R.-E. Precup, Applications of metaheuristic algorithms to fuzzy control and model building, learning-based control, and mobile robot navigation, 15th European Symposium on Computational Intelligence and Mathematics ESCIM 2024, Krakow, Poland, 2024.

Applications of metaheuristic algorithms to fuzzy control and model building, learning-based control, and mobile robot navigation

Radu-Emil Precup
Department of Automation and Applied Informatics
Politehnica University of Timisoara
Center for Fundamental and Advanced Technical Research
Romanian Academy-Timisoara Branch
Timisoara, Romania
radu.precup@upt.ro

KEYNOTE SPEECH

***Abstract*—An optimization problem finds the best (i.e., optimal) solution among all feasible solutions. An optimization problem consists of two key components: the objective function and the constraints, which are optional. The objective function evaluates and compares solutions in the context of all feasible solutions by computing the desired quantity to be minimized or maximized. Constraints can be added to limit the possible values for the variables of the objective function and possibly to link these variables.**

The optimization algorithms find the solutions to the optimization problems (i.e., the optimal solutions) by trying variations of the initial solution and using the information gained to improve the solution. This solution finding can also be considered as learning, which is a popular topic nowadays. The complexity of classical algorithms is very high, which requires rather large amount of computation. Therefore, alternative algorithms with lower complexity are appreciated. Metaheuristic algorithms for finding optimal solutions have become very popular because they are much better in terms of efficiency and complexity than classical algorithms.

This presentation highlights some of the results obtained by the Process Control Group of the Politehnica University of Timisoara, Romania. The presentation will focus on representative applications implemented in our labs, with real-time validation against experimental results. The results highlighted here include various laboratory equipment such as pendulum crane systems, multi-tank systems, servo systems, twin rotor aerodynamic systems, magnetic levitation systems, anti-lock braking systems, mobile robots, magnetic levitation systems, active mass damper systems, and shape memory alloy systems.

The scope of development of these metaheuristic algorithms is to solve optimization problems involving tuning of low-cost fuzzy controllers, tuning of fuzzy models, reinforcement-based control in various schemes including adaptive ones, and solving optimization problems specific to mobile robot navigation.

***Keywords*—fuzzy controllers, fuzzy models, lab equipment, metaheuristic algorithms, mobile robots, reinforcement learning.**

SHORT BIO

Radu-Emil Precup is currently with the Politehnica University of Timisoara (UPT), Romania, where he became a Professor in the Department of Automation and Applied Informatics, in 2000, and he is currently a Ph.D. supervisor in automation and systems engineering. Since 2022 he is also a senior researcher (CS I) and the head of the Data Science and Engineering Laboratory of the Center for Fundamental and Advanced Technical Research, Romanian Academy – Timisoara Branch, Romania. From 2016 to 2022, he was an Adjunct Professor within the School of Engineering, Edith Cowan University, Joondalup, WA, Australia. He is currently the director of the Automatic Systems Engineering Research Centre of the UPT. From 1999 to 2009, he held research and teaching positions with the Université de Savoie, Chambéry and Annecy, France, Budapest Tech Polytechnical Institution, Budapest, Hungary, Vienna University of Technology, Vienna, Austria, and Budapest University of Technology and Economics, Budapest, Hungary. He has been an associate editor of IEEE Transactions on Fuzzy Systems (2018-2022), and serves on the editorial boards of several prestigious journals, including IEEE Transactions on Cybernetics, Information Sciences (Elsevier), Engineering Applications of Artificial Intelligence (Elsevier), Applied Soft Computing (Elsevier), Expert Systems with Applications (Elsevier), Evolving Systems (Springer), Applied Artificial Intelligence (Taylor & Francis), Healthcare Analytics (Elsevier), and Communications in Transportation Research (Elsevier).

Prof. Precup is a corresponding member of the Romanian Academy, a Doctor Honoris Causa of the Óbuda University, Budapest, Hungary, and a Doctor Honoris Causa of the Széchenyi István University, Győr, Hungary. He received the Elsevier Scopus Award for Excellence in Global Contribution (2017), was named a 2022 academic data leader by Chief Data Officer (CDO) Magazine, and was listed as one of the top 10 researchers in artificial intelligence and automation (according to IIoT World as of July 2017).

SELECTED REFERENCES

[1] P. Angelov, I. Škrjanc, and S. Blažič, "Robust evolving cloud-based controller for a hydraulic plant," in *Proc. 2013 IEEE Conf. Evolv. Adapt. Syst.*, Singapore, 2013, pp. 1–8.

[2] S. Blažič, I. Škrjanc, and D. Matko, "A robust fuzzy adaptive law for evolving control systems," *Evolv. Syst.*, vol. 5, pp. 3–10, Mar. 2014.

[3] D. Leite, R. M. Palhares, V. C. S. Campos, and F. A. C. Gomide, "Evolving granular fuzzy model-based control of nonlinear dynamic systems," *IEEE Trans. Fuzzy Syst.*, vol. 23, no. 4, pp. 923–938, Aug. 2015.

[4] S. Blažič, "On periodic control laws for mobile robots," *IEEE Trans. Ind. Electron.*, vol. 61, no. 7, pp. 3660–3670, July 2014.

