DATA-DRIVEN NEUROENDOCRINE-PID CONTROLLER FOR MIMO PLANTS BASED ON ADAPTIVE SAFE EXPERIMENTATION DYNAMICS ALGORITHM

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ABSTRAK

Kajian ini memfokuskan pada mekanisma yang berasaskan data dan struktur pengawal dalam skema kawalan berdasarkan data. Mekanisma berasaskan data adalah kaedah pengoptimuman untuk mencari parameter pengawal yang optimum menggunakan data input dan output sistem dan struktur pengawal merujuk kepada reka bentuk pengawal yang bergantung pada sistem input dan output. "Neuroendocrine-PID"(NEPID) sedia ada menggunakan algoritma "simultaneous perturbation stochastic approximation"(SPSA) sebagai mekanisma yang berasaskan oleh data. Walau bagaimanapun, kaedah ini tidak dapat mencari nilai optimum dari parameter reka bentuk kerana penumpuan tidak stabil yang diperoleh dan menurunkan prestasi pengawal dalam sistem MIMO. Oleh itu, algoritma "safe experimentation dynamics"(SED) dipilih untuk menyelesaikan penumpuan yang tidak stabil ini tetapi masih tidak cukup untuk mencapai ketepatan yang tinggi kerana parameter yang dikemas kini hanya bergantung pada kenaikan langkah tetap. Untuk struktur pengawal, parameter kadar rembesan hormon NEPID yang ada adalah tetap sepanjang masa eksperimen yang mana ketepatan kawalan tidak mencukupi kerana kadar rembesan dan ralat pemboleh ubah kawalan tidak dapat berinteraksi secara langsung dan membatasi kemampuan pengawal. Selain itu, struktur pengawal NEPID yang ada pada sistem SISO, hanya satu nod peraturan hormon digunakan kerana satu pemboleh ubah kawalan. Sementara itu, bagi sistem MIMO, terdapat banyak pemboleh ubah kawalan yang saling berinteraksi, dan peraturan hormon tunggal NEPID masih tidak mencukupi bagi menghasilkan ketepatan kawalan sistem MIMO yang lebih baik. Oleh itu, kajian ini mencadangkan algoritma "adaptive safe experimentation dynamics"(ASED) untuk meningkatkan ketepatan prestasi algoritma SED dengan meminimumkan fungsi objektifnya dari segi analisis min, terbaik, terburuk, dan sisihan piawai. Untuk meningkatkan ketepatan kawalan pengawal NEPID yang ada, kajian ini juga menetapkan "sigmoid-based secretion rate-neuroendocrine-PID"(SbSR-NEPID) dengan mengubah kadar rembesan hormon mengikut perubahan ralat. Akhirnya, kajian ini juga memfokuskan pada struktur pengawal "multiple-node hormone regulation-neuroendocrine-PID"(MnHR-NEPID) untuk meningkatkan ketepatan kawalan NEPID sedia ada dengan mengutamakan peraturan kawalan setiap nod dari tahap kesalahan mereka. Prestasi pengawal PID dan NEPID dibandingkan dengan prestasi SbSR-NEPID dan MnHR-NEPID berdasarkan ralat dan penjejakan input. Hasil kajian menunjukkan bahawa kaedah berasaskan ASED dan SED menghasilkan penumpuan yang stabil. Kaedah ASED memberikan prestasi penjejakan yang lebih baik daripada kaedah SED dengan mendapatkan nilai fungsi yang lebih rendah. Selain itu, dari hasil kerja simulasi, reka bentuk SbSR-NEPID dan MnHR-NEPID memberikan ketepatan kawalan yang lebih baik dari segi fungsi objektif yang lebih rendah, norma ralat total, dan jumlah norma input berbanding dengan pengawal PID dan NEPID. Lebih-lebih lagi, pengawal SbSR-NEPID mencapai peningkatan ketepatan kawalan sebanyak 4.95% dan 5.89% untuk sistem kren dan sistem TRMS. Selain itu, pengawal MnHR-NEPID mencapai peningkatan ketepatan kawalan sebanyak 5.7% dan 5.1% untuk sistem kren dan sistem TRMS. Kaedah ASED meningkatkan ketepatan SED dengan menggunakan konsep adaptif berdasarkan perubahan fungsi objektif dalam prosedurnya. Selain itu, SbSR-NEPID berkesan dalam mengurangkan ralat dalam keadaan sementara, dan MnHR-NEPID memberikan interaksi yang berkesan antara nod yang terdapat dalam sistem MIMO yang menyumbang kepada peningkatan ketepatan.

