Evolutionary Approach with Multiple Quality Criteria for Controller Design

Jacek Szczypta[1], Andrzej Przybył[1], and Lipo Wang[2]

[1] Częstochowa University of Technology,
Institute of Computational Intelligence, Poland
{jacek.szczypta,andrzej.przybyl}@iisi.pcz.pl
[2] Nanyang Technological University,
School of Electrical & Electronic Engineering, Singapore
elpwang@ntu.edu.sg

Abstract. In the paper we propose a new approach to control system design. The approach is characterized by automated parameters tuning and structure selection of the controller. Structure selection and parameter tuning are performed using evolutionary algorithm and allow accurate control with elimination or minimizing of unfavourable phenomena like overshoot or harmonic distortion. Our method was tested on a model of quarter car active suspension system.

1 Introduction

Automatic control is an important issue from scientific and practical point of view (see e.g. [62]-[63]). In the literature, various approaches to design of parameters and the structure of control systems are considered. More of them are in one of the following groups: **(a) Controllers based on the combination of linear correction terms: P, I, D**. These terms can be coupled as e.g.: PI, PID, PI in cascade, PI with feed-forward (see e.g. [1], [38]), PI or PID with additional low-pass filter (see e.g. [38]), PID with anti-windup and compensation mechanism (see e.g. [47]). In this group controllers based on state-feedback, in which the current state vector (estimated or measured) of the controlled object is used for proportional control (see e.g. [59]), are also included. It is important to remark that the task of controller structure design (i.e. selection of the best configuration of linear correction terms) requires from designer comprehensive knowledge supported by the experience. It should be noted that design of controller structure and tuning of parameters are very time-consuming. **(b) Controllers based on computational intelligence**. In this group, controller structure is not strictly defined. Controller uses neural networks (see e.g. [7]-[10], [27]-[31], [41]-[42], [60]), fuzzy systems (see e.g. [2]-[6], [18]-[21], [25], [32], [40], [57]-[58]), neuro-fuzzy systems (see e.g. [11]-[16], [33], [36]-[37], [52]-[55], [64]-[68]), etc. **(c) Hybrid controllers**. In this group, controller combines approaches from other groups. In hybrid controller we can distinguish correction term and additional supporting mechanism (for example based on an artificial intelligence) for adaptive control (see e.g. [17], [44]-[46], [55]-[56]).

L. Rutkowski et al. (Eds.): ICAISC 2014, Part I, LNAI 8467, pp. 455–467, 2014.

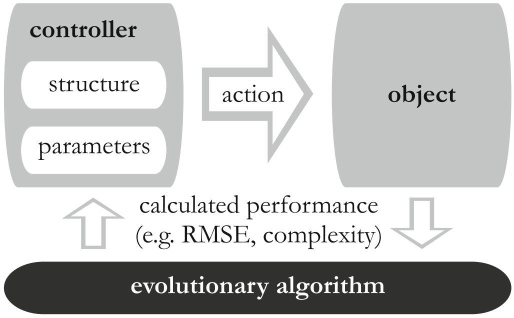

Fig. 1. Idea of the new method for controller design

In this paper a new method for designing control system based on combination of linear correction terms is proposed. Our method is characterized by automation of both operations: structure selection and parameter tuning (see Fig. 1). Concurrent parameter tuning and structure selection is important, because it eliminates mentioned earlier control design problems. Our method also offers strictly, but very flexibly, defined control criteria as a tool for control system tuning, what allows to reach objective expected by its designer.

This paper is organised into four sections. Section 2 presents a detailed description of the new method for controller design. In Section 3 simulation results are presented. Conclusions are drawn in Section 4.

2 Description of the New Method for Designing Optimal Controllers

Presented method gives to designer the freedom of choice of controller blocks (CB) number, connection and definition. In Fig. 2 initial controller structure idea is presented: in Fig. 2.a CB connection idea for the MISO system is presented, in Fig. 2.b CB processing element idea is presented. Dashed lines in Fig. 2.a and in Fig. 2.b denote freedom of connection between CBs and simple correction terms. Existence or lack of connection depends on evolutionary algorithm execution result. Signal fb_n, n=1, ..., N, denotes feedback signal, signal ff_m, m = 1, ..., M, denotes feedforward signal. CB connection idea (see Fig. 2.a) is a result of generalisation of PID controller, cascaded PID controller with feedforward signals and state-feedback controller. CB definition idea (see Fig. 2.b) is combination of simple correction terms like P, I and D. There is a possibility to place inside CB other processing elements like finite impulse response filter, infinite response filter, saturation or nonlinear block. Generalised controller structure (CB connection and definition) is initial point of evolutionary algorithm.