[5] R.-E. Precup, M. L. Tomescu, S. Preitl, E. M. Petriu, J. Fodor, and C. Pozna, "Stability analysis and design of a class of MIMO fuzzy control systems," *J. Intell. Fuzzy Syst.*, vol. 25, no. 1, pp. 145–155, Mar. 2013.

[6] E. Osaba, R. Carballedo, F. Diaz, E. Onieva, A. Masegosa, and A. Perallos, "Good practice proposal for the implementation, presentation, and comparison of metaheuristics for solving routing problems," *Neurocomput.*, vol. 271, pp. 2–8, Jan. 2018.

[7] R. Radiša, N. Dučić, S. Manasijević, N. Marković, and Ž Ćojbašić, "Casting improvement based on metaheuristic optimization and numerical simulation," *Facta Univ. Ser. Mech. Eng.*, vol. 15, no. 3, pp. 397–411, Jul. 2017.

[8] R.-E. Precup and R.-C. David, *Nature-Inspired Optimization Algorithms for Fuzzy Controlled Servo Systems*. Oxford, UK: Butterworth-Heinemann, Elsevier, 2019.

[9] P. Korondi, H. Hashimoto, and V. Utkin, "Discrete sliding mode control of two mass system," in *Proc. 1995 IEEE Intl. Symp. Ind. Electron.*, Athens, Greece, 1995, pp. 338–343.

[10] R.-E. Precup and S. Preitl, *Fuzzy Controllers*. Timisoara: Editura Orizonturi Universitare, 1999.

[11] R.-E. Precup and S. Preitl, "Development of fuzzy controllers with non-homogeneous dynamics for integral-type plants," *Electr. Eng.*, vol. 85, no. 3, pp. 155–168, Jul. 2003.

[12] R.-E. Precup, M.-L. Tomescu, and C.-A. Dragos, "Stabilization of Rössler chaotic dynamical system using fuzzy logic control algorithm," *Int. J. Gen. Syst.*, vol. 43, no. 5, pp. 413–433, Jul. 2014.

[13] Á. Takács, L. Kovács, I. J. Rudas, R.-E. Precup, and T. Haidegger, "Models for force control in telesurgical robot systems," *Acta Polyt. Hung.*, vol. 12, no. 8, pp. 95–114, Dec. 2015.

[14] J. Kennedy and R. C. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Networks (ICNN'95)*, Perth, Australia, 1995, pp. 1942–1948.

[15] J. Kennedy and R. C. Eberhart, "A new optimizer using particle swarm theory," in *Proc. 6th Int. Symp. Micro Machine and Human Science*, Nagoya, Japan, 1995, pp. 39–43.

[16] S. Preitl and R.-E. Precup, "On the algorithmic design of a class of control systems based on providing the symmetry of open-loop Bode plots," *Scientific Bulletin of "Politehnica" University of Timisoara, Romania, Transactions on Automatic Control and Computer Science*, vol. 41 (55), no. 2, pp. 47–55, Dec. 1996.

[17] P. Baranyi, P. Korondi, H. Hashimoto, and M. Wada, "Fuzzy inversion and rule base reduction," in *Proc. IEEE Int. Conf. Intell. Eng. Syst, (INES'97)*, Budapest, Hungary, 1997, pp. 301–306.

[18] R.-E. Precup and S. Preitl, "Popov-type stability analysis method for fuzzy control systems," in *Proc. Fifth Eur. Congr. Intell. Technol. Soft Comput. (EUFIT'97)*, Aachen, Germany, 1997, vol. 2, pp. 1306–1310.

[19] S. Preitl and R.-E. Precup, *Introducere în conducerea fuzzy a proceselor*. Bucharest: Editura Tehnica, 1997.

[20] R.-E. Precup and S. Preitl, *Fuzzy Controllers*. Timisoara: Editura Orizonturi Universitare, 1999.

[21] S. Preitl, Z. Preitl, and R.-E. Precup, "Low cost fuzzy controllers for classes of second-order systems," *IFAC Proc. Vol.*, vol. 35, no. 1, pp. 397–402, Jul. 2002.

[22] I. Dumitrache and M. Dragoicea, "Intelligent techniques for cognitive mobile robots," *Control Eng. Appl. Informat.*, vol. 6, no. 2, pp. 3–8, Jun. 2004.

[23] L. Horváth and I. J. Rudas, *Modeling and Problem Solving Methods for Engineers*. Burlington, MA: Academic Press, Elsevier, 2004.

[24] R.-E. Precup, S. Preitl, M. Balas, and V. Balas, "Fuzzy controllers for tire slip control in anti-lock braking systems," in *Proc. IEEE Int. Conf. Fuzzy Syst. (FUZZ-IEEE 2004)*, Budapest, Hungary, 2004, vol. 3, pp. 1317–1322.

[25] I. Škrjanc, S. Blažič, and O. E. Agamennoni, "Identification of dynamical systems with a robust interval fuzzy model," *Autom.*, vol. 41, no. 2, pp. 327–332, Feb. 2005.

