances corrupt the parameter tuning in this combined solution, the RFPT-based feedback efficiently can compensate the effects of temporal external perturbations of short duration. Furthermore, I have designed a new fixed point transformation-based parameter identification strategy for the Modified Adaptive Inverse Dynamics Robot Controller. The proposed new algorithm is far simpler and has lower computational need. I have illustrated these effects via numerical simulations.

Selected publications linked to the Thesis 1

[T1-1] Dineva, A., Várkonyi-Kóczy, A. Tar, J.K.: "**Combination of RFPT-based Adaptive Control and Classical Model Identification**", In Proc. of the IEEE 12th Int. Symp. on Applied Machine Intelligence and Informatics (SAMI 2014), 2014, Herlány, Slovakia, 2014, pp. 35-40, **2014**

[T1-2] Tar, J.K., Rudas, I., Dineva, A. and Várkonyi-Kóczy A.: "**Stabilization of a Modified Slotine-Li Adaptive Robot Controller by Robust Fixed Point Transformations**", In Proc. of Recent Advances in Intelligent Control, Modeling and Simulation, 2014, Cambridge, MA, USA, 2014, pp. 35-40, **2014**

[T1-3] Tar, J.K., Bitó, J., Várkonyi-Kóczy, A. and Dineva, A.: "**Symbiosys of RFPT-Based Adaptivity and the Modified Adaptive Inverse Dynamics Controller**", In: Advances in Soft Computing, Intelligent Robotics and Control (Eds. J. Fodor and R. Fullér), Springer Heidelberg, London, New York, 2014, pp. 95-106, **2014**

[T1-4] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Application of Fixed Point Transformation to Classical Model Identification using New Tuning Rule**", Accepted for publication for the 15th IEEE International Symposium on Applied Machine Intelligence and Informatics (SAMI), to be held in Herlány, Slovakia, between 26-28 January, **2017**

IV.2. New Generation of Fixed Point Transformation for Adaptive Control

Thesis 2: *I have introduced a new family of fixed point transformations that can be generated from sigmoid functions in similar manner as certain fuzzy aggregation, t-norm, and s-norm operators are produced by the use of appropriate generator functions. I have shown that by the use of this generation technique a pair of repulsive and attractive fixed points can be generated as in the case of the originally used RFPT. This new construction can be used for the adaptive control of SISO systems and also allows tuning only one of the control parameters*.

Thesis 2.1.: *I have given an extension and its proof of the 'Sigmoid Generated Fixed Point Transformation' to MIMO systems. I have shown that: the only parameter of the controller A that must be set according to the dynamic properties of the system under control within a wide range can provide acceptable solution. The increase in its absolute value from a small initial one considerably can improve the tracking precision. However, the increase in this parameter quickly leads to oscillations in the iterative adaptive control*.

Thesis 2.2.: *In the present statement I have given further improvements in order to enhance the precision of the suggested adaptive control scheme by replacing the parameter tuning with simple calculation. The proposed estimation and its digital realization is considerably simpler than the previously used.*

IV.2.1. Detailed explanation of Thesis-2

The previous investigations belong to a special fixed point transformation the so-called RFPT, which raised the question whether it is possible to construct other type of fixed point transformations for adaptive control. In *Thesis 2* a novel family of fixed point transformations were suggested that can be generated from sigmoid functions in similar manner as certain fuzzy aggregation, t-norm, and s-norm operators are produced by the use of appropriate generator functions. Additionally, in signal aggregation a similar technique can be used in which the monotonicity of the generator function is of crucial significance. I have shown that by the use of this generation technique a pair of repulsive and attractive fixed points can be generated as in the case of the originally used RFPT transformations, so the new construction can be used for the adaptive control of SISO systems as the original one, i.e. it also allows tuning of one of the control parameters by producing the phenomenon of "precursor oscillations" that can be observed by model-independent observers. As an application paradigm the adaptive control of a strongly nonlinear system, a FitzHugh-Nagumo neuron model was considered. Though this system has two DoF, by abandoning the control of one of the state variables it behaves as a SISO system in which the controlled quantity is in dynamic coupling with some internal subsystem.

