SCIENTIFIC REPORT

on the implementation of the project during January – December 2022 (stage 2)

The research team who carried out research activities in the project "Data-driven fuzzy control with experimental validation", project number 192 / 19.02.2021, registration code PN-III-P4-ID-PCE-2020-0269, is the one nominated in the funding application form: Prof.Dr.Eng. Radu-Emil Precup (project leader), Assoc.Prof.Dr.Eng. Claudia-Adina Bojan-Dragoş, Assoc.Prof.Dr.Eng. Adriana Albu, Lect.Dr.Eng. Alexandra-Iulia Szedlak-Stînean, Lect.Dr. Ciprian Hedrea, Assist.Lect.Dr. Raul-Cristian Roman, M.Sc.Eng. Ion-Cornel Mituleţu, Phd student, Assist.Lect.Dr. Elena-Lorena Hedrea.

This research report is posted at https://www.aut.upt.ro/~rprecup/RS_PCE_2022.pdf.

A. PROGRESS SUMMARY

The results expected to be obtained during this stage of the project according to the funding application form are:

- The publication of one paper in a high impact leading journal and the participation and presentation of two papers to important conferences.
- Preparing the reports for the documentation of the activities.

The main results obtained in this stage of the project exceed the expected results. These are:

- The research report.
- A PhD thesis successfully finalized and defended by a member of the research team: Ms. Eng. Elena-Lorena Hedrea defended in September 1, 2022, the PhD Thesis "Tensor Product-based Model Transformation Used in Control System Modeling and Design", PhD supervisor: Prof.Dr.Eng. Radu-Emil Precup. The PhD committee gave the thesis the Excellent qualification. The thesis contains chapters connected with the main objective of this project.
- 21 published papers: [C1]-[C21].
- Details on the published papers: 6 papers [C1]-[C6] published in journals indexed in Clarivate Analytics Web of Science (with one of the former names ISI Web of Knowledge) with impact factor, 4 papers [C7], [C8], [C10], [C11] published in conference proceedings indexed in Clarivate Analytics Web of Science (with one of the former names ISI Web of Knowledge or ISI Proceedings), 8 papers published in conference proceedings indexed in international databases (IEEE Xplore, INSPEC, Scopus, DBLP), 1 book published in Editura Politehnica, 2 book chapters published in Springer and World Scientific.
- The cumulative impact factor of the published papers according to 2021 Journal Citation Reports (JCR) published by Clarivate Analytics in 2022 = 38.843.
- High impact leading journals in which the papers were published: IEEE Transactions on Fuzzy Systems, International Journal of General Systems (Taylor & Francis), Information Sciences (Elsevier), Expert Systems with Applications (Elsevier).
- Important conferences in whose proceedings the papers were published: 2022 IEEE 31st International Symposium on Industrial Electronics ISIE 2022, 2022 IEEE International Conference on Fuzzy Systems FUZZ-IEEE 2022, 6th IFAC International Conference on Intelligent Control and Automation Sciences ICONS'22, 2022 IEEE Conference on Control Technology and Applications CCTA 2022, 48th Annual Conference of the IEEE Industrial Electronics Society IECON 2022, 2022 IEEE Symposium Series on Computational Intelligence SSCI 2022, 9th International Conference on Information Technology and Quantitative Management ITQM 2022.

THE EXECUTIVE SUMMARY OF THE PERFORMED ACTIVITIES IN THE IMPLEMENTATION STAGE

The main objective of the project was fulfilled according to the funding application form:
(2) The analysis, the design, the implementation and the validation of new Data-Driven Control (DDC) and Fuzzy Control (FC) algorithms through experiments made on several laboratory equipment also including Shape Memory Alloy (SMA) actuators and through cooperation with our external partners. The performed activities are 2.1, 2.2, 2.3 and 2.4:
2.1. The analysis of the actual stage of the research concerning the possibility of designing new DDC and FC algorithms used for improving the performance of the control system structures. The analysis was conducted and the brief results along with the corresponding references are presented in Chapter B.
2.2. Ensuring the desired control performance for the control system structures with controllers designed using DDC and FC algorithms and also ensuring the stability of these structures using stability criteria. The results of a stability analysis are presented in Chapter B. New controllers were analyzed and designed such as: fuzzy controllers [C1], [C5], [C6], [C9], [C10], [C11], [C19], [C20], [C21], Iterative Feedback Tuning-based controllers [C8], Active Disturbance Rejection Control, Model-Free Adaptive Control and Model Free Control-based controllers [C12], tensor product model transformation-based controllers [C16], artificial neural networks combined with reinforcement learning and metaheuristic optimization algorithms [C4] (details given in the published papers).
2.3. The design, testing and validation of new control system structures with controllers designed using DDC and FC algorithms through real time experiments conducted on several laboratory equipment including SMA processes. The processes and the equipment on which the design, testing and validation of the new control system structures were conducted are: servo systems [C1], [C4], [C5], [C12], tower crane systems [C6], [C8], [C9], [C10], [C16], big data systems [C7], SMA systems [C11], [C12], and magnetic levitation systems [C19]. Many preparations were made concerning the development of new control system structures through the analysis of processes and derivation of models for systems such as: strip winding systems [C2], [C14], vertical three tank systems [C3], tower crane systems [C13], mobile robots [C15], [C18], brain-computer interfaces [C17], prosthetic hand [C20], electromagnetic actuated clutch systems [C19], continuously variable transmission vehicles [C19].
2.4. The validation of the new control system structures designed using DDC and FC algorithms with the support of the external partners (Continental Automotive Timisoara, Airbus Helicopters – through direct timely consolidated links, Ontario Centres of Excellence – through Prof. Emil M. Petriu, our Canadian partner, Centre of Autonomous and Cyber-Physical Systems of Cranfield University, UK – a fresh cooperation with Dr. Argyrios Zolotas, and ECU Security Research Institute, Australia – through the Project Leader and his colleagues from Edith Cowan University). Due to the pandemics, the experiments at the external partners could not be conducted. However, many experiments were conducted in the laboratories of the research team and the published papers contain the simulation and real-time experimental results obtained with the support of the external partners. These results concern the algorithms and models from the papers whose co-author is Prof. Emil M. Petriu, our partner from Canada: [C1], [C2], [C4], [C8]–[C11], [C13]–[C15] and the book [2] published in 2021 in CRC Press, Taylor & Francis with our external partner Dr. Ali Safaei from Canada. Three of the controllers are in the validation stage, to be finalized in 2023, at Continental Automotive Timişoara (the partnership was created in 2008-2011 through the project PCCA "Real-time informatics technologies for embedded-system-control of power-train in automotive design and applications (SICONA)", project leader, Prof.Dr.Eng. Corneliu Lazăr, Technical University "Gheorghe Asachi" of Iaşi; the partnership was materialized, among others, with a testing stand) and at the company from Canada where Dr. Ali Safaei works. Due to privacy and non-competition reasons, the results cannot be published. However, in the research report from in there will be presented minimal information on the processes on which the controllers designed by the research team were tested and the results obtained at the external partners. For protecting the algorithms proposed in this project, the design methodologies and the corresponding source programs of three Data-Driven Control, Fuzzy Control and Data-Driven Fuzzy Control algorithms will be registered in the National Register of Works handled by the Romanian Office for Copyright (ORDA) in 2023. In 2022 the contract of the project leader as Adjunct Professor at Edith Cowan University (Australia, 2016-2022) has ended; therefore, the connections with Australia weakened. However, the research team started the cooperation with a team from the University of Craiova for developing new fuzzy controllers for discrete events systems; the cooperation started with the published paper [C3] and the team from Craiova has good connections with external partners in the region.