[26] R.-E. Precup and S. Preitl, "PI and PID controllers tuning for integral-type servo systems to ensure robust stability and controller robustness," *Electr. Eng.*, vol. 88, no. 2, pp. 149–156, Jan. 2006.

[27] R.-E. Precup and S. Preitl, "Stability and sensitivity analysis of fuzzy control systems. Mechatronics applications," *Acta Polyt. Hung.*, vol. 3, no. 1, pp. 61–76, Mar. 2006.

[28] S. Preitl, R.-E. Precup, J. Fodor, and B. Bede, "Iterative feedback tuning in fuzzy control systems. Theory and applications," *Acta Polyt. Hung.*, vol. 3, no. 3, pp. 81–96, Sep. 2006.

[29] R.-E. Precup, M. L. Tomescu, and S. Preitl, "Lorenz system stabilization using fuzzy controllers," *Int. J. Comput. Commun. Control*, vol. 2, no. 3, pp. 279–287, Sep. 2007.

[30] M. L. Tomescu, S. Preitl, R.-E. Precup, and J. K. Tar, "Stability analysis method for fuzzy control systems dedicated controlling nonlinear processes," *Acta Polyt. Hung.*, vol. 4, no. 3, pp. 127–141, Sep. 2007.

[31] R.-E. Precup and S. Preitl, "PI-fuzzy controllers for integral plants to ensure robust stability," *Inf. Sci.*, vol. 177, no. 20, pp. 4410–4429, Oct. 2007.

[32] T. Orlowska-Kowalska and K. Szabat, "Damping of torsional vibrations in two-mass system using adaptive sliding neuro-fuzzy approach," *IEEE Trans. Ind. Informat.*, vol. 4, no. 1, pp. 47–57, Feb. 2008.

[33] Z. C. Johanyák and S. Kovács, "Polar-cut based fuzzy model for petrophysical properties prediction," *Scientific Bulletin of "Politehnica" University of Timisoara, Romania, Transactions on Automatic Control and Computer Science*, vol. 57 (67), no. 2, pp. 195–200, Dec. 2008.

[34] D. Hládek, J. Vaščák, and P. Sinčák, "Hierarchical fuzzy inference system for robotic pursuit evasion task," in *Proc. 6th Int. Symp. Appl. Mach. Intell. Informat. (SAMI 2008)*, Herľany, Slovakia, 2008, pp. 273–277.

[35] F.-G. Filip and K. Leiviskä, "Large-scale complex systems," in *Springer Handbook of Automation*, S. Y. Nof, Ed. Berlin, Heidelberg: Springer-Verlag, pp. 619–638, 2009.

[36] E. Rashedi, H. Nezamabadi-pour, and S. Saryazdi, "GSA: A gravitational search algorithm," *Inf. Sci.*, vol. 179, no. 13, pp. 2232–2248, Jun. 2009.

[37] R.-E. Precup, M. L. Tomescu, and S. Preitl, "Fuzzy logic control system stability analysis based on Lyapunov's direct method," *Int. J. Comput. Commun. Control*, vol. 4, no. 4, pp. 415–426, Dec. 2009.

[38] E. Rashedi, H. Nezamabadi-pour, and S. Saryazdi, "BGSA: binary gravitational search algorithm," *Nat. Comput.*, vol. 9, pp. 727–745, Sep. 2010.

[39] S. Blažič, D. Matko, and I. Škrjanc, "Adaptive law with a new leakage term," *IET Control Theory Appl.*, vol. 4, no. 3, pp. 1533–1542, Sep. 2010.

[40] J. Vaščák and L. Madarász, "Adaptation of fuzzy cognitive maps – a comparison study," *Acta Polyt. Hung.*, vol. 7, no. 3, pp. 109–122, Sep. 2010.

[41] E. Masehian and D. Sedighizadeh, "Multi-objective PSO-and NPSO-based algorithms for robot path planning," *Adv. Electr. Comput. Eng.*, vol. 10, no. 4, pp. 69–76, Nov. 2010.

[42] L. Tang and X. Wang, "An improved particle swarm optimization algorithm for the hybrid flow-shop scheduling to minimize total weighted completion time in process industry," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 6, pp. 586–592, Nov. 2010.

[43] S. Mirjalili and S. Z. M. Hashim, "A new hybrid PSOGSA algorithm for function optimization," in *Proc. IEEE Int. Conf. Computer and Information Application*, Tianjin, China, 2010, pp. 374–377.

[44] A. Sánchez Boza, R. Haber-Guerra, and A. Gajate, "Artificial cognitive control system based on the shared circuits model of sociocognitive capacities. A first approach," *Eng. Appl. Artif. Intell.*, vol. 24, no. 2, pp. 209–219, Mar. 2011.

[45] E. Hashemi, M. Ghaffari Jadidi, and N. Ghaffari Jadidi, "Model-based PI-fuzzy control of four-wheeled omni-directional mobile robots," *Robot. Auton. Syst.*, vol. 59, no. 11, pp. 930–942, Nov. 2011.