In proposed method full controller (with its structure and parameters) is encoded in a single chromosome $\mathbf{X}_{ch}$. Chromosome $\mathbf{X}_{ch}$ is described as follows:

$$\mathbf{X}_{ch} = \left\{ \mathbf{X}_{ch}^{\mathrm{par}}, \mathbf{X}_{ch}^{\mathrm{red}} \right\}, \tag{1}$$

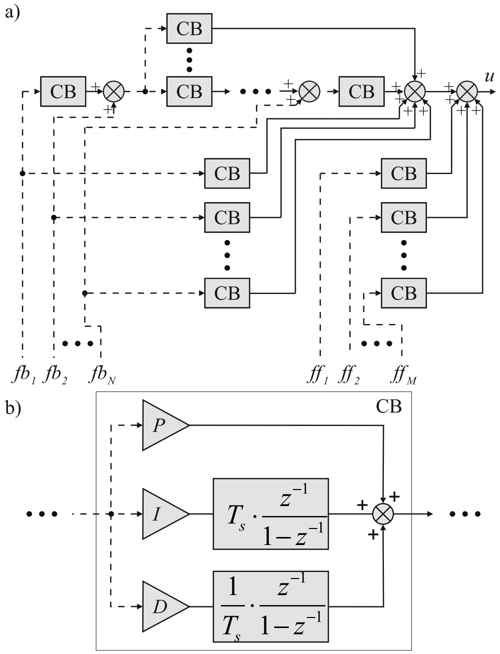

Fig. 2. Initial controller structure idea: a)CB connection idea, b)CB definition idea

where $\mathbf{X}_{ch}^{\mathrm{par}}$ is a chromosome encoding correction term parameters, $\mathbf{X}_{ch}^{\mathrm{red}}$ is a chromosome encoding CB connection. Chromosome $\mathbf{X}_{ch}^{\mathrm{par}}$ is described as follows:

$$\mathbf{X}_{ch}^{\mathrm{par}} = (P_1, I_1, D_1, P_2, I_2, D_2, \ldots) = \left(X_{ch,1}^{\mathrm{par}}, X_{ch,2}^{\mathrm{par}}, \ldots, X_{ch,L}^{\mathrm{par}}\right), \tag{2}$$

where P_1, I_1, D_1, $\ldots$, denote control system parameter values, $ch = 1,..,Ch$, denotes index of the chromosome in the population, Ch denotes a number of chromosomes in the population, L denotes length of the chromosome $\mathbf{X}_{ch}^{\mathrm{par}}$. Chromosome $\mathbf{X}_{ch}^{\mathrm{red}}$ is described as follows:

$$\mathbf{X}_{ch}^{\mathrm{red}} = \left(X_{ch,1}^{\mathrm{red}}, X_{ch,2}^{\mathrm{red}}, \ldots, X_{ch,L}^{\mathrm{red}}\right), \tag{3}$$

where every gene $X_{ch,g}^{\mathrm{red}} \in \{0,1\}$, $ch = 1,..,Ch$, $g = 1,..,L$, decides if relevant part of control system occurs in control process (relevant gene $X_{ch,g}^{\mathrm{red}} = 1$).

The steps of the method used in this paper are the same as in typical evolutionary algorithm (see e.g. [12], [22]-[24], [26], [34]-[35], [39], [43], [48]). The evolutionary algorithm is a method of solving problems (mainly optimisation problems) which is based on natural evolution. Evolutionary algorithms are search procedures based on the natural selection and inheritance mechanisms. Method steps are following: chromosomes initialisation, chromosomes evaluation,

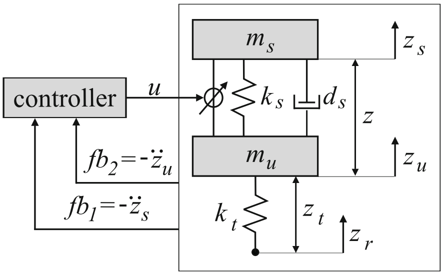

Fig. 3. Active suspension control system

stop condition checking, chromosomes selection, chromosomes crossover, mutation and repair, offspring population generation. For more details see our previous papers, e.g. [61].