ABSTRACT

This study focused on data-driven tools and controller structure in the data-driven control scheme. Data-driven tools are an optimization method to find the optimal controller parameters using the system's input and output data. Meanwhile, the controller structure refers to the controller design that is highly dependent on the input and output system. The existing data-driven neuroendocrine-PID (NEPID) utilizes the simultaneous perturbation stochastic approximation (SPSA) algorithm as the data-driven tool. However, this SPSA-based method is unable to find the optimal value of the design parameter due to unstable convergence obtained that degrades the controller performance in MIMO systems. Thus, a safe experimentation dynamics (SED) algorithm is selected to solve this unstable convergence but still not enough to achieve high accuracy because the update designed parameter only depends on the fixed step size gain. For the controller structure, the hormone secretion rate parameter of the existing NEPID is constant during the experimental time. However, control accuracy is insufficient because the secretion rate and control variable error are not able to interact directly and limits the controller capability. Besides, in the existing NEPID controller structure of the SISO system, only a single node of hormone regulation is used due to a single control variable. Meanwhile, in the MIMO systems, many control variables available that interact with each other, and the single node hormone regulation of NEPID is still inadequate in producing better control accuracy of nonlinear MIMO systems. Therefore, this study proposed the adaptive safe experimentation dynamics (ASED) algorithm to improve the SED algorithm performance accuracy by minimizing its objective function in terms of mean, best, worst, and standard deviation analysis. In order to increase the control accuracy of the existing NEPID controller, this study also established the sigmoid-based secretion rate neuroendocrine-PID (SbSR-NEPID) controller structure by varying the hormone secretion rate according to the change of error. Finally, this study also focused on developing a multiple node hormone regulation neuroendocrine-PID (MnHR–NEPID) controller structure to improve the control accuracy of existing NEPID by prioritizing the control regulation of each node from their level of error. The performance of PID and NEPID controllers was compared with those of SbSR-NEPID and MnHR-NEPID performances based on error and input tracking. The results show that the ASED- and SED-based methods produced stable convergence. The ASED-based method provided better tracking performance than the SED method by obtaining the objective function's lower values. Besides, from the simulation work, the SbSR-NEPID and MnHR-NEPID designs provided better control accuracy in terms of lower objective function, total norm of error, and total norm of input compared to those of the PID and NEPID controllers. Moreover, the SbSR-NEPID controller achieved control accuracy improvement of 4.95% and 5.89% for the container gantry crane and TRMS systems, respectively. Besides, the MnHR-NEPID controller achieved control accuracy improvement of 5.7% and 5.1% for the container gantry crane and TRMS systems, respectively. The ASED-based method significantly improved the SED method's accuracy by using adaptive terms based on changing the objective function in the updated procedure. Besides, the SbSR-NEPID was effective in reducing the error in a transient state, and MnHR-NEPID provided effective interaction between nodes available in MIMO systems which contributed to accuracy improvement.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE

CHAPTER 5 CONCLUSION

REFERENCES

APPENDIXES

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\alpha_{ij\max}$	upper bound of element $\tilde{\alpha}_{ij}$
$\alpha_{ij\min}$	lower bound of element $\tilde{\alpha}_{ij}$
α_{ij}	secretion rate
α_h	horizontal plane TRMS
α_v	vertical plane TRMS
$\bar{f}$	present best value of objective function
$\bar{\tau}_i$	stored value for best present design parameter
$\bar{e}_j$	performance index of error
$\bar{u}_i$	performance index of control input
β_{ij}	positive real number
$\boldsymbol{\alpha}$	secretion rate vector
$\boldsymbol{\alpha}_{\max}$	vector of upper bound
$\boldsymbol{\alpha}_{\min}$	vector of lower bound
$\boldsymbol{\varepsilon}_{ij}$	vector of shift the centre coefficient
$\boldsymbol{\gamma}_{ij}$	vector of sharpness curve coefficient
$\boldsymbol{\psi}$	logarithm scale of design parameter
$\boldsymbol{\psi}_{opt}$	optimal logarithm scale of design parameter
$\boldsymbol{\tau}(0)$	initial value of design parameter
$\boldsymbol{\tau}_{opt}$	upper bound of design parameter
$\boldsymbol{\lambda}$	constant number vector
$\boldsymbol{\zeta}$	constant number vector
$\boldsymbol{K_D}$	derivative time vector
$\boldsymbol{K_I}$	integral time vector
$\boldsymbol{K_P}$	proportional gain vector
$\boldsymbol{N}$	filter coefficient vector
$\boldsymbol{r}(t)$	reference vector
$\boldsymbol{r}(t)$	vector of reference
$\boldsymbol{u}(t)$	control input vector
$\boldsymbol{u}(t)$	output of NEPID
$\boldsymbol{u}_{C_U}(t)$	output of $C_U(s)$
$\boldsymbol{u}_{N_E}(t)$	output of $N_E(\boldsymbol{e}(t), \Delta\boldsymbol{h}(t))$
$\boldsymbol{y}(t)$	output vector