[46] R.-E. Precup, R.-C. David, E. M. Petriu, S. Preitl, and A. S. Paul, "Gravitational search algorithm-based tuning of fuzzy control systems with a reduced parametric sensitivity," in *Soft Computing in Industrial Applications*, A. Gaspar-Cunha, R. Takahashi, G. Schaefer, and L. Costa, Eds. Berlin, Heidelberg: Springer-Verlag, Advances in Intelligent and Soft Computing, vol. 96, pp. 141–150, 2011.

[47] S. M. Islam, S. Das, S. Ghosh, S. Roy, and P. N. Suganthan, "An adaptive differential evolution algorithm with novel mutation and crossover strategies for global numerical optimization," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 42, no. 4, pp. 482–500, Apr. 2012.

[48] Y. Zhong and L. Zhang, "Remote sensing image sub-pixel mapping based on adaptive differential evolution," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 42, no. 10, pp. 1306–1329, Oct. 2012.

[49] A. Tuncer and M. Yildirim, "Dynamic path planning of mobile robots with improved genetic algorithm," *Comput. Electr. Eng.*, vol. 38, no. 6, pp. 1564–1572, Nov. 2012.

[50] Z. C. Johanyák and O. Papp, "A hybrid algorithm for parameter tuning in fuzzy model identification," *Acta Polyt. Hung.*, vol. 9, no. 4, pp. 153–165, Dec. 2012.

[51] R. Diao and Q. Shen, "Feature selection with harmony search," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 42, no. 12, pp. 1509–1523, Dec. 2012.

[52] I. Chaari, A. Koubaa, H. Bennaceur, S. Trigui, and K. Al-Shalfan, "smartPATH: A hybrid ACO-GA algorithm for robot path planning," in *Proc. 2012 IEEE Congress on Evolutionary Computation (CEC 2012)*, Brisbane, QLD, Australia, 2012, pp. 1–8.

[53] Y. Maldonado, O. Castillo, and P. Melin, "Particle swarm optimization of interval type-2 fuzzy systems for FPGA applications," *Appl. Soft Comput.*, vol. 13, no. 1, pp. 496–508, Jan. 2013.

[54] Y. Zhang, D.-W. Gong, and J.-H. Zhang, "Robot path planning in uncertain environment using multi-objective particle swarm optimization," *Neurocomput.*, vol. 103, pp. 172–185, Mar. 2013.

[55] S. Formentin, A. Karimi, and S. M. Savaresi, "Optimal input design for direct data-driven tuning of model-reference controllers," *Autom.*, vol. 49, no. 6, pp. 1874–1882, Jun. 2013.

[56] C. Purcaru, R.-E. Precup, D. Iercan, L.-O. Fedorovici, E. M. Petriu, and E.-I. Voisan, "Multi-robot GSA- and PSO-based optimal path planning in static environments," in *Proc. 9th Int. Workshop Robot Motion Control (RoMoCo'13)*, Wasowo, Poland, 2013, pp. 197–202.

[57] K.-J. Åström and T. Hägglund, *PID Controllers Theory: Design and Tuning*. Research Triangle Park, NC: Instrument Society of America, 1995.

[58] M. Araki and H. Taguchi, "Two-degree-of-freedom PID controllers," *Int. J. Control Automat. Syst.*, vol. 1, pp. 401–411, Dec. 2003.

[59] A. Visioli, "A new design for a PID plus feedforward controller," *J. Process Contr.*, vol. 14, no. 4, pp. 457–463, Jun. 2004.

[60] L. Bascetta and A. Leva, "FIR based causal design of 2-d.o.f. controllers for optimal set point tracking," *J. Process Contr.*, vol. 18, no. 5, pp. 465–478, Jun. 2008.

[61] C. M. Liaw and S. Y. Cheng, "Fuzzy two-degrees-of-freedom speed controller for motor drives," *IEEE Trans. Ind. Electron.*, vol. 42, pp. 209–216, Apr. 1995.

[62] A. Visioli, "Fuzzy logic based set-point weight tuning of PID controllers," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 29, no. 6, pp. 587–592, Nov. 1999.

[63] R. K. Barai and K. Nonami, "Optimal two-degree-of-freedom fuzzy control for locomotion control of a hydraulically actuated hexapod robot," *Inf. Sci.*, vol. 177, no. 8, pp. 1892–1915, Apr. 2007.

[64] E. Yeşil, M. Güzelkaya, İ. Eksin, and Ö. A. Tekin, "Online tuning of set-point regulator with a blending mechanism using PI controller," *Turk. J. Elec. Engin. Comp. Sci.*, vol. 16, pp. 143–157, Jul. 2008.

[65] S.-Q. Shu, X.-Y. Ding, W. Wu, and H.-Y. Ren, "Application of a self-tuning two degree of freedom PID controller based on fuzzy inference for PMSM," in *Proc. 2008 Int. Conf. Electr. Mach. Syst. (ICEMS 2008)*, Wuhan, China, 2008, pp. 1629–1632.

[66] Y.-Q. Peng, J. Luo, J.-F. Zhuang and C.-Q. Wu, "Model reference fuzzy adaptive PID control and its applications in typical industrial processes," in *Proc. 2008 IEEE Int. Conf. Autom. Logistics (ICAL 2008)*, Qingdao, China, 2008, pp. 896–901.