Remarks:

1. In this scientific report the texts, the figures and partially the equations were taken from the papers developed by the research team. This is the reason why the formulations are in English. For some of the equations the numbering will be kept in the research report.

2. All published papers and papers currently in publication, which contain research results obtained in this project, mentioned the support of UEFISCDI in the Acknowledgements section, along with specifying the project registration code from the funding application form.

3. Some of the papers specified in Chapter C contain more than one project in the Acknowledgements section. Several projects contributed In the process of creating these papers because the same processes were controlled but using different controllers designed in different projects. Therefore, the fair comparison of all recent designed controllers was necessary.

B. SCIENTIFIC AND TECHNICAL DESCRIPTION

The description is focused on the synthetic presentation of the research carried out in the framework of the activities 2.1 and 2.2.

As specified in this project proposal (application form) and the paper [C5], also given in Section C as [1], in contrast to model-based control, data-driven control avoids the system (process) identification by constructing controllers directly from data. That is the reason why data-driven control is also referred to as model-free control (i.e. no model in controller tuning), justifying the high interest in nonlinear controllers whose parameters are tuned using process input-output data after conducting few experiments, or, more generally, data-driven model-free control [2]. Instead, one or more experiments are conducted in order to use the information in controller tuning, and non-parametric system or process models) can be employed in this regard.

A concise discussion on the popular data-driven control techniques is given in Precup et al. [3] pointing out the following ones that ensure the iterative experiment-based update of controller parameters: Iterative Feedback Tuning (IFT) [4], [5], Model-free Adaptive Control (MFAC) [6], [7], Simultaneous Perturbation Stochastic Approximation [8], [9], Correlation-based Tuning [10], [11], Frequency Domain Tuning [12], [13], Iterative Regression Tuning [14], and adaptive online IFT [15]. A review on data-driven control [16] offers classifications and highlights the role of observers and estimation in control, also leading to non-iterative data-driven control techniques: Model-Free Control (MFC) [17], [18], Virtual Reference Feedback Tuning (VRFT) [19], [20], Active Disturbance Rejection Control (ADRC) [21], [22], data-driven predictive control [23], [24], unfalsified control [25], [26], Data-Driven Inversion Based Control [27], [28], and the investigation of equivalent conditions on the given data under which different analysis and control problems can be solved [29]. Other representative techniques are emphasized in book [2]. It is suggestively stated in [3] and [30] that MFC is an efficient tool for Machine Learning; moreover, as specified earlier in [25], unfalsified control is also an efficient tool for Machine Learning.

As pointed out in the studies conducted in [1] and [31], fuzzy control is an important subject in the area of nonlinear control as the fuzzy controllers are relatively easily understandable and also offer very good control system performance indices. However, the heuristic approach to design and tune fuzzy controllers is compensated by the systematic design of fuzzy controllers that can employ the stable design of fuzzy control systems, the optimal and robust controller design and tuning. Classical and recent applications of fuzzy control deal with Popov-type stability analysis [32], embedded fuzzy control system for machining processes [33], tire slip control [34], predictive functional control based on fuzzy models [35], stability and sensitivity analysis of fuzzy control systems [36], stability analysis dedicated to the fuzzy control of nonlinear processes [37], robust evolving cloud-based control [38], power control of series hybrid electric vehicles [39], vehicle navigation by fuzzy cognitive maps [40], fuzzy control for the iron ore sintering process [41], type-2 fuzzy control for line following [42], and singularity-free fixed-time fuzzy control for robotic systems [43].