$\boldsymbol{\tau}(k)$	design parameter vector
$\Delta\alpha_{ij}$	change of $\alpha_{ij\max}$ and $\alpha_{ij\min}$
$\Delta e_j(t)$	change of error
$\Delta h_{ij}(t)$	variance of $h_{ij}(t)$
$\Delta(k)$	random perturbation
ε_{ij}	shift the centre coefficient
η_j	multiple–node switching mechanism
γ_{ij}	sharpness curve coefficient
λ_{ij}	positive real number
$\mathbb{R}_+$	positive real number sets
$\mathbb{R}$	real number sets
μ_{ij}	centre of vector ij node
$\omega(t)$	bidirectional angular velocity
σ_{ij}^2	variance of ij node
$\tau_{\max}$	upper bound of design parameter
$\tau_{\min}$	lower bound of design parameter
τ_i	each element design parameter
$\theta(t)$	sway angle
$\tilde{\alpha}_{ij}$	variable secretion rate of each element
$\tilde{\boldsymbol{\alpha}}$	vector variable secretion rate
ζ_{ij}	positive real number
$a(k)$	gain sequence
$c(k)$	gain sequence
$C_U(s)$	PID controller unit
D	number of sample
E	scalar defines probability
$e_j(t)$	error of element output
$f(\boldsymbol{\tau})$	objective function
t_s	sampling time
u_h	main propeller input voltage
u_v	tail propeller input voltage
$v(t)$	converter voltage
V_{ij}	neuroendocrine controller
w_{ij}	weight coefficient for element ij
$x(t)$	trolley displacement
$Y_{V_{ij}}$	multiple–node hormone intensity

$F_l(t)$	hoist force
$F_x(t)$	trolley force
$g(\boldsymbol{\tau}(k))$	gradient approximation
$G(e_j)$	Gaussian function
H	MIMO plants
$h_{ij}(t)$	each element of $\boldsymbol{u}_{C_U}$
$h_1(t)$	level of tank 1
$h_2(t)$	level of tank 2
i	element input
j	element output
$\boldsymbol{J}_{SbSR}$	SbSR–NEPID objective function $(\boldsymbol{J}(\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D},\boldsymbol{N},\boldsymbol{\zeta},\boldsymbol{\lambda},\boldsymbol{\alpha}_{\min},\Delta\boldsymbol{\alpha},\boldsymbol{\gamma},\boldsymbol{\varepsilon}))$
$\boldsymbol{J}_{MnHR}$	MnHR–NEPID objective function $(\boldsymbol{J}(\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D},\boldsymbol{N},\boldsymbol{\zeta},\boldsymbol{\lambda},\boldsymbol{\alpha},\boldsymbol{\sigma}^2))$
$\boldsymbol{J}$	objective function for NEPID $(\boldsymbol{J}(\boldsymbol{K_P},\boldsymbol{K_I},\boldsymbol{K_D},\boldsymbol{N},\boldsymbol{\alpha},\boldsymbol{\zeta},\boldsymbol{\lambda}))$
$\boldsymbol{J}_{\psi}$	control accuracy improvement
k	iteration
K_{Dij}	derivative time
K_{g1}	ASED interval size
K_{Iij}	integral time
k_{max}	maximum number of iteration
K_{Pij}	proportional gain
K_g	interval size
$l(t)$	length of rope
L_1 ,L_2	direction factor
n	number of design parameter
N_{ij}	filter coefficient
p	number of input
q	number of output
rv_1	random number 0 to 1
rv_2	new random number
t	time
t_0	initial time equal to zero
T_1	threshold error
t_f	final time