[67] H. Li and S. Xiong, "A new type of control method for electro-hydraulic servo systems," in *Proc. 7th World Congress on Intelligent Control and Automation (WCICA 2008)*, Chongqing, China, 2008, pp. 6450–6453.

[68] S.-Y. Bei, "Fuzzy controller for automotive semi-active suspension based on damping control", in *Proc. 2009 ISECS International Colloquium on Computing, Communication, Control, and Management (CCCM 2009)*, Sanya, China, 2009, vol. 4, pp. 296–299.

[69] R.-E. Precup, S. Preitl, I. J. Rudas, M. L. Tomescu, and J. K. Tar, "Design and experiments for a class of fuzzy controlled servo systems", *IEEE/ASME Trans. Mechatron.*, vol. 13, no. 1, pp. 22–35, Feb. 2008.

[70] R.-E. Precup, S. Preitl, E. M. Petriu, J. K. Tar, M. L. Tomescu, and C. Pozna, "Generic two-degree-of-freedom linear and fuzzy controllers for integral processes," *J. Franklin Inst.*, vol. 346, no. 10, pp. 980–1003, Dec. 2009.

[71] S. Preitl and R. -E. Precup, "An extension of tuning relations after symmetrical optimum method for PI and PID controllers," *Autom.*, vol. 35, no. 10, pp. 1731–1736, Oct. 1999.

[72] S. Preitl, R.-E. Precup, and Z. Preitl, "Two degree of freedom fuzzy controllers: Structure and development," in *Proc. Int. Conf. in Memoriam John von Neumann*, Budapest, Hungary, 2003, pp. 49–60.

[73] R.-E. Precup, Z. Preitl, S. Preitl, S. Vaivoda, J. K. Tar, and M. Takács, "Two-degree-of-freedom fuzzy control in decentralized trajectory tracking," in *Proc. 4th Int. Symp. Appl. Comput. Intell. Informat. (SACI'07)*, Timisoara, Romania, 2007, pp. 93–98.

[74] S. Galichet and L. Foulloy, "Fuzzy controllers: synthesis and equivalences," *IEEE Trans. Fuzzy Syst.*, vol. 3, no. 2, pp. 140–148, May 1995.

[75] J. Yoneyama, "H_∞ output feedback control for fuzzy systems with immeasurable premise variables: Discrete-time case", *Appl. Soft Comput.*, vol. 8, no. 2, pp. 949–958, Mar. 2008.

[76] R. Qi and M. A. Brdys, "Stable indirect adaptive control based on discrete-time T-S fuzzy model," *Fuzzy Sets Syst.*, vol. 159, no. 8, pp. 900–925, Apr. 2008.

[77] J. Dong and G.-H. Yang, "Dynamic output feedback H_∞ control synthesis for discrete-time T-S fuzzy systems via switching fuzzy controllers," *Fuzzy Sets Syst.*, vol. 160, no. 4, pp. 482–499, Feb. 2009.

[78] L. Bin and J. H. David, "Uniform stability and ISS of discrete-time impulsive hybrid systems," *Nonl. Anal. Hybrid Syst.*, vol. 4, pp. 319–333, May 2010.

[79] L. Horváth and I. J. Rudas, *Modeling and Problem Solving Methods for Engineers*. Burlington, MA: Academic Press, Elsevier, 2004.

[80] I. Škrjanc, S. Blažič, S. Oblak, and J. Richalet, "An approach to predictive control of multivariable time-delayed plant: Stability and design issues," *ISA Trans.*, vol. 43, no. 4, pp. 585–595, Oct. 2004.

[81] B. Paláncz, Z. Benyó, and L. Kovács, "Control System Professional Suite," *IEEE Control Syst. Mag.*, vol. 25, no. 2, pp. 67-75, Apr. 2005.

[82] I. Harmati and K. Skrzypczyk, "Robot team coordination for target tracking using fuzzy logic controller in game theoretic framework," *Robot. Auton. Syst.*, vol. 57, no. 1, pp. 75–86, Jan. 2009.

[83] X. Li, G. M. Dimirovski, Y. Jing, and S. Zhang, "A Q-learning model-independent flow controller for high-speed networks," in *Proc. Amer. Control Conf. (ACC '09)*, St. Louis, MO, USA, 2009, pp. 1544–1548.

[84] R. E. Haber, R. Haber-Haber, A. Jiménez, and R. Galán, "An optimal fuzzy control system in a network environment based on simulated annealing. An application to a drilling process," *Appl. Soft Comput.*, vol. 9, no. 3, pp. 889–895, Jun. 2009.

[85] J. Vaščák, "Using neural gas networks in traffic navigation," *Acta Tech. Jaur., Ser. Intell. Comput.*,vol. 2, pp. 203–215, Dec. 2009.

[86] D. Stojić and M. Stojić, "Speed-controlled electrical drive with novel disturbance observer," *Facta Univ. Ser. Autom. Control Robot.*, vol. 8, pp. 13-24, Dec. 2009.

[87] E. Mininno, F. Cupertino, and D. Naso, "Real-valued compact genetic algorithms for embedded microcontroller optimization," *IEEE Trans. Evol. Comput.*, vol. 12, no. 2, pp. 203–219, Apr. 2008.