The model-free tuning of fuzzy controllers is an alternative approach to the model-based design resulting in data-driven fuzzy control [1] to benefit from the advantages of data-driven control and fuzzy control and to mitigate their drawbacks. The combinations of data-driven model-free and fuzzy control include H_∞ fuzzy control [44], fault tolerant fuzzy control [45], parameterized data-driven fuzzy control [46], data-driven interpretable fuzzy control [47], MFC merged with Proportional-Derivative (PD) Takagi-Sugeno fuzzy control [48], [49], MFAC merged with PD Takagi-Sugeno fuzzy control [50], [51], ADRC mixed with PD Takagi-Sugeno fuzzy control [52] and tuned by VRFT [22] as well, fuzzy logic-based adaptive ADRC [53], data-driven arithmetic fuzzy control using the distending function [54], and data-driven MFC developed around continuous-time intelligent Proportional-Integral (PI) control [31]. The indirect model-free tuning of fuzzy controllers has initially been proposed in authors' papers [55] and [56], and continued in [48] and [50] by controller structures that combine data-driven control and fuzzy control in order to incorporate model-free features in fuzzy control system structures. However, it is preferred to use the term "data-driven fuzzy control" instead of "model-free fuzzy control" because non-parametric models are actually used in controller tuning in several model-free control techniques.

The Model-Free Control (MFC) approach will be presented as follows along with stability analysis results in terms of the useful information given in [2] in the continuous time case. MFC is a data-driven technique that uses the input/output data of the control process in the controller design, it uses the online linear approximation of the process and an estimator to update the linear approximation [Fli13], [Rom16b], [Rom18c].

The control algorithms tuned by MFC, also known as MFC algorithms, are well-known in the state-of-the-art as "intelligent" controllers or MFC controllers to highlight the controllers that are implemented based on the MFC technique, usually designed based on Proportional (P), Proportional-Integral (PI) or Proportional-Integral-Derivative (PID) type controllers. The MFC controllers that contain P, PI, or PID elements are also known as intelligent P, PI and PID controllers, with the abbreviations iP, iPI and iPID, respectively. The MFC technique is also known in the literature ad model-free tuning [Fli13], [Rom18c]. Within the MFC-based tuning the parameters of the controllers, non-parametric mathematical models of the processes cand be used in the form of process responses to various input signals, i.e. control signals [Fli13], [Rom16b], [Rom18c].

The MFC algorithm uses an ultra-local model $\mathbf{y}^{(\nu)} = \mathbf{F} + \boldsymbol{\alpha}\,\mathbf{u}$ to replace the unknown mathematical model of the process, where the controlled output (i.e. the process output) vector $\mathbf{y}^{(\nu)}(t)$ is the ν^{th} order derivative of $\mathbf{y}$ with $\nu \geq 1$ ($\nu = 1$ in the case of first order MFC algorithm, and $\nu = 2$ in the case of the second order MFC algorithm), $\mathbf{u}$ is the control input vector or the control signal vector, the vector $\mathbf{F}$ plays a disturbance role that is continuously updated, and $\boldsymbol{\alpha}$ is a constant matrix.

The iPID controllers are PID controllers equipped with an online parameter estimation method for estimating the unknown nonlinear or linear dynamics of the controlled system. In this regard, their structure is generally similar to PID controllers, while estimated parameters of the system are included.

The theory of iPID controllers for continuous-time dynamic systems is focused as follows on the description of the structure of iPID controllers for continuous-time dynamic systems offered in [2].

Definition 1. The dynamics of a generic system is defined as follows [Fli13]:

$$\dot{\mathbf{y}} = \mathbf{F} + \mathbf{B}\,\mathbf{u}, \tag{1}$$

where $\mathbf{y} \in \Re^n$ is the system output (or the controlled output) vector, $\mathbf{u} \in \Re^n$ is the system input (the control signal or the control input) vector, $\mathbf{F} \in \Re^n$ is representing the entire nonlinear dynamics of the system, $\mathbf{B} \in \Re^{n \times n}$ is the input matrix of the system, and n is the number of system inputs and outputs, i.e. supposed to be equal. The structure defined in (1) is known as *ultra-local* model for a generic dynamic system. In general case, $\mathbf{F}$ and $\mathbf{B}$ are assumed unknown.

Theorem 1 [2]. For the ultra-local model defined in *Definition 1*, the iPID controller is defined as

$$\mathbf{u} = \hat{\mathbf{B}}^{-1}(\dot{\mathbf{y}}_d - \hat{\mathbf{F}} + \mathbf{v}), \tag{2}$$

where $\mathbf{v} \in \Re^n$ is the regular PID term of the controller (see *Remark 1* given as follows), $\mathbf{y}_d \in \Re^n$ is the reference input vector (or the set-point vector or the desired set-points for system outputs). The term $\mathbf{v}$ is proposed based on the control error $\mathbf{e} \in \Re^n$, i.e. the output tracking error vector of the system, which is defined in terms of

$$\mathbf{e} = \mathbf{y}_d - \mathbf{y}. \tag{3}$$

Proof. Here, the proof is presented in the generic case of a PID controller for $\mathbf{v}$ but it can also be generalized to the other definitions pointed out in this proof. Let us define the following Lyapunov function candidate:

$$V = \frac{1}{2}\mathbf{e}^T(\mathbf{I}_n + \mathbf{k}_d)\mathbf{e} + \xi^T \mathbf{k}_i \xi, \tag{4}$$

where $\xi = \int \mathbf{e}\,dt$ and $\mathbf{I}_n \in \Re^{n\times n}$ is an identity matrix. Then, the first time-derivative of this function is

$$\dot{V} = \mathbf{e}^T\dot{\mathbf{e}} + \mathbf{e}^T\mathbf{k}_d\dot{\mathbf{e}} + \mathbf{e}^T\mathbf{k}_i\xi. \tag{5}$$