LIST OF ABBREVIATIONS

ACO	Ant Colony Optimization
ACTH	Adrenocoticotropic Hormone
ASED	Adaptive Safe Experimentation Dynamics
BEL	Brain Emotional Learning
BF	Bacteria Foraging
CbT	Correlation–Based Tuning
CCU	Conventional Control Unit
CRH	Corticotrophin Release Hormone
FRIT	Fictitious Reference Iterative Tuning
GA	Genetic Algorithm
GT	Game-Theoretic
I/O	Input–Output
IFT	Iterative Feedback Tuning
LTI	Linear-Time-Invariant
MIMO	Multi-Input-Multi-Output
MnHR	Multipl–Node Hormone Regulation
NEPID	Neuroendocrine-Proportional-Integration–Differentiate
PCU	Primary Control Unit
PID	Proportional-Integration-Differentiate
PSO	Particle Swam Optimization
SA	Simulated Annealing
SbSR	Sigmoid-based Secretion Rate
SCU	Secondary Control Unit
SED	Safe Experimentation Dynamics
SISO	Single-Input-Single-Output
SPSA	Simultaneous Perturbation Stochastic Approximation
TRMS	Twin Rotor MIMO System
UC	Un-Falsified Control
UFU	Ultra-Short Feedback Unit
VRFT	Virtual Reference Feedback Tuning

LIST OF APPENDICES

REFERENCES

Ablay, G. (2015). Variable structure controllers for unstable processes. *Journal of Process Control*, 32:10–15.

Aghababa, M. P. (2016). Optimal design of fractional-order pid controller for five bar linkage robot using a new particle swarm optimization algorithm. *soft Computing*, 20(10):4055–4067.

Ahmad, M. A., Azuma, S.-i., and Sugie, T. (2014). Performance analysis of model-free pid tuning of mimo systems based on simultaneous perturbation stochastic approximation. *Expert Systems with Applications*, 41(14):6361–6370.

Ahmad, M. A. and Ismail, R. M. T. R. (2017). A data-driven sigmoid-based pi controller for buck-converter powered dc motor. *2017 IEEE Symposium on Computer Applications and Industrial Electronics*, pages 81–86.

Ahmad, M. A., Mustapha, N. M. Z. A., Nasir, A. N. K., Tumari, M. Z. M., Ismail, R. M. T. R., and Ibrahim, Z. (2018). Using normalized simultaneous perturbation stochastic approximation for stable convergence in model-free control scheme. In *2018 IEEE International Conference on Applied System Invention (ICASI)*, pages 935–938. IEEE.

Ahmad, M. A., Rohani, M., Ismail, R. R., Jusof, M. M., Suid, M. H., and Nasir, A. N. K. (2015). A model-free pid tuning to slosh control using simultaneous perturbation stochastic approximation. In *2015 IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, pages 331–335. IEEE.

Ateş, A., Alagöz, B. B., Yeroğlu, C., and Alisoy, H. (2015). Sigmoid based pid controller implementation for rotor control. In *Control Conference (ECC), 2015 European*, pages 458–463. IEEE.

Azar, A. T., Sayed, A. S., Shahin, A. S., Elkholy, H. A., and Ammar, H. H. (2019). Pid controller for 2-dofs twin rotor mimo system tuned with particle swarm optimization. In *International Conference on Advanced Intelligent Systems and Informatics*, pages 229–242. Springer.

Azar, A. T. and Serrano, F. E. (2018). Fractional order sliding mode pid controller/observer for continuous nonlinear switched systems with pso parameter tuning. In *International Conference on Advanced Machine Learning Technologies and Applications*, pages 13–22. Springer.

Boiko, I. (2013). Variable-structure pid controller for level process. *Control Engineering Practice*, 21(5):700–707.

Cao, F. (2018). Pid controller optimized by genetic algorithm for direct-drive servo system. *Neural Computing and Applications*, pages 1–8.

Chiou, J.-S., Tsai, S.-H., and Liu, M.-T. (2012). A pso-based adaptive fuzzy pid-controllers. *Simulation Modelling Practice and Theory*, 26:49–59.