[88] J. Vaščák, "Fuzzy cognitive maps in path planning," *Acta Tech. Jaur., Ser. Intell. Comput.*, vol. 1, pp. 467–479, Dec. 2008.

[89] D. Mitić, D. Antić, and M. Milojković, "On error-signal based design of digital minimum variance control with fuzzy-sliding mode," *Facta Univ. Ser. Autom. Control Robot.*, vol. 7, pp. 122–129, Dec. 2008.

[90] J. K. Tar, J. F. Bitó, I. J. Rudas, S. Preitl, and R.-E. Precup, "An SVD-based modification of the adaptive inverse dynamics controller," in *Proc. 5th International Symposium on Applied Computational Intelligence and Informatics (SACI'09)*, Timisoara, Romania, 2009, pp. 193–198.

[91] N. Smolić-Ročak, S. Bogdan, Z. Kovačić, and T. Petrović, "Time windows based dynamic routing in multi-AGV systems," *IEEE Trans. Autom. Sci. Eng.*, vol. 7, no. 1, pp. 151–155, Jan. 2010.

[92] S. K. Cho, H. Z. Jin, J. M. Lee, and B. Yao, "Teleoperation of a mobile robot using a force-reflection joystick with sensing mechanism of rotating magnetic field," *IEEE/ASME Trans. Mechatron.*, vol. 15, no. 1, pp. 17–26, Feb. 2010.

[93] R.-E. Precup, S. Preitl, and G. Faur, "PI predictive fuzzy controllers for electrical drive speed control: Methods and software for stable development," *Comput. Ind.*, vol. 52, no. 3, pp. 253–270, Dec. 2003.

[94] C. Pozna and R.-E. Precup, "Aspects concerning the observation process modelling in the framework of cognition processes," *Acta Polyt. Hung*., vol. 9, no. 1, pp. 203–223, Mar. 2012.

[95] R.-E. Precup, T. Haidegger, S. Preitl, B. Benyó, A. S. Paul, and L. Kovács, "Fuzzy control solution for telesurgical applications," *Appl. Comput. Math*., vol. 11, no. 3, pp. 378–397, Sep. 2012.

[96] R.-E. Precup, S. Preitl, E. M. Petriu, R.-C. Roman, C.-A. Bojan-Dragos, E.-L. Hedrea, and A.-I. Szedlak-Stinean, "A center manifold theory-based approach to the stability analysis of state feedback Takagi-Sugeno-Kang fuzzy control systems," *Facta Univ. Ser. Mech. Eng.*, vol. 18, no. 2, pp. 189–204, Jun. 2020.

[97] R.-C. David, R.-E. Precup, S. Preitl, A.-I. Szedlak-Stinean, R.-C. Roman, and E. M. Petriu, "Design of low-cost fuzzy controllers with reduced parametric sensitivity based on whale optimization algorithm," in *Proc. 2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE 2020)*, Glasgow, UK, 2020, pp. 1–6.

[98] R.-E. Precup, S. Preitl, K. J. Burnham, and B. Vinsonneau, "Virtual reference feedback tuning approach to fuzzy control systems development," *IFAC Proc. Vol.*, vol. 40, no. 8, pp. 123–128, May 2007.

[99] R.-C. Roman, R.-E. Precup, E. M. Petriu, C.-A. Bojan-Dragos, V.-B. Vanya, and M.-D. Rarinca, "Second order active disturbance rejection control - virtual reference feedback tuning for twin rotor aerodynamic systems," in *Proc. 2020 IEEE Int. Conf. Syst. Man Cybern. (SMC 2020)*, Toronto, ON, Canada, 2020, pp. 1693–1698.

[100] R.-E. Precup, A.-B. Borlea, E. M. Petriu, and F. Dragan, "Iterative Feedback Tuning of two-degree-of-freedom controllers for lighting process control," in *Proc. 14th Annual IEEE International Systems Conference (SysCon 2020)*, Montreal, QC, Canada, 2020, pp. 1–6.

[101] R.-C. David, R.-E. Precup, S. Preitl, E. M. Petriu, A.-I. Szedlak-Stinean, and R.-C. Roman, "Whale optimization algorithm-based tuning of low-cost fuzzy controllers with reduced parametric sensitivity," in *Proc. 28th Mediterranean Conference on Control and Automation (MED 2020)*, Saint-Raphael, France, 2020, pp. 440–445.

[102] R.-E. Precup, R.-C. Roman, T.-A. Teban, A. Albu, E. M. Petriu, and C. Pozna, "Model-free control of finger dynamics in prosthetic hand myoelectric-based control systems," *Stud. Informat. Control*, vol. 29, no. 4, pp. 399–410, Dec. 2020.

[103] K. Michail, K. M. Deliparaschos, S. G. Tzafestas, and A. C. Zolotas, "AI-based actuator/sensor fault detection with low computational cost for industrial applications," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 1, pp. 293–301, Jan. 2016.