Replacing $\dot{\mathbf{e}}$ in the first term on the right-hand side of (5), the relations (3) and (1) lead to

$$\dot{V} = \mathbf{e}^T(\dot{\mathbf{y}}_d - \mathbf{F} - \mathbf{B}\,\mathbf{u}) + \mathbf{e}^T\mathbf{k}_d\dot{\mathbf{e}} + \mathbf{e}^T\mathbf{k}_i\xi. \tag{6}$$

Now, utilizing

$$\dot{\mathbf{y}}_d - \mathbf{F} + \mathbf{k}_p\mathbf{e} + \mathbf{k}_i\xi + \mathbf{k}_d\dot{\mathbf{e}}, \tag{7}$$

we reach at

$$\dot{V} = -\mathbf{e}^T\mathbf{k}_p\mathbf{e} \le 0. \tag{8}$$

Based on the *Lyapunov* stability theorem [Kha02], since $V > 0$ and $\dot{V} \le 0$, then $\mathbf{e}$ will be asymptotically stable and converge to zero. Moreover, by replacing $\mathbf{F}$ and $\mathbf{B}$ in (6), with their corresponding estimated vector variables and parameters $\hat{\mathbf{F}}$ and $\hat{\mathbf{B}}$, the controller given in (2) will be achieved. The usage of the estimated variables are permissible according to the *separation principal* [Ata99], if these estimated variables are computed utilizing stable observers (or state estimators). This completes the proof.

Remark 1 [2]. The term $\mathbf{v}$ in (2) is defined as follows for a regular P controller:

$$\mathbf{v} = \mathbf{k}_p\mathbf{e}, \tag{9}$$

for a regular PI controller is

$$\mathbf{v} = \mathbf{k}_p\mathbf{e} + \mathbf{k}_i\int \mathbf{e}\,dt, \tag{10}$$

for a regular PD controller is

$$\mathbf{v} = \mathbf{k}_p\mathbf{e} + \mathbf{k}_d\dot{\mathbf{e}}, \tag{11}$$

and finally for a regular PID controller is considered as

$$\mathbf{v} = \mathbf{k}_p + \mathbf{k}_i\int \mathbf{e}\,dt + \mathbf{k}_d\dot{\mathbf{e}}. \tag{12}$$

Here, $\mathbf{k}_p \in \Re^{n\times n}$ is the proportional controller gain matrix, $\mathbf{k}_i \in \Re^{n\times n}$ is the integral controller gain matrix and $\mathbf{k}_d \in \Re^{n\times n}$ is the derivative controller gain matrix.

Remark 2 [2]. As it is observed in (2), the estimated parameters and vectors of the dynamic system, i.e. $\hat{\mathbf{F}}$ and $\hat{\mathbf{B}}$, are incorporated into the iP controller. This is the basic feature of all model-free controllers. The values of $\hat{\mathbf{F}}$ and $\hat{\mathbf{B}}$ should be estimated online, in order to implement the proposed iPID controller in (2). The different approaches to this online parameter estimation problem are presented in [2].

Remark 3 [2]. In (2), the time-derivative of the desired system output vector, i.e. $\dot{\mathbf{y}}_d$, is required in the controller. In order to provide correctness and robustness into the differentiation process and consequently into the controlled system, the sliding mode differentiator [Lev03] is suggested to compute $\dot{\mathbf{y}}_d$ as follows:

$$\dot{\mathbf{y}}_d = \boldsymbol{\eta}, \tag{13}$$

where for $\boldsymbol{\eta} = [\eta_1 \quad \eta_2 \quad \dots \quad \eta_n]^T$ the following relationships hold [Lev03]:

$$\begin{aligned} \dot{w}_i &= \eta_i, \\ \eta_i &= -k_1\sqrt{|w_i - y_{di}|}\,\mathrm{sgn}(w_i - y_{di}) + \tau_i, \\ \dot{\tau}_i &= -k_2\,\mathrm{sgn}(w_i - y_{di}), \end{aligned} \tag{14}$$

for $i = 1 \dots n$, where $\mathrm{sgn}(.)$ is the sign function.

Iterated time integrals for online parameter estimations and Adaptive observers for online parameter estimations are thoroughly investigated in [2]. The theory is again backed up by the Lyapunov stability theorem.

References of Section B

[1] Precup, R.-E., Preitl, S., Bojan-Dragoş, C.-A., Hedrea, E.-L., Roman, R.-C., Petriu, E.M., 2021, A low-cost approach to data-driven fuzzy control of servo systems, Facta Universitatis, Series: Mechanical Engineering, 20(1), pp. 21-36.

[2] Precup, R.-E., Roman, R.-C., Safaei, A., 2021, Data-driven Model-free Controllers, 1st Ed. CRC Press, Taylor and Francis.

[3] Precup, R.-E., Roman, R.-C., Teban, T.-A., Albu, A., Petriu, E.M., Pozna, C., 2020, Model-free control of finger dynamics in prosthetic hand myoelectric-based control systems, Studies in Informatics and Control, 29(4), pp. 399-410.

[4] Hjalmarsson H., 2002, Iterative feedback tuning - an overview, International Journal of Adaptive Control and Signal Processing, 16(5), pp. 373-395.

[5] Jung, H., Jeon, K., Kang, J.-G., Oh, S., 2020, Iterative feedback tuning of cascade control of two-inertia system, IEEE Control Systems Letters, 5(3), pp. 785-790.

[6] Hou, Z.-S., Wang Z., 2013, From model-based control to data-driven control: survey, classification and perspective, Information Sciences, 235, pp. 3-35.