3 Simulations Results

In the simulations a model of controller design for quarter car active suspension control system was considered (see e.g. [33], [59]). Alternative approaches to nonlinear modelling can be found in [49]-[51]. Active suspension control system is presented in Fig. 3. Assumed values of the parameters of the model are presented in Table 1. Parameters of active suspension model are following: m_u denotes unsprung mass, m_s denotes sprung mass, k_t denotes tire stiffness, k_s denotes sprung stiffness, d_s denotes sprung damping. Meaning of the rest of the active suspension model parameters is following: z_r denotes road profile, z_t denotes tire compression, z_u denotes displacement of unsprung mass, z denotes suspension travel, z_s denotes displacement of sprung mass. Aim of the controller is to improve the passenger comfort and car handling, etc. We assume that improvement of ride comfort is more important that handling improvement.

In order to create model and perform simulations, following assumptions were taken:

– Controlled object is modelled as follows:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{f}, \tag{4}$$

where $\mathbf{A}$ is a state matrix in the form:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_s}{m_s} & -\frac{d_s}{m_s} & \frac{k_s}{m_s} & \frac{d_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \frac{k_s}{m_u} & \frac{d_s}{m_s} & -\frac{k_s+k_t}{m_u} & -\frac{d_s}{m_s} \end{bmatrix}, \tag{5}$$

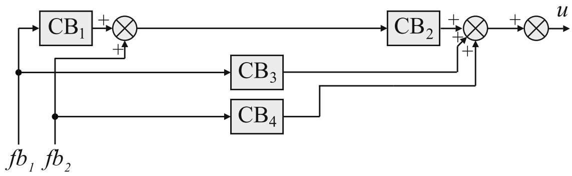

Fig. 4. Initial controller structure for active suspension controller

$\mathbf{x}$ is a state vector (initial values of state vector were set to zero) described as follows:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} z_s \\ \dot{z}_s \\ z_u \\ \dot{z}_u \end{bmatrix}, \tag{6}$$

$\mathbf{B}$ is an input matrix represented by the formula:

$$\mathbf{B} = \left[0 \ \tfrac{1}{m_s} \ 0 \ -\tfrac{1}{m_u}\right]^{\mathrm{T}}, \tag{7}$$

$\mathbf{u}$ is an input vector from controller, $\mathbf{f}$ is an input vector from kinematic extortion described by the following equation:

$$\mathbf{f} = \left[0 \ 0 \ 0 \ -\tfrac{k_t}{m_u}\right]^{\mathrm{T}} z_r. \tag{8}$$

– The road profile is presented in Fig. 6.a. It represents the typical situations which may occur on the road.

Table 1. Parameters of active suspension control system

name	value	unit
m_u	48.3	kg
m_s	395.3	kg
k_s	30 010	N/m
k_t	340 000	N/m
d_s	1450	Ns/m

– Controlled object was discretized with the first order equation with time step $T = 0.1$ ms as follows: $\mathbf{x}(i+1) = \mathbf{A}_d \cdot \mathbf{x}(i) + \mathbf{B}_d \cdot \mathbf{u}(i) + \mathbf{f}_d$, where $\mathbf{A}_d = \mathbf{I} + \mathbf{A} \cdot T$, $\mathbf{B}_d = \mathbf{B} \cdot T$ and $\mathbf{f}_d = \mathbf{f} \cdot T$.
– Initial controller structure, directly derived from the structure shown in Fig. 2 on the basis on available feedback signals, is shown in Fig. 4 and equipped with four CBs. Every CB is equipped with P, I, D processing elements.
– Feedback signals: fb_1 and fb_2 were set to -$\ddot{z}_s$ and -$\ddot{z}_u$ respectively.

- Search range for controller parameter encoding gene in every control block was experimentally set as follows: for term P: [0, 2000], for term I: [0, 200000], for term D: [0, 20].
- In order to model actuator constrains, output signal of the controller u was limited to the range $[-1000, +1000]$ (see e.g. [59]).
- In order to model sensor constrains, quantisation resolution for the output signal u and feedback signals (fb_1, fb_2) was set to 0.0001.
- Simulation length T was set to 8 seconds. Simulation time step T_s was set to 0.1ms, while interval between subsequent controller activations was set to five simulation steps ($T_r = 5T = 0.5$ ms). This is reasonable value for the implementation of the controller in real microprocessor system.