In *Sub-thesis IV.2.1*. I have given its extension to MIMO systems. The application has been confirmed by simulation investigations of the adaptive control for a partly passively driven Classical Mechanical system.

With only the correct setting of the one adaptive parameter *A*, which can vary in a wide range, excellent performance of the SGFPT-based controller can be achieved. It has considerable advantages in comparison with the original RFPT transformation in which three adaptive parameters are required to precisely set. However, as it theoretically was expected some increase in the absolute value of parameter *A* was also found to improve the precision, but the presence of strong fluctuations in the control signal strongly limited the performance. In *Sub-thesis IV.2.2.* I have introduced further improvements in order to enhance the precision of the suggested adaptive control scheme by replacing the parameter tuning with simple calculation.

Selected publications linked to the Thesis 2

[T2-1] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A.: "**Novel Generation of Fixed Point Transformation for the Adaptive Control of a Nonlinear Neuron Model**", In Proc. of the IEEE International Conference on System, Man, and Cybernetics (SMC2015), 2015, 9-12 October, HongKong, China, pp. 987-992, **2015**

[T2-2] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Generalization of a Sigmoid Generated Fixed Point Transformation from SISO to MIMO Systems**", In Proc. of the IEEE 19th International Conference on Intelligent Engineering Systems (INES2015), September 3-5, 2015, Bratislava, Slovakia, pp. 135-140, **2015**

[T2-3] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Replacement of Parameter Tuning with Simple Calculation in Adaptive Control Using "Sigmoid Generated Fixed Point Transformation**", In Proc. of the IEEE International Symposium on Intelligent Systems and Informatics, Subotica, Serbia, 2015.09.17-2015.09.19., pp. 173-178, **2015**

[T2-4] Dineva, A., Várkonyi-Kóczy, A., Tar, J.K. and Piuri, V.: "**Intelligent Neural Network Design for Nonlinear Control using Simultaneous Perturbation Stochastic Approximation**

(SPSA) Optimization", JAPANESE JOURNAL OF APPLIED PHYSICS (JJAP) CP, 4, doi: 10.7567/jjapcp.4.011612, pp. 011612-1 - 011612-6, **2016**

IV.3. Advances in the Sigmoid Generated Fixed Point Transformation

Thesis 3: *In this Thesis I have introduced the new Stretched Sigmoid function for the SGFPT-based control design. In this improved technique the sigmoid is stretched instead of simple shifting. The main advantage is that it allows excellent positioning in the vicinity of the solution of the control task. The new design has been introduced by the combination of optimal controllers and adaptive controllers that allows overcoming the difficulties of controlling underactuated mechanical systems.*

Thesis 3.1.: *I have introduced a new function of this family. The applicability and effectiveness of the proposed control method using this novel type of function have been confirmed by the adaptive control of the inverted pendulum with vertical vibration of the pivot.*

Thesis 3.2.: *I have shown that the Improved SGFPT type control design can be supported by Soft Computing techniques. The approximations of trigonometric functions of the dynamic model has been realized with fuzzy rules. I have proofed via comparative simulation investigations of an "affine" and a "soft computing-based" model that this new construction is able to deal with imprecisions, uncertainties, etc. by an efficient and robust way.*

IV.3.1. Detailed explanation of Thesis 3

The results provided in *Thesis 2*. indicated the further investigations on the class of applicable functions. I have found by introducing a new transformation generation technique using "Stretched Sigmoid Functions" the limitations of this design can be avoided.
The available model of the system under control normally is complicated and can be obtained at the costs of huge efforts. However, when the characteristics of the system under control nonlinearly vary over a broad range of various conditions, the use of progressive and adaptive control approaches may be especially beneficial. Typical examples of application area are underactuated mechanical systems where it is impossible to drive them on an arbitrary trajectory along by simultaneously precisely ensuring each state variables position in time. In order to distribute the tracking error between the state variables, a possible solution is minimizing a cost function that is constructed as a sum of the errors. Due to a complicated mathematical framework of Lyapunov's Direct method it is far difficult to combine it with the optimal controllers. I have introduced the above improvements for the the realization of the "Adaptive Optimal Control" design for an underactuated Classical Mechanical system. The cost functional-based techniques were replaced by the resolution of the contradictions regarding the prescriptions for the tracking precision of the various state-variables of underactuated systems by time-sharing on a rotary basis. In *Sub-thesis IV.3.1*. I have shown, that this new design can be further improved by introducing a new type of function for the adaptive deformation.