[7] Yu, W., Wang, R., Bu, X.-H., Hou, Z.-S., 2020, Model free adaptive control for a class of nonlinear systems with fading measurements, Journal of the Franklin Institute, 357(12), pp. 7743-7760.

[8] Spall, J.C., Cristion, J.A., 1998, Model-free control of nonlinear stochastic systems with discrete-time measurements, IEEE Transactions on Automatic Control, 43(9), pp. 1198-1210.

[9] Zamanipour, M., 2020, A novelty in Blahut-Arimoto type algorithms: optimal control over noisy communication channels, IEEE Transactions on Vehicular Technology, 69(6), pp. 6348-6358.

[10] Karimi, A., Miskovic, L., Bonvin, D., 2004, Iterative correlation-based controller tuning, International Journal of Adaptive Control and Signal Processing, 18(8), pp. 645-664.

[11] Sato, T., Kusakabe, T., Himi, K., Araki, N., Konishi, Y., 2021, Ripple-free data-driven dual-rate controller using lifting technique: application to a physical rotation system, IEEE Transactions on Control Systems Technology, 29(3), pp. 1332-1339.

[12] Kammer, L.C., Bitmead, R.R., Bartlett, P.L., 2000, Direct iterative tuning via spectral analysis, Automatica, 36(9), pp. 1301-1307.

[13] da Silva Moreira, J., Acioli Júnior, G., Rezende Barros, G., 2018, Time and frequency domain data-driven PID iterative tuning, IFAC-PapersOnLine, 51(15), pp. 1056-1061.

[14] Halmevaara, K., Hyötyniemi, H., 2006, Data-based parameter optimization of dynamic simulation models, Proc. 47th Conference on Simulation and Modelling; Helsinki, Finland, pp. 68-73.

[15] McDaid, A.J., Aw, K.C., Haemmerle, E., Xie, S.-Q., 2012, Control of IPMC actuators for microfluidics with adaptive "online" iterative feedback tuning, IEEE/ASME Transactions on Mechatronics, 17(4), pp. 789-797.

[16] Huang, J.-W., Gao, J.-W., 2020, How could data integrate with control? A review on data-based control strategy, International Journal of Dynamics and Control, 8(4), pp. 1189-1199.

[17] Fliess, M., Join, C., 2009, Model-free control and intelligent PID controllers: towards a possible trivialization of nonlinear control?, IFAC Proceedings Volumes, 42(10), pp. 1531-1550.

[18] Fliess, M., Join, C., 2013, Model-free control, International Journal of Control, 86(12), pp. 2228-2252.

[19] Campi, M.C., Lecchini, A., Savaresi, S.M., 2002, Virtual reference feedback tuning: a direct method for the design of feedback controllers, Automatica, 38(8), pp. 1337-1346.

[20] Formentin, S., Campi, M.C., Caré, A., Savaresi, S.M., 2019, Deterministic continuous-time Virtual Reference Feedback Tuning (VRFT) with application to PID design, Systems and Control Letters, 127, pp. 25-34.

[21] Gao, Z., 2006, Active disturbance rejection control: a paradigm shift in feedback control system design, Proc. 2006 American Control Conference, Minneapolis, MN, USA, pp. 2399-2405.

[22] Roman, R.-C., Precup, R.-E., Petriu. E.M., 2021, Hybrid data-driven fuzzy active disturbance rejection control for tower crane systems, European Journal of Control, 58, pp. 373-387.

[23] Kadali, R., Huang, B., Rossiter, A., 2003, A data driven subspace approach to predictive controller

design, Control Engineering Practice, 11(3), pp. 261-278.

[24] Lucchini, A., Formentin, S., Corno, M., Piga, D., Savaresi, S.M., 2020, Torque vectoring for high-performance electric vehicles: An efficient MPC calibration, IEEE Control Systems Letters, 4(3), pp. 725-730.

[25] Safonov, M.G., Tsao, T.-C., 1997, The unfalsified control concept and learning, IEEE Transactions on Automatic Control, 42(6), pp. 843-847.

[26] Jiang, P., Cheng, Y.-Q., Wang, X.-N., Feng, Z., 2016, Unfalsified visual servoing for simultaneous object recognition and pose tracking, IEEE Transactions on Cybernetics, 46(12), pp. 3032-3046.

[27] Novara, C., Formentin, S., Savaresi, S.M., Milanese, M., 2015, A data-driven approach to nonlinear braking control, Proc. 54th IEEE Conference on Decision and Control, Osaka, Japan, pp. 1-6.

[28] Galluppi, O., Formentin, S., Novara, C., Savaresi, S.M., 2019, Multivariable D2-IBC and application to vehicle stability control, ASME Journal of Dynamic Systems, Measurement, and Control, 141(10), pp. 1-12.

[29] Van Waarde, H.J., Eising, J., Trentelman, H.L., Camlibel, M.K., 2020, Data informativity: a new perspective on data-driven analysis and control, IEEE Transactions on Automatic Control, 65(11), pp. 4753-4768.

[30] Fliess, M., Join, C., 2020, Machine learning and control engineering: the model-free case, in Proceedings of the Future Technologies Conference (FTC) 2020, Volume 1, Arai, K., Kapoor, S., Bhatia, R., Eds. Springer, Cham, pp. 258-278.

[31] Precup, R.-E., Roman, R.-C., Hedrea, E.-L., Petriu, E.M., Bojan-Dragos, C.-A., 2021, Data-driven model-free sliding mode and fuzzy control with experimental validation, International Journal of Computers Communications & Control, 16(1), 4076, pp. 1-17.

[32] Precup, R.-E., Preitl, S., 1997, Popov-type stability analysis method for fuzzy control systems, Proc. Fifth European Congress on Intelligent Technologies and Soft Computing, Aachen, Germany, vol. 2, pp. 1306-1310.