[104] I.-D. Borlea, R.-E. Precup, F. Dragan, and A.-B. Borlea, "Centroid update approach to K-means clustering," *Adv. Electr. Comput. Eng.*, vol. 17, no. 4, pp. 3–10, Dec. 2017.

[105] L. Nyulászi, R. Andoga, P. Butka, L. Főző, R. Kovacs, and T. Moravec, "Fault detection and isolation of an aircraft turbojet engine using a multi-sensor network and multiple model approach," *Acta Polyt. Hung.*, vol. 15, no. 2, pp. 189–209, Apr. 2018.

[106] A. Lucchini, S. Formentin, M. Corno, D. Piga, and S. M. Savaresi, "Torque vectoring for high-performance electric vehicles: a data-driven MPC approach," *IEEE Control Syst. Lett.*, vol. 4, no. 3, pp. 725–730, Jul. 2020.

[107] M. Parigi Polverini, S. Formentin, L. Merzagora, and P. Rocco, "Mixed data-driven and model-based robot implicit force control: a hierarchical approach," *IEEE Trans. Control Syst. Technol.*, vol. 28, no. 4, pp. 1258–1271, Jul. 2020.

[108] R.-E. Precup, E.-L. Hedrea, R.-C. Roman, E. M. Petriu, A.-I. Szedlak-Stinean, and C.-A. Bojan-Dragos, "Experiment-based approach to teach optimization techniques," *IEEE Trans. Educ.*, vol. 64, no. 2, pp. 88–94, May 2021.

[109] E. Osaba, J. Del Ser, A. D. Martinez, J. L. Lobo, and F. Herrera, "AT-MFCGA: An adaptive transfer-guided multifactorial cellular genetic algorithm for evolutionary multitasking," *Inf. Sci.*, vol. 570, pp. 577–598, Sep. 2021.

[110] R.-E. Precup, C.-A. Bojan-Dragos, E.-L. Hedrea, R.-C. Roman, and E. M. Petriu, "Evolving fuzzy models of shape memory alloy wire actuators," *Rom. J. Inf. Sci. Technol.*, vol. 24, no. 4, pp. 353–365, Dec. 2021.

[111] P. Angelov and D. Filev, "On-line design of Takagi-Sugeno models," in *Fuzzy Sets and Systems – IFSA 2003*, T. Bilgiç, B. De Baets, and O. Kaynak, Eds. Berlin, Heidelberg, Lecture Notes in Computer Science, vol. 2715, pp. 576–584, 2003.

[112] P. Angelov, J. Victor, A. Dourado, and D. Filev, "On-line evolution of Takagi-Sugeno fuzzy models," *IFAC Proc. Vol.*, vol. 37, no. 16, pp. 67–72, Sep. 2004.

[113] E.-L. Hedrea, R.-E. Precup, E. M. Petriu, C.-A. Bojan-Dragos, and C. Hedrea, "Tensor product-based model transformation approach to cart position modeling and control in pendulum-cart systems," *Asian J. Control*, vol. 23, no. 3, pp. 1238–1248, May 2021.

[114] C.-B. Gale-Cazan, C.-A. Bojan-Dragos, R.-E. Precup, R.-C. Roman, E. M. Petriu, and A.-I. Szedlak-Stinean, "GWO-based modeling of an unstable transport system," *Proc. Comput. Sci.*, vol. 214, pp. 195–202, Aug. 2022.

[115] R.-E. Precup, G. Duca, S. Travin, and I. Zinicovscaia, "Processing, neural network-based modeling of biomonitoring studies data and validation on Republic of Moldova data," *Proceedings of the Romanian Academy, Series A: Mathematics, Physics, Technical Sciences, Information Science*, vol. 23, no. 4, pp. 403–410, Dec. 2022.

[116] I. Škrjanc, S. Blažič, and O. E. Agamennoni, "Interval fuzzy modeling applied to Wiener models with uncertainties," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 35, no. 5, pp. 1092–1095, Oct. 2005.

[117] F. Matía, V. Jiménez, B. P. Alvarado, and R. Haber, "The fuzzy Kalman filter: Improving its implementation by reformulating uncertainty representation," *Fuzzy Sets Syst.*, vol. 402, pp. 78–104, Jan. 2021.

[118] A.-I. Szedlak-Stinean, R.-E. Precup, E. M. Petriu, R.-C. Roman, E.-L. Hedrea, and C.-A. Bojan-Dragos, "Extended Kalman filter and Takagi-Sugeno fuzzy observer for a strip winding system," *Expert Syst. Appl.*, vol. 208, paper 118215, Dec. 2022.

[119] A. Villalonga, E. Negri, G. Biscardo, F. Castaño, R. E. Haber, L. Fumagalli, and M. Macchi, "A decision-making framework for dynamic scheduling of cyber-physical production systems based on digital twins," *Annu. Rev. Control*, vol. 51, pp. 357–373, Dec. 2021.

[120] R.-E. Precup, S. Preitl, C.-A. Bojan-Dragos, E.-L. Hedrea, R.-C. Roman, and E. M. Petriu, "A low-cost approach to data-driven fuzzy control of servo systems," *Facta Univ. Ser. Mech. Eng.*, vol. 20, no. 1, pp. 21–36, Mar. 2022.