In *Sub-thesis IV.3.2.* I have introduced a possible way for the combination of fuzzy modeling and the SGFPT control by using fuzzy approximation of the trigonometric terms in the approximate dynamic model. The applicability of this approach has been confirmed by the adaptive control of the inverted pendulum.

Selected publications linked to the Thesis 3

[T3-1] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Adaptive Control of Underactuated Mechanical Systems using Improved Sigmoid Generated Fixed Point Transformation and Scheduling Strategy**", In Proc. of the IEEE 14th International Symposium on Applied Machine Intelligence and Informatics, (SAMI 2016), pp. 193-197, **2016**

[T3-2] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Sigmoid Generated Fixed Point Transformation Control Scheme for Stabilization of Kapitza's Pendulum System**",In Proc. of the IEEE 20th Jubilee International Conference on Intelligent Engineering Systems: INES 2016, 2016.06.30-07.02., Budapest, Hungary, pp. 213-218, **2016**

[T3-3] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Adaptive Controller using Fuzzy Modeling and Sigmoid Generated Fixed Point Transformation**", In Proc. of the IEEE 8th International Conference on Intelligent Systems, (IS'16), Sofia, Bulgaria, 04.09.-07.09, 2016, pp. 522-527, **2016**

IV.4. Improved Denoising in the Wavelet Transform Domain

Thesis 4: *I have introduced a new method that relies on the combination of anytime and other soft computing techniques for thresholding the coefficients in the wavelet transform domain. The proposed method combines the main advantages of multiresolution analysis and robust fitting. The anytime supervisory system supports the automatic wavelet shrinkage procedure. The wavelet function and the level of decomposition that are the most suitable in the given scenario and the parameters of the fitting are determined online by the fuzzy supervisory expert. The system applies orthogonal wavelet functions in order to significantly reduce the processing time of reconstruction.*

IV.4.1. Detailed explanation of Thesis 4

The other important issue includes the maintenance of unwanted sensor noises, which are mainly introduced by feedback into the system under control. In the development of a control system the signals of noisy measurements has to be addressed first so that more sophisticated signal pre-processing methods are required. Most of the applications of adaptive signal processing and data representation, etc., require the development of highly efficient data processing techniques. The classical approaches, such as linear filtering, can smooth the corrupted signal, but with weak feature localization and incomplete noise suppression. These are especially important in applications that require online responses. Nonlinear filters have been proposed to overcome these limitations. Among the fundamental methods of signal processing, transform domain techniques for e.g. wavelet-based noise reduction, has been successfully applied to filter data. This technique is so advantageous due to providing information at a level of detail that is not available with the Fourier method. In Thesis *4* I have focused on the well-adapted signal processing techniques that require less assumption about the properties of the signal while simultaneously ensuring high performance and robustness to outliers. I have shown that by using the advantages of the robust fitting and discrete wavelet transform, a new improved denoising method can be obtained. Additionally, an anytime supervisory system supports its operation and provides fast response time, thus on the cost of accuracy overall performance can be maintained.

Selected publications linked to the Thesis 4

[T4-1] Dineva, A., Várkonyi-Kóczy, A., Tar, J.K.: "**Wavelet-based Technique for Feedback Control of Uncertain Systems – A Case Study**", In Proc. of the IEEE 14th International Symposium on Computational Intelligence and Informatics,(CINTI 2013), Budapest, Hungary, 2013.11.19-2013.11.21, 2013, pp. 281-285, **2013**

[T4-2] Dineva, A., Várkonyi-Kóczy, A., Tar, J.K.: "**Compactly Supported Wavelet Based Multiresolution PID Controller**", In Proc. of the 12th Int. Conf. on Global Research and Education in Intelligent Systems, Inter-academia’2013, Sofia, Bulgaria, 2013.09.23-2013.09.27., pp. 281-285, **2013**

[T4-3] Dineva, A., Várkonyi-Kóczy, A., Tar, J.K.: "**Fuzzy Expert System for Automatic Wavelet Shrinkage Procedure Selection for Noise Suppression**", In Proc. of the 18th International Conference on Intelligent Engineering Systems