[33] Haber, R.-E., Alique J.R., Alique, A., Hernández, J., Uribe-Etxebarria. R., 2003, Embedded fuzzy-control system for machining processes: Results of a case study, Computers in Industry, 50(3), pp. 353-366.

[34] Precup, R.-E., Preitl, S., Balas, M., Balas, V., 2004, Fuzzy controllers for tire slip control in anti-lock braking systems, Proc. 2004 IEEE International Conference on Fuzzy Systems, Budapest, Hungary, vol. 3, pp. 1317-1322.

[35] Škrjanc, I., Blažič, S., 2005, Predictive functional control based on fuzzy model: design and stability study, Journal of Intelligent and Robotic Systems, 43(2-4), pp. 283-299.

[36] Precup, R.-E, Preitl, S., 2006, Stability and sensitivity analysis of fuzzy control systems. Mechatronics applications, Acta Polytechnica Hungarica, 3(1), pp. 61-76.

[37] Tomescu, M.L., Preitl, S., Precup, R.-E., Tar, J.K., 2007, Stability analysis method for fuzzy control systems dedicated controlling nonlinear processes, Acta Polytechnica Hungarica, 4(3), pp. 127-141.

[38] Angelov, P., Škrjanc, I., Blažič, S., 2013, Robust evolving cloud-based controller for a hydraulic plant, Proc. 2013 IEEE Conference on Evolving and Adaptive Intelligent Systems, Singapore, pp. 1-8.

[39] Johanyák, Z.C., 2015, A simple fuzzy logic based power control for a series hybrid electric vehicle, Proc. 9th IEEE European Modelling Symposium on Mathematical Modelling and Computer Simulation, Madrid, Spain, pp. 207-212.

[40] Vaščák, J., Hvizdoš, J., 2016, Vehicle navigation by fuzzy cognitive maps using sonar and RFID technologies, Proc. IEEE 14th International Symposium on Applied Machine Intelligence and Informatics, Herľany, Slovakia, pp. 75-80.

[41] Du, S., Wu, M., Chen, L.-F., Zhou, K.-L., Hu, J., Cao. W.-H., Pedrycz, W., 2020, A fuzzy control strategy of burn-through point based on the feature extraction of time-series trend for iron ore sintering process, IEEE Transactions on Industrial Informatics, 16(4), pp. 2357-2368.

[42] Castillo, O., Cortés-Antonio, P., Melin, P., Valdez, F., 2020, Type-2 fuzzy control for line following using line detection images, Journal of Intelligent & Fuzzy Systems, 39(5), pp. 6089-6097.

[43] Pan, Y.-N., Du, P.-H., Xue, H., Lam, H.-K., 2021, Singularity-free fixed-time fuzzy control for robotic

systems with user-defined performance, IEEE Transactions on Fuzzy Systems, 29(8), pp. 2388-2398.

[44] Wu, H.-N., Wang, J.-W., Li, H.-X., 2012, Design of distributed H? fuzzy controllers with constraint for nonlinear hyperbolic PDE systems, Automatica, 48(10), pp. 2535-2543.

[45] Simani, S., Alvisi, S., Venturini, M., 2015, Data-driven design of a fault tolerant fuzzy controller for a simulated hydroelectric system, IFAC-PapersOnLine, 48 (21), pp. 1090-1095.

[46] Kamesh, R., Rani, K.Y., 2016, Parameterized data-driven fuzzy model based optimal control of a semi-batch reactor, ISA Transactions, 64, pp. 418-430.

[47] Juang, C.-F., Chang, Y.-C., 2016, Data-driven interpretable fuzzy controller design through multi-objective genetic algorithm, Proc. 2016 IEEE International Conference on Systems, Man, and Cybernetics, Budapest, Hungary, pp. 2403-2408.

[48] Roman, R.-C., Precup, R.-E., David R.-C., 2018, Second order intelligent proportional-integral fuzzy control of twin rotor aerodynamic systems, Procedia Computer Science, 139, pp. 372-380.

[49] Roman, R.-C., Precup, R.-E., Radac, M.-B., 2017, Model-free fuzzy control of twin rotor aerodynamic systems, Proc. 25th Mediterranean Conference on Control and Automation, Valletta, Malta, pp. 559-564.

[50] Roman, R.-C., Precup, R.-E., Bojan-Dragos, C.-A., Szedlak-Stinean, A.-I., 2019, Combined model-free adaptive control with fuzzy component by virtual reference feedback tuning for tower crane systems, Procedia Computer Science, 162, pp. 267-274.

[51] Roman, R.-C., Precup, R.-E., Petriu, E.M., Hedrea, E.-L., Bojan-Dragos, C.-A., Radac, M.-B., 2019, Model-free adaptive control with fuzzy component for tower crane systems, Proc. 2019 IEEE International Conference on Systems, Man and Cybernetics, Bari, Italy, pp. 1384-1389.

[52] Roman, R.-C., Precup, R.-E., Petriu, E.M., Dragan, F., 2019, Combination of data-driven active disturbance rejection and Takagi-Sugeno fuzzy control with experimental validation on tower crane systems, Energies, 12(8), pp. 1-19.

[53] Touhami, M., Hazzab, A., Mokhtari, F., Sicard, P., 2019, Active disturbance rejection controller with ADRC-fuzzy for MAS control, Electrotehnica, Electronica, Automatica (EEA), 67(2), pp. 89-97.

[54] Dombi, J., Hussain, A., 2019, Data-driven arithmetic fuzzy control using the distending function, in IHIET: Human Interaction and Emerging Technologies, Ahram, T., Taiar, R., Colson, S., Choplin, A., Eds. Springer, Cham, Advances in Intelligent Systems and Computing, vol. 1018. pp. 215-221.