In order to design controller, following assumptions were taken:

- Fitness function was defined with elements improving operating conditions of genetic algorithm (i.e. accelerating the search of the optimal solution). Those elements are: reference to passive suspension system performance, unification by adding 1 and respectively multiplying by 1000. Fitness function was defined as follows:

$$\mathrm{ff}(\mathbf{X}_{ch}) = \begin{pmatrix} cf_{ch} \cdot w_{cf} + hd_{ch} \cdot w_{hd} + st_{ch} \cdot w_{st} + \\ +cp_{ch} \cdot w_{cp} + os_{ch} \cdot w_{os} + cn_{ch} \cdot w_{cn} \end{pmatrix}, \tag{9}$$

  where

  - cf_{ch} denotes passenger comfort and was defined as follows:

$$cf_{ch} = (1 + cf_p) - \sqrt{\frac{1}{Z} \cdot \sum_{i=1}^{Z} \ddot{z}_{s,i}^2}, \tag{10}$$

    where cf_p denotes, found by experiment, passenger comfort for passive suspension value equal 0.861 (see Table 3), $i = 1, \ldots, Z$, denotes sample index, Z denotes the number of samples and was defined as follows:

$$Z = \frac{T}{T_s}. \tag{11}$$

  - w_{cf} denotes weight of cf_{ch} and was set to 5.
  - hd_{ch} denotes car handling and was defined as follows:

$$hd_{ch} = (1 + hd_p) - \sqrt{\frac{1}{Z} \cdot \sum_{i=1}^{Z} z_{t,i}^2}, \tag{12}$$

    where hd_p denotes, found by experiment, car handling for passive suspension value equal 1.09 (see Table 3).
  - w_{hd} denotes weight of hd_{ch} and was set to 1.

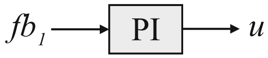

Fig. 5. Evolutionary designed controller structure for active suspension system

- st_{ch} denotes suspension travel and was defined as follows:

$$st_{ch} = \left((1 + st_p) - 1000 \cdot \max_{z=1,\ldots,Z} \{\text{abs}\,(z_i)\} \right), \tag{13}$$

  where st_p denotes, found by experiment, passive system suspension travel value equal 50.9 (see Table 3).
- w_{st} denotes weight of st_{ch} and was set to 0.01.
- cp_{ch} denotes controller structure complexity and was defined as follows:

$$cp_{ch} = \sum_{g=1}^{L} \mathbf{X}_{ch,g}^{\text{red}}. \tag{14}$$

- w_{cp} denotes weight of cp_{ch} and was set to 0.5.
- os_{ch} denotes oscillation of controller output signal and was defined as follows:

$$os_{ch} = \frac{1}{1 + \sum\limits_{i=1}^{Z} \begin{cases} 1 & \text{for}\,\Delta u_i > 200 \\ 0 & \text{otherwise} \end{cases}}, \tag{15}$$

  where $\Delta u_i = \text{abs}\,(u\,(i) - u\,(i-1))$.
- w_{os} denotes weight of os_{ch} and was set to 0.01.
- cn_{ch} denotes average control force and was defined as follows:

$$cn_{ch} = \frac{1}{1 + \sqrt{\frac{1}{Z} \cdot \sum\limits_{i=1}^{Z} {u_i}^2}}. \tag{16}$$

- w_{cn} denotes weight of cn_{ch} and was set to 0.1.

– Evolutionary algorithm parameters were set as follows: (a) the number of chromosomes in the population was set to 20, (b) the algorithm performs 10 000 steps (generations), (c) the crossover probability was set as $p_c = 0.8$, (d) the mutation probability was set as $p_m = 0.3$, (e) the mutation intensity was set as $\sigma = 0.3$.

Simulation results can be summarised as follows: **(a)** Goal of significant passenger comfort improvement and slight car handling improvement was achieved (see Table 3). **(b)** Proposed method has automatically selected controller structure for control of quarter car active suspension system (see Fig. 5 and Table 2). **(c)** In simulation two operation modes of suspension system were tested: active and passive (see Fig. 6).

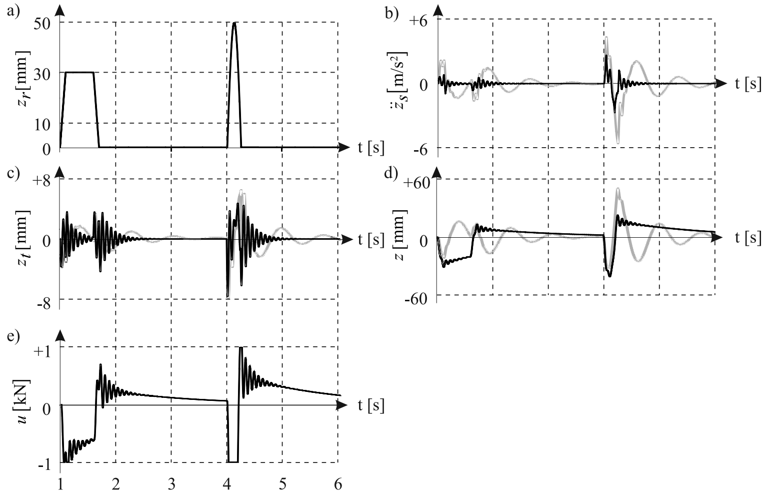

Fig. 6. Simulation results: a) road profile, b) passenger comfort, c) car handling, d) suspension travel, e) actuator force. In b)-d) grey line relates to the passive system and the black line relates to the active system.