Civelek, Z., Lüy, M., Çam, E., and Barışçı, N. (2016). Control of pitch angle of wind turbine by fuzzy pid controller. *Intelligent Automation & Soft Computing*, 22(3):463–471.

Dashti, J. M., Shojaee, G. K., Seyedkashi, S. M. H., and Behnam, T. (2010). Novel simulated annealing algorithm in order to optimal adjustment of digital pid controller. In *2010 11th International Conference on Control Automation Robotics & Vision*, pages 1766–1771. IEEE.

Dawood, N. B. (2016). Review of different dc to dc converters based for renewable energy applications. *International Research Journal of Engineering and Technology*, 3(3):46–50.

Ding, Y., Chen, L., and Hao, K. (2018). Human body based intelligent cooperative decoupling controllers. In *Bio-Inspired Collaborative Intelligent Control and Optimization*, pages 25–80. Springer.

Ding, Y., Xu, N., Ren, L., and Hao, K. (2015). Data-driven neuroendocrine ultra-short feedback-based cooperative control system. *IEEE Trans. Contr. Sys. Techn.*, 23(3):1205–1212.

Ding, Y., Zhang, T., Ren, L., Jin, Y., Hao, K., and Chen, L. (2016). Immune-inspired self-adaptive collaborative control allocation for multi-level stretching processes. *Inf. Sci.*, 342:81–95.

Do, S. T. (2012). *Application of spsa-type algorithms to production optimization*. University of Tulsa.

El-Samahy, A. A. and Shamseldin, M. A. (2018). Brushless dc motor tracking control using self-tuning fuzzy pid control and model reference adaptive control. *Ain Shams Engineering Journal*, 9(3):341–352.

Fang, W., Chao, F., Lin, C.-M., Yang, L., Shang, C., and Zhou, C. (2019). An improved fuzzy brain emotional learning model network controller for humanoid robots. *Frontiers in neurorobotics*, 13:2.

Farhan, M. F., Shukor, N. S. A., Ahmad, M. A., Suid, M. H., Ghazali, M. R., and Jusof, M. F. M. (2019). A simplify fuzzy logic controller design based safe experimentation dynamics for pantograph-cateary system. *Indonesian Journal of Electrical Engineering and Computer Science*, 14(2):903–911.

Farhy, L. S. (2004). Modeling of oscillations in endocrine networks with feedback. In *Methods in enzymology*, volume 384, pages 54–81. Elsevier.

Formentin, S., Campi, M. C., and Savaresi, S. M. (2014). Virtual reference feedback tuning for industrial pid controllers. *IFAC Proceedings Volumes*, 47(3):11275–11280.

Gebraad, P. M., van Dam, F. C., and van Wingerden, J.-W. (2013). A model-free distributed approach for wind plant control. In *2013 American Control Conference*, pages 628–633. IEEE.

Goodall, P., Sharpe, R., and West, A. (2019). A data-driven simulation to support remanufacturing operations. *Computers in Industry*, 105:48–60.

Hernández-Márquez, E., Silva-Ortigoza, R., García-Sánchez, J. R., Marcelino-Aranda, M., and Saldaña-González, G. (2018). A dc/dc buck-boost converter–inverter–dc motor system: Sensorless passivity-based control. *IEEE Access*, 6:31486–31492.

Hjalmarsson, H. (2002). Iterative feedback tuning—an overview. *International journal of adaptive control and signal processing*, 16(5):373–395.

Hjalmarsson, H., Gunnarsson, S., and Gevers, M. (1994). A convergent iterative restricted complexity control design scheme. In *Proceedings of 1994 33rd IEEE Conference on Decision and Control*, volume 2, pages 1735–1740. IEEE.

Hou, Z. and Bu, X. (2011). Model free adaptive control with data dropouts. *Expert Systems with Applications*, 38(8):10709–10717.

Hou, Z. and Jin, S. (2011). A novel data-driven control approach for a class of discrete-time nonlinear systems. *IEEE Transactions on Control Systems Technology*, 19(6):1549–1558.

Hou, Z. and Jin, S. (2013). *Model free adaptive control: theory and applications*. CRC press.

Hou, Z.-S. and Wang, Z. (2013). From model-based control to data-driven control: Survey, classification and perspective. *Information Sciences*, 235:3–35.