(INES 2014), 2014.07.03-2014.07.05., Tihany, Hungary, pp.163-168, **2014**

[T4-4] Dineva, A., Várkonyi-Kóczy, A., Tar, J.K.: "**Improved Denoising with Robust Fitting in the Wavelet Transform Domain**", L. M. Camarinha-Matos and T. A. Baldissera and G. Di-Orio G and F. Marques (Eds.), IFIP Advances in Information and Communication Technology; Technological Innovation for Cloud-Based Engineering System 450, Cham: Springer, pp. 179-187, **2015**

[T4-5] Dineva, A., Várkonyi-Kóczy, A., Tar, J.K.: "**Anytime Fuzzy Supervisory System for Signal Auto-Healing**", ADVANCED MATERIALS RESEARCH, 1117, Trans Tech Publications, Switzerland, doi:10.4028/www.scientific.net/AMR.1117.269, pp. 269-272, **2015**

IV.5. Adaptive Multi-round Smoothing based on the Savitzky-Golay Filter

Thesis 5: *I have developed a new adaptive smoothing strategy based on the Savitzky-Golay filtering technique. The proposed method allows to evade the main difficulties of the original SG filter by automatically setting the smoothing parameters. Furthermore, for the precise reconstruction of the signal a multi-round correction has been applied using the linear approximation of the signal. For the reconstruction of the peaks and valleys that may contain the important information, a new weighting function has been introduced.*

IV.5.1. Detailed explanation of Thesis 5

An important premise of the classical Savitzky-Golay (SG) smoothing and differentiating filter is that the signal should be slowly-varying. The Savitzky-Golay method was originally developed to make discernible the relative widths and heights of spectral lines. It smooths equally the noise and the signal components, as it leads to bias and reduction in resolution. In *Thesis 5* I have designed a new adaptive strategy based on the SG-filtering technique. The proposed method automatically selects the polynomial order and windowlength according to the signal form, thus signals with high rate of change are also can be smoothed correctly. For precise smoothing the algorithm applies linear approximation of the signal. The optimal resolution of the signal is based on the local extrema points. The method iteratively performs the adaptive smoothing and correction, hence the shape of also fast-varying signals can be precisely detected. Since, the important details of the signal can be preserved besides full elimination of the contaminating components independent of the character of noise process. In order to support highly precise linear approximation, I have introduced a new parametric weighting function. Further, such a decomposition of the signal with linear approximation allows convenient data compression.

Selected publications linked to the Thesis 5

[T5-1] Dombi, József, Dineva, Adrienn: "**Adaptive Multi-round Smoothing based on the Savitzky- Golay Filter** ", accepted for publication in: Advances in Intelligent Systems and Computing, Springer (ISSN 2194-5357), **2016**

[T5-2] Dombi, József, Dineva, Adrienn: "**Adaptive Savitzky-Golay Filtering and Its Applications**", In Press: INTERNATIONAL JOURNAL OF ADVANCED INTELLIGENCE PARADIGMS (IJAIP), ISSN: 1755-0386, Inderscience Publishers, Switzerland, **2017**

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[A. 2] Dineva, A., Várkonyi-Kóczy, A., Piuri, V. and Tar, J.K.: "**Point Cloud Processing with the Combination of Fuzzy Information Measure and Wavelets**", accepted for publication in: Advances in Intelligent Systems and Computing, Springer Verlag, **2016**

[A. 3] Dineva, A., Tar, J.K., Várkonyi-Kóczy, A. and Piuri, V.: "**Adaptive Controller Using Fixed Point Transformation for Regulating Propofol Administration Through Wavelet-based Anesthetic Value**" In Proc. of the IEEE International Symposium on Medical Measurements and Applications, (MeMeA 2016), 05.15-05.18, Benevento, Italy, pp. 650-655, **2016**

[A. 4] Dineva, A., Nagy, I.: "**Adaptiv Wavelet-alapú Zajcsökkentö Eljárás Mobilrobot Távérzékelési Adatfeldolgozó Rendszerében**", MÜSZAKI TUDOMÁNYOS KÖZLEMÉNYEK 5:(5), pp. 129-132, **2016**

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