Table 2. Parameters of evolutionary designed controller structure

	K_P	K_I	K_D
CB_1	reduced	reduced	reduced
CB_2	reduced	reduced	reduced
CB_3	343	45743	reduced
CB_4	reduced	reduced	reduced

Table 3. Result comparison of evolutionary designed controller structure

name	ff	cf [m/s^2]	hd [mm]	st [mm]
passive	6.619	0.861	1.09	50.9
evolutionary	9.373	0.273	0.94	41.7

4 Summary

In this paper a new approach to designing controller based on linear correction terms was proposed. During simulation it was possible to select controller structure and tune its parameters including diverse control criteria. Results presented in the paper show that initial controller structure was significantly reduced - by 83% (see Table 2). Proposed method for controller design includes not only control accuracy, but also other control related criteria, e.g. harmonic distortion or overshoot.

Acknowledgement. The project was financed by the National Science Centre (Poland) on the basis of the decision number DEC-2012/05/B/ST7/02138.

References

1. Boiko, I.: Variable-structure PID controller for level process. Control Engineering Practice 21(5), 700–707 (2013)
2. Bartczuk, Ł., Dziwiński, P., Starczewski, J.T.: A new method for dealing with unbalanced linguistic term set. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2012, Part I. LNCS, vol. 7267, pp. 207–212. Springer, Heidelberg (2012)
3. Bartczuk, Ł., Dziwiński, P., Starczewski, J.T.: New Method for Generation Type-2 Fuzzy Partition for FDT. In: Rutkowski, L., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2010, Part I. LNCS (LNAI), vol. 6113, pp. 275–280. Springer, Heidelberg (2010)
4. Bartczuk, Ł., Przybył, A., Dziwiński, P.: Hybrid state variables - fuzzy logic modelling of nonlinear objects. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part I. LNCS, vol. 7894, pp. 227–234. Springer, Heidelberg (2013)
5. Bartczuk, Ł., Rutkowska, D.: A New Version of the Fuzzy-ID3 Algorithm. In: Rutkowski, L., Tadeusiewicz, R., Zadeh, L.A., Żurada, J.M. (eds.) ICAISC 2006. LNCS (LNAI), vol. 4029, pp. 1060–1070. Springer, Heidelberg (2006)
6. Bartczuk, Ł., Rutkowska, D.: Medical Diagnosis with Type-2 Fuzzy Decision Trees. In: Kącki, E., Rudnicki, M., Stempczyńska, J. (eds.) Computers in Medical Activity. AISC, vol. 65, pp. 11–21. Springer, Heidelberg (2009)
7. Bilski, J., Rutkowski, L.: Numerically Robust Learning Algorithms for Feed Forward Neural Networks. In: Advances in Soft Computing - Neural Networks and Soft Computing, pp. 149–154. Physica-Verlag, A Springer-Verlag Company (2003)
8. Bilski, J., Smoląg, J.: Parallel Approach to Learning of the Recurrent Jordan Neural Network. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part I. LNCS (LNAI), vol. 7894, pp. 32–40. Springer, Heidelberg (2013)
9. Bilski, J., Smoląg, J.: Parallel Realisation of the Recurrent Elman Neural Network Learning. In: Rutkowski, L., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2010, Part II. LNCS (LNAI), vol. 6114, pp. 19–25. Springer, Heidelberg (2010)
10. Bilski, J., Smoląg, J.: Parallel Realisation of the Recurrent Multi Layer Perceptron Learning. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2012, Part I. LNCS (LNAI), vol. 7267, pp. 12–20. Springer, Heidelberg (2012)
11. Cpalka, K.: A Method for Designing Flexible Neuro-fuzzy Systems. In: Rutkowski, L., Tadeusiewicz, R., Zadeh, L.A., Żurada, J.M. (eds.) ICAISC 2006. LNCS (LNAI), vol. 4029, pp. 212–219. Springer, Heidelberg (2006)
12. Cpałka, K.: On evolutionary designing and learning of flexible neuro-fuzzy structures for nonlinear classification. Nonlinear Analysis Series A: Theory, Methods and Applications 71, 1659–1672 (2009)
13. Cpałka, K., Łapa, K., Przybył, A., Zalasiński, M.: A new method for designing neuro-fuzzy systems for nonlinear modelling with interpretability aspects. Neurocomputing (in print, 2014), `http://dx.doi.org/10.1016/j.neucom.2013.12.031`