[55] Preitl, S., Precup, R.-E., Preitl, Z., Vaivoda, S., Kilyeni, S., Tar J.K., 2007, Iterative feedback and learning control. Servo systems applications, IFAC Proceedings Volumes, 40(8), pp. 16-27.

[56] Precup, R.-E., Preitl, S., Rudas, I.J., Tomescu, M.L., Tar, J.K., 2008, Design and experiments for a class of fuzzy controlled servo systems, IEEE/ASME Transactions on Mechatronics, 13(1), pp. 22-35.

[Ata99] A. N. Atassi, H. Khalil, A separation principle for the stabilization of a class of nonlinear systems, IEEE Transactions on Automatic Control, vol. 44, no. 9, pp. 1672-1687, Sep. 1999.

[Fli13] M. Fliess, C. Join, Model-free control, International Journal of Control, vol. 86, no. 12, pp. 2228–2252, Dec. 2013.

[Kha02] H. Khalil, Nonlinear Systems, Prentice Hall, Upper Saddle River, NJ, 2002.

[Lev03] A. Levant, Higher-order sliding modes, differentiation and output-feedback control, International Journal of Control, vol. 76, no. 9-10, pp. 924-941, Sep. 2003.

[Rom16b] R.-C. Roman, M.-B. Radac, R.-E. Precup, Multi-input-multi-output system experimental validation of model-free control and virtual reference feedback tuning techniques, IET Control Theory & Applications, vol. 10, no. 12, pp. 1395-1403, Aug. 2016.

[Rom18c] R.-C. Roman, Tehnici de tip model-free de acordare a parametrilor regulatoarelor automate, PhD thesis, Editura Politehnica, Timişoara, 2018.

C. RESEARCH TEAM'S PUBLICATIONS

[C1] C. Pozna, R.-E. Precup (corresponding author), E. Horvath and E. M. Petriu, Hybrid Particle Filter-Particle Swarm Optimization Algorithm and Application to Fuzzy Controlled Servo Systems, IEEE Transactions on Fuzzy Systems, vol. 30, no. 10, pp. 4286-4297, 2022, impact according to 2021 Journal Citation Reports (JCR) released by Clarivate Analytics in 2022 = 12.253.

[C2] A.-I. Szedlak-Stînean, R.-E. Precup (corresponding author), E. M. Petriu, R.-C. Roman, E.-L. Hedrea and C.-A. Bojan-Dragoş, Extended Kalman filter and Takagi-Sugeno fuzzy observer for a strip winding system, Expert Systems with Applications (Elsevier), vol. 208, paper 118215, pp. 1-15, 2022, impact factor according to 2021 Journal Citation Reports (JCR) released by Clarivate Analytics in 2022 = 8.665.

[C3] M. Brezovan, R.-E. Precup (corresponding author), D. Selişteanu and L. Stănescu, Colored Petri nets-based control and experimental validation on three-tank system level control, International Journal of General Systems (Taylor & Francis), DOI: 10.1080/03081079.2022.2086542, pp. 1-47, 2022, impact factor according to 2021 Journal Citation Reports (JCR) released by Clarivate Analytics in 2022 = 2.435.

[C4] I. A. Zamfirache, R.-E. Precup (corresponding author), R.-C. Roman and E. M. Petriu, Reinforcement learning-based control using Q-learning and gravitational search algorithm with experimental validation on a nonlinear servo system, Information Sciences (Elsevier), vol. 583, pp. 99-120, 2022, impact factor according to 2021 Journal Citation Reports (JCR) released by Clarivate Analytics in 2022 = 8.233.

[C5] R.-E. Precup, S. Preitl, C.-A. Bojan-Dragoş, E.-L. Hedrea, R.-C. Roman and E. M. Petriu, A low-cost approach to data-driven fuzzy control of servo systems, Facta Universitatis, Series: Mechanical Engineering (University of Nis), vol. 20, no. 1, pp. 21-36, 2022, impact factor according to 2021 Journal Citation Reports (JCR) released by Clarivate Analytics in 2022 = 4.622.

[C6] R.-E. Precup, R.-C. Roman, E.-L. Hedrea, C.-A. Bojan-Dragoş, M.-M. Damian and M.-L. Nedelcea, Performance Improvement of Low-Cost Iterative Learning-Based Fuzzy Control Systems for Tower Crane Systems, International Journal of Computers Communications & Control, vol. 17, no. 1, 4623, pp. 1-18, 2022, impact factor according to 2021 Journal Citation Reports (JCR) released by Clarivate Analytics in 2022 = 2.635.

[C7] I.-D. Borlea, R.-E. Precup (corresponding author) and A.-B. Borlea, Improvement of K-means Cluster Quality by Post Processing Resulted Clusters, Proceedings of 8th International Conference on Information Technology and Quantitative Management ITQM 2020 & 2021, Chengdu, China, 2021, Procedia Computer Science (Elsevier), vol. 199, pp. 63-70, 2022, indexed in Clarivate Analytics Web of Science.

[C8] R.-C. Roman, R.-E. Precup, E.-L. Hedrea, S. Preitl, I. A. Zamfirache, C.-A. Bojan-Dragoş and E. M. Petriu, Iterative Feedback Tuning Algorithm for Tower Crane Systems, Proceedings of 8th International Conference on Information Technology and Quantitative Management ITQM 2020 & 2021, Chengdu, China, 2021, Procedia Computer Science (Elsevier), vol. 199, pp. 157-165, 2022, indexed in Clarivate Analytics Web of Science.