[121] C.-A. Bojan-Dragos, R.-E. Precup, E. M. Petriu, R.-C. Roman, E.-L. Hedrea, and A.-I. Szedlak-Stinean, "GWO-based optimal tuning of controllers for shape memory alloy wire actuators," *IFAC-PapersOnLine*, vol. 55, no. 15, pp. 39–44, Jul. 2022.

[122] R.-C. Roman, R.-E. Precup, S. Preitl, A.-I. Szedlak-Stinean, C.-A. Bojan-Dragos, E.-L. Hedrea, and E. M. Petriu, "PI controller tuning via data-driven algorithms for shape memory alloy systems," *IFAC-PapersOnLine*, vol. 55, no. 40, pp. 181–186, Nov. 2022.

[123] H. Costin and S. Bejinariu, "Medical image registration by means of a bio-inspired optimization strategy," *Comput. Sci. J. Moldova*, vol. 20, no. 2, pp. 178–202, Jun. 2012.

[124] J. Vaščák, I. Zolotová, and E. Kajáti, "Navigation fuzzy cognitive maps adjusted by PSO," in *Proc. 23rd International Conference on System Theory, Control and Computing (ICSTCC 2019)*, Sinaia, Romania, 2019, pp. 107–112.

[125] S. I. Boucetta and Z. C. Johanyák, "Optimized ad-hoc multi-hop broadcast protocol for emergency message dissemination in vehicular ad-hoc networks," *Acta Polyt. Hung.*, vol. 19, no. 5, pp. 23–42, May 2022.

[126] A.-I. Borlea, R.-E. Precup, and R.-C. Roman, "Discrete-time model-based sliding mode controllers for tower crane systems," *Facta Univ. Ser. Mech. Eng.*, vol. 21, no. 1, pp. 1–20, Mar. 2023.

[127] R.-C. Roman, R.-E. Precup, E. M. Petriu, and M. Muntyan, "Fictitious reference iterative tuning of discrete-time model-free control for tower crane systems," *Stud. Informat. Control*, vol. 32, no. 1, pp. 5–14, Mar. 2023.

[128] S. M. Abramov, S. Travin, G. Duca, and R.-E. Precup, "New opportunities model for monitoring, analyzing and forecasting the official statistics on coronavirus disease pandemic," *Rom. J. Inf. Sci. Technol.*, vol. 26, no. 1, pp. 49–64, Mar. 2023.

[129] M. Brezovan, R.-E. Precup, D. Selisteanu, and L. Stanescu, "Colored Petri nets-based control and experimental validation on three-tank

system level control," *Int. J. Gen. Syst.*, vol. 51, no. 1, pp. 1–47, Mar. 2023.

[130] G. Duca, S. Travin, I. Zinicovscaia, and R.-E. Precup, "Approach to evaluate the data of moss biomonitoring studies: preprocessing and preliminary ranking," *Rom. J. Inf. Sci. Technol.*, vol. 26, no. 3–4, pp. 276–288, Sep 2023.

[131] I. A. Zamfirache, R.-E. Precup, and E. M. Petriu, "Q-learning, policy iteration and actor-critic reinforcement learning combined with metaheuristic algorithms in servo system control," *Facta Univ. Ser. Mech. Eng.*, vol. 21, no. 4, pp. 615–630, Dec. 2023.

[132] M. Stankovic, H. Ting, and R. Madonski, "From PID to ADRC and back: Expressing error–based active disturbance rejection control schemes as standard industrial 1DOF and 2DOF controllers," *Asian J. Control*, vol. 26, no. 6, pp. 2796–2806, Nov. 2024.

[133] S.-H. Tsai, W.-H. Lee, K. Tanaka, Y.-J. Chen, and H.-K. Lam, "Polynomial fuzzy observer-based feedback control for nonlinear hyperbolic PDEs systems," *IEEE Trans. Cybern.*, vol. 54, no. 9, pp. 5257–5269, Sep. 2024.

[134] B. Costa, I. Škrjanc, S. Blažič, and P. Angelov, "A practical implementation of self-evolving cloud-based control of a pilot plant," in *Proc. 2013 IEEE Int. Conf. Cybern.*, Lausanne, Switzerland, 2013, pp. 7–12.

[135] R.-E. Precup, A.-T. Nguyen, and S. Blažič, "A survey on fuzzy control for mechatronics applications," *Int. J. Syst. Sci.*, vol. 55, no. 4, pp. 771–813, Mar. 2024.

[136] Z.-S. Hou and Z. Wang, "From model-based control to data-driven control: Survey, classification and perspective," *Inf. Sci.*, vol. 235, pp. 3–35, Jun. 2013.

[137] R.-H. Chi, Y. Hui, and Z.-S. Hou, *Data-Driven Iterative Learning Control for Discrete-Time Systems*. Singapore: Springer, 2022.

[138] Q.-X. Yu and Z.-S. Hou, "Adaptive fuzzy iterative learning control for high-speed trains with both randomly varying operation lengths and system constraints," *IEEE Trans. Fuzzy Syst.*, vol. 29, no. 8 pp. 2408–2418, Aug. 2021.