14. Cpałka, K., Rutkowski, L.: A New Method for Designing and Reduction of Neuro-fuzzy Systems. In: Proceedings of the 2006 IEEE International Conference on Fuzzy Systems (IEEE World Congress on Computational Intelligence, WCCI 2006), Vancouver, BC, Canada, pp. 8510–8516 (2006)
15. Cpałka, K., Rutkowski, L.: Flexible Takagi-Sugeno Fuzzy Systems. In: Proceedings of the International Joint Conference on Neural Networks 2005, Montreal, pp. 1764–1769 (2005)
16. Cpałka, K., Rutkowski, L.: Flexible Takagi-Sugeno Neuro-fuzzy Structures for Nonlinear Approximation. WSEAS Transactions on Systems 4(9), 1450–1458 (2005)
17. Duana, X.-G., Li, H.-X., Denga, H.: Robustness of fuzzy PID controller due to its inherent saturation. Journal of Process Control 22, 470–476 (2012)
18. Dziwiński, P., Bartczuk, Ł., Starczewski, J.T.: Fully controllable ant colony system for text data clustering. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) SIDE 2012 and EC 2012. LNCS, vol. 7269, pp. 199–205. Springer, Heidelberg (2012)
19. Dziwiński, P., Rutkowska, D.: Algorithm for generating fuzzy rules for WWW document classification. In: Rutkowski, L., Tadeusiewicz, R., Zadeh, L.A., Żurada, J.M. (eds.) ICAISC 2006. LNCS (LNAI), vol. 4029, pp. 1111–1119. Springer, Heidelberg (2006)
20. Dziwiński, P., Rutkowska, D.: Ant focused crawling algorithm. In: Rutkowski, L., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2008. LNCS (LNAI), vol. 5097, pp. 1018–1028. Springer, Heidelberg (2008)
21. Dziwiński, P., Starczewski, J.T., Bartczuk, Ł.: New linguistic hedges in construction of interval type-2 FLS. In: Rutkowski, L., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2010, Part II. LNCS (LNAI), vol. 6114, pp. 445–450. Springer, Heidelberg (2010)
22. El-Abd, M.: On the hybridization on the artificial bee colony and particle swarm optimization algorithms. Journal of Artificial Intelligence and Soft Computing Research 2(2), 147–155 (2012)
23. Fogel, D.B.: Evolutionary Computation: Toward a New Philosophy of Machine Intelligence, 3rd edn. IEEE Press, Piscataway (2006)
24. Gabryel, M., Cpałka, K., Rutkowski, L.: Evolutionary strategies for learning of neuro-fuzzy systems. In: Proceedings of the I Workshop on Genetic Fuzzy Systems, Granada, pp. 119–123 (2005)
25. Gabryel, M., Korytkowski, M., Scherer, R., Rutkowski, L.: Object Detection by Simple Fuzzy Classifiers Generated by Boosting. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part I. LNCS (LNAI), vol. 7894, pp. 540–547. Springer, Heidelberg (2013)
26. Gabryel, M., Woźniak, M., Nowicki, R.K.: Creating Learning Sets for Control Systems Using an Evolutionary Method. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) EC 2012 and SIDE 2012. LNCS, vol. 7269, pp. 206–213. Springer, Heidelberg (2012)
27. Horzyk, A., Tadeusiewicz, R.: Self-Optimizing Neural Networks. In: Yin, F.-L., Wang, J., Guo, C. (eds.) ISNN 2004. LNCS, vol. 3173, pp. 150–155. Springer, Heidelberg (2004)
28. Jelonkiewicz, J., Przybył, A.: Accuracy improvement of neural network state variable estimator in induction motor drive. In: Rutkowski, L., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2008. LNCS (LNAI), vol. 5097, pp. 71–77. Springer, Heidelberg (2008)