[C9] R.-E. Precup, E.-L. Hedrea, R.-C. Roman, E. M. Petriu, C.-A. Bojan-Dragoş and A.-I. Szedlak-Stînean, GWO-Based Performance Improvement of PD-Type Iterative Learning Fuzzy Control of Tower Crane Systems, Proceedings of 2022 IEEE 31st International Symposium on Industrial Electronics ISIE 2022, Anchorage, AK, USA, pp. 1041-1046, 2022, indexed in INSPEC and Scopus.

[C10] R.-E. Precup, E.-L. Hedrea, R.-C. Roman, E.-M. Petriu, C.-A. Bojan-Dragoş, A.-I. Szedlak-Stînean and F.-C. Paulescu, AVOA-Based Tuning of Low-Cost Fuzzy Controllers for Tower Crane Systems, Proceedings of 2022 IEEE International Conference on Fuzzy Systems FUZZ-IEEE 2022, Padova, Italy, pp. 1-8, 2022, indexed in Clarivate Analytics Web of Science.

[C11] C.-A. Bojan-Dragoş, R.-E. Precup, E. M. Petriu, R.-C. Roman, E.-L. Hedrea and A.-I. Szedlak-Stînean, GWO-Based Optimal Tuning of Controllers for Shape Memory Alloy Wire Actuators, Proceedings of 6th IFAC International Conference on Intelligent Control and Automation Sciences ICONS'22, Cluj-Napoca, Romania, 2022, IFAC-PapersOnLine, vol. 55, no. 15, pp. 39-44, 2022, indexed in Clarivate Analytics Web of Science.

[C12] R.-E. Roman, R.-E. Precup, S. Preitl, C.-A. Bojan-Dragoş, A.-I. Szedlak-Stînean and E.-L. Hedrea, Data-Driven Control Algorithms for Shape Memory Alloys, Proceedings of 2022 IEEE Conference on Control Technology and Applications CCTA 2022, Trieste, Italy, pp. 1306-1312, 2022, to be indexed in IEEE Xplore.

[C13] R.-E. Precup, E.-L. Hedrea, R.-C. Roman, E. M. Petriu, C.-A. Bojan-Dragoş, A.-I. Szedlak-Stînean and C. Hedrea, Evolving Fuzzy and Tensor Product-based Models for Tower Crane Systems, Proceedings of 48th Annual Conference of the IEEE Industrial Electronics Society IECON 2022, Brussels, Belgium, pp. 1-6, 2022, to be indexed in IEEE Xplore.

[C14] A.-I. Szedlak-Stînean, R.-E. Precup, R.-C. Roman, E. M. Petriu, C.-A. Bojan-Dragoş and E.-L. Hedrea, Discrete-time Linear and Nonlinear Observers for an Electromechanical Plant with State Feedback Control, Proceedings of 2022 IEEE Symposium Series on Computational Intelligence SSCI 2022, Singapore, pp. 1-6, 2022, to be indexed in IEEE Xplore.

[C15] C.-B. Gale-Cazan, C.-A. Bojan-Dragoş, R.-E. Precup, R.-C. Roman, E. M. Petriu and A.-I. Szedlak-Stînean, GWO-based Modeling of an Unstable Transport System, Proceedings of 9th International Conference on Information Technology and Quantitative Management ITQM 2022, Beijing and Zhangjiakou, China, pp. 1-8, 2022, to be indexed in sciencedirect.

[C16] E.-L. Hedrea, R.-E. Precup, R.-C. Roman, C.-A. Bojan-Dragoş, A.-I. Szedlak-Stînean and C. Hedrea, Tensor Product-based and State Feedback Structures for Level Control of Vertical Three Tank Systems, Proceedings of 26th International Conference on System Theory, Control and Computing ICSTCC 2022, Sinaia, Romania, pp. 195-200, 2022, to be indexed in IEEE Xplore.

[C17] M.-M. Damian and R.-E. Precup, Signal Preprocessing and Artifact Removal for Brain-Computer Interfaces, Proceedings of IEEE 16th International Symposium on Applied Computational Intelligence and Informatics SACI 2022, Timisoara, Romania, pp. 51-54, 2022, indexed in IEEE Xplore.

[C18] F.-C. Paulescu and R.-E. Precup, Fuzzy Models for a Two-Wheeled Self-Balancing Robot, Proceedings of IEEE 16th International Symposium on Applied Computational Intelligence and Informatics SACI 2022, Timisoara, Romania, pp. 277-282, 2022, indexed in IEEE Xplore.

[C19] C.-A. Bojan-Dragoş, R.-E. Precup and E.-L. Hedrea, Fuzzy Control Systems with Mechatronics Applications (in Romanian: Sisteme de reglare fuzzy cu aplicații mecatronice), Editura Politehnica, Timisoara, 162 pp., 2022.

[C20] A. Albu, R.-E. Precup and T.-A. Teban, Intelligent Paradigms for Diagnosis, Prediction and Control in Healthcare Applications, in: Handbook of Artificial Intelligence in Healthcare, Vol. 2: Practicalities and Prospects, C.-P. Lim, Y.-W. Chen, A. Vaidya, C. Mahorkar and L. C. Jain, Eds., Springer, Cham, Intelligent Systems Reference Library, vol. 212, pp. 3-41, 2022, indexed in Scopus.

[C21] R.-E. Precup and R.-C. David, Nature-Inspired Optimal Tuning of Fuzzy Controllers, Chapter 20 in Handbook on Computer Learning and Intelligence, 2nd Edition, P. P. Angelov, Ed., World Scientific, Singapore, Volume 2: Deep Learning, Intelligent Control and Evolutionary Computation, pp. 775-808, 2022.

Project leader,

Prof.Dr.Eng. Radu-Emil Precup