29. Korytkowski, M., Rutkowski, L., Scherer, R.: On combining backpropagation with boosting. In: Proceedings of the IEEE International Joint Conference on Neural Network (IJCNN), vols. 1-10, pp. 1274–1277 (2006)
30. Laskowski, Ł.: A novel hybrid-maximum neural network in stereo-matching process. Neural Comput. & Applic. 23, 2435–2450 (2013)
31. Laskowski, Ł.: Objects Auto-selection from Stereo-Images Realised by Self-Correcting Neural Network. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2012, Part I. LNCS, vol. 7267, pp. 119–125. Springer, Heidelberg (2012)
32. Li, J., Li, J., Xia, Z.: Delay-dependent generalized H2 control for discrete T-S fuzzy large-scale stochastic systems with mixed delays. International Journal of Applied Mathematics and Computer Science 21(4) (2011)
33. Lin, J., Lian, R.: Intelligent Control of Active Suspension Systems. IEEE Transactions on Industrial Electronics 58(2), 618–628 (2011)
34. Lobato, F.S., Steffen Jr., V.: A new multi-objective optimization algorithm based on differential evolution and neighborhood exploring evolution strategy. Journal of Artificial Intelligence and Soft Computing Research 1(4), 259–267 (2011)
35. Lobato, F.S., Steffen Jr., V., Silva Neto, A.J.: Solution of singular optimal control problems using the improved differential evolution algorithm. Journal of Artificial Intelligence and Soft Computing Research 1(3), 195–206 (2011)
36. Łapa, K., Przybył, A., Cpałka, K.: A new approach to designing interpretable models of dynamic systems. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part II. LNCS (LNAI), vol. 7895, pp. 523–534. Springer, Heidelberg (2013)
37. Łapa, K., Zalasiński, M., Cpałka, K.: A new method for designing and complexity reduction of neuro-fuzzy systems for nonlinear modelling. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part I. LNCS (LNAI), vol. 7894, pp. 329–344. Springer, Heidelberg (2013)
38. Maggio, M., Bonvini, M., Leva, A.: The PID + p controller structure and its contextual autotuning. Journal of Process Control 22, 1237–1245 (2012)
39. Michalewicz, Z.: Genetic Algorithms + Data Structures = Evolution Programs. Springer (1999)
40. Nowicki, R., Scherer, R., Rutkowski, L.: A method for learning of hierarchical fuzzy systems. In: Sincak, P., Vascak, J., Kvasnicka, V., Pospichal, J. (eds.) Intelligent Technologies - Theory and Applications, pp. 124–129. IOS Press (2002)
41. Patan, K., Patan, M.: Optimal training strategies for locally recurrent neural network. Journal of Artificial Intelligence and Soft Computing Research 1(2) (2011)
42. Pławiak, P., Tadeusiewicz, R.: Approximation of phenol concentration using novel hybrid computational intelligence methods. Applied Mathematics and Computer Science 24(1) (in print, 2014)
43. Prampero, P.S., Attux, R.: Magnetic particle swarm optimization. Journal of Artificial Intelligence and Soft Computing Research 2(1), 59–72 (2012)
44. Przybył, A., Cpałka, K.: A new method to construct of interpretable models of dynamic systems. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2012, Part II. LNCS (LNAI), vol. 7268, pp. 697–705. Springer, Heidelberg (2012)
45. Przybył, A., Jelonkiewicz, J.: Genetic algorithm for observer parameters tuning in sensorless induction motor drive. In: Rutkowski, L., Kacprzyk, J. (eds.) Neural Networks and Soft Computing (6th International Conference on Neural Networks and Soft Computing 2002), Zakopane, Poland, pp. 376–381 (2003)

46. Przybył, A., Smoląg, J., Kimla, P.: Distributed Control System Based on Real Time Ethernet for Computer Numerical Controlled Machine Tool (in Polish). Przeglad Elektrotechniczny 88(2), 342–346 (2010)
47. Ribića, A.I., Mataušek, M.R.: A dead-time compensating PID controller structure and robust tuning. Journal of Process Control 22, 1340–1349 (2012)
48. Rutkowski, L.: Computational Intelligence. Springer (2008)
49. Rutkowski, L.: Multiple Fourier series procedures for extraction of nonlinear regressions from noisy data. IEEE Transactions on Signal Processing 41(10), 3062–3065 (1993)
50. Rutkowski, L.: Nonparametric identification of quasi-stationary systems. Systems and Control Letters 6, 33–35 (1985)
51. Rutkowski, L.: On Bayes risk consistent pattern recognition procedures in a quasi-stationary environment. IEEE Transactions on Pattern Analysis and Machine Intelligence PAMI-4(1), 84–87 (1982)
52. Rutkowski, L., Cpałka, K.: Compromise approach to neuro-fuzzy systems. In: Sincak, P., Vascak, J., Kvasnicka, V., Pospichal, J. (eds.) Intelligent Technologies - Theory and Applications, vol. 76, pp. 85–90. IOS Press (2002)
53. Rutkowski, L., Cpałka, K.: Flexible weighted neuro-fuzzy systems. In: Proceedings of the 9th International Conference on Neural Information Processing (ICONIP 2002), Orchid Country Club, Singapore, CD, November 18-22 (2002)
54. Rutkowski, L., Cpałka, K.: Neuro-fuzzy systems derived from quasi-triangular norms. In: Proceedings of the IEEE International Conference on Fuzzy Systems, Budapest, July 26-29, vol. 2, pp. 1031–1036 (2004)
55. Rutkowski, L., Przybył, A., Cpałka, K.: Novel on-line speed profile generation for industrial machine tool based on flexible neuro-fuzzy approximation. IEEE Transactions on Industrial Electronics 59, 1238–1247 (2012)
56. Rutkowski, L., Przybył, A., Cpałka, K., Er, M.J.: Online Speed Profile Generation for Industrial Machine Tool Based on Neuro-fuzzy Approach. In: Rutkowski, L., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2010, Part II. LNCS (LNAI), vol. 6114, pp. 645–650. Springer, Heidelberg (2010)
57. Scherer, R.: Neuro-fuzzy relational systems for nonlinear approximation and prediction. Nonlinear Analysis Series A: Theory, Methods and Applications 71(12), e1420–e1425 (2009)
58. Scherer, R., Rutkowski, L.: Connectionist fuzzy relational systems. In: Halgamuge, S.K., Wang, L. (eds.) 9th International Conference on Neural Information and Processing; 4th Asia-Pacific Conference on Simulated Evolution and Learning; 1st International Conference on Fuzzy Systems and Knowledge Discovery, Computational Intelligence for Modelling and Prediction Book Series. SCI, vol. 2, pp. 35–47. Springer, Heidelberg (2005)
59. van der Sande, T.P.J., Gysen, B.L.J., Besselink, I.J.M., Paulides, J.J.H., Lomonova, E.A., Nijmeijer, H.: Robust control of an electromagnetic active suspension system: Simulations and measurements. Mechatronics 23(2) (2013)
60. Szaleniec, M., Goclon, J., Witko, M., Tadeusiewicz, R.: Application of artificial neural networks and DFT-based parameters for prediction of reaction kinetics of ethylbenzene dehydrogenase. Journal of Computer-Aided Molecular Design 20(3), 145–157 (2006)
61. Szczypta, J., Przybył, A., Cpałka, K.: Some aspects of evolutionary designing optimal controllers. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part II. LNCS, vol. 7895, pp. 91–100. Springer, Heidelberg (2013)

62. Theodoridis, D.C., Boutalis, Y.S., Christodoulou, M.A.: Robustifying analysis of the direct adaptive control of unknown multivariable nonlinear systems based on a new neuro-fuzzy method. Journal of Artificial Intelligence and Soft Computing Research 1(1), 59–79 (2011)
63. Tran, V.N., Brdys, M.A.: Optimizing control by robustly feasible model predictive control and application to drinking water distribution systems. Journal of Artificial Intelligence and Soft Computing Research 1(1), 43–57 (2011)
64. Zalasiński, M., Cpałka, K.: A new method of on-line signature verification using a flexible fuzzy one-class classifier, pp. 38–53. Academic Publishing House EXIT (2011)
65. Zalasiński, M., Łapa, K., Cpałka, K.: New Algorithm for Evolutionary Selection of the Dynamic Signature Global Features. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part II. LNCS (LNAI), vol. 7895, pp. 113–121. Springer, Heidelberg (2013)
66. Zalasiński, M., Cpałka, K.: New Approach for the On-Line Signature Verification Based on Method of Horizontal Partitioning. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part II. LNCS (LNAI), vol. 7895, pp. 342–350. Springer, Heidelberg (2013)
67. Zalasiński, M., Cpałka, K.: Novel algorithm for the on-line signature verification. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2012, Part II. LNCS (LNAI), vol. 7268, pp. 362–367. Springer, Heidelberg (2012)
68. Zalasiński, M., Cpałka, K.: Novel Algorithm for the On-Line Signature Verification Using Selected Discretization Points Groups. In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds.) ICAISC 2013, Part I. LNCS (LNAI), vol. 7894, pp. 493–502. Springer, Heidelberg (2013)