Ibrahim, H., Hassan, F., and Shomer, A. O. (2014). Optimal pid control of a brushless dc motor using pso and bf techniques. *Ain Shams Engineering Journal*, 5(2):391–398.

Jaafar, H. I. and Mohamed, Z. (2017). Pso-tuned pid controller for a nonlinear double-pendulum crane system. In *Asian Simulation Conference*, pages 203–215. Springer.

Jacknoon, A. and Abido, M. (2017). Ant colony based lqr and pid tuned parameters for controlling inverted pendulum. In *2017 International Conference on Communication, Control, Computing and Electronics Engineering (ICCCCEE)*, pages 1–8. IEEE.

Jagatheesan, K., Anand, B., Samanta, S., Dey, N., Ashour, A. S., and Balas, V. E. (2017). Particle swarm optimisation-based parameters optimisation of pid controller for load frequency control of multi-area reheat thermal power systems. *International Journal of Advanced Intelligence Paradigms*, 9(5-6):464–489.

Jian-Xin, X. and Zhong-Sheng, H. (2009). Notes on data-driven system approaches. *Acta Automatica Sinica*, 35(6):668–675.

Jusof, M. F. M., Nasir, A. N. K., Ahmad, M. A., and Ibrahim, Z. (2018). An exponential based simulated kalman filter algorithm for data-driven pid tuning in liquid slosh controller. In *2018 IEEE International Conference on Applied System Invention (ICASI)*, pages 984–987. IEEE.

Kang, J., Meng, W., Abraham, A., and Liu, H. (2014). An adaptive pid neural network for complex nonlinear system control. *Neurocomputing*, 135:79–85.

Kangwanrat, S., Tipsuwannaporn, V., and Numsomran, A. (2010). Design of pi controller using mrac techniques for coupled-tanks process. In *Control Automation and Systems (ICCAS), 2010 International Conference on*, pages 485–490. IEEE.

Karimi, A., Mišković, L., and Bonvin, D. (2004). Iterative correlation-based controller tuning. *International journal of adaptive control and signal processing*, 18(8):645–664.

Kinoshita, K., Wakitani, S., and Ohno, S. (2018). Design of neural network pid controller based on e-frit. *Electrical Engineering in Japan*, 205(2):33–42.

Ko, C.-N. and Wu, C.-J. (2008). A pso-tuning method for design of fuzzy pid controllers. *Journal of Vibration and Control*, 14(3):375–395.

Li, C., Mao, Y., Zhou, J., Zhang, N., and An, X. (2017a). Design of a fuzzy-pid controller for a nonlinear hydraulic turbine governing system by using a novel gravitational search algorithm based on cauchy mutation and mass weighting. *Applied Soft Computing*, 52:290–305.

Li, X., Wang, Y., Li, N., Han, M., Tang, Y., and Liu, F. (2017b). Optimal fractional order pid controller design for automatic voltage regulator system based on reference model using particle swarm optimization. *International Journal of Machine Learning and Cybernetics*, 8(5):1595–1605.

Liang, X., Ding, Y., Ren, L., Hao, K., and Jin, Y. (2014). Data-driven cooperative intelligent controller based on the endocrine regulation mechanism. *IEEE Transactions on Control Systems Technology*, 22(1):94–101.

Lin, C.-M. and Muthusamy, P. K. (2017). Intelligent brain emotional learning control system design for nonlinear systems. In *2017 11th Asian Control Conference (ASCC)*, pages 958–963. IEEE.

Liu, B., Ren, L., and Ding, Y. (2005). A novel intelligent controller based on modulation of neuroendocrine system. In *International Symposium on Neural Networks*, pages 119–124. Springer.

Liu, X. (2016). Optimization design on fractional order pid controller based on adaptive particle swarm optimization algorithm. *Nonlinear Dynamics*, 84(1):379–386.

Marden, J. R., Ruben, S. D., and Pao, L. Y. (2013). A model-free approach to wind farm control using game theoretic methods. *IEEE Transactions on Control Systems Technology*, 21(4):1207–1214.

Marden, J. R., Young, H. P., Arslan, G., and Shamma, J. S. (2009). Payoff-based dynamics for multiplayer weakly acyclic games. *SIAM Journal on Control and Optimization*, 48(1):373–396.

Mišković, L., Karimi, A., Bonvin, D., and Gevers, M. (2007). Correlation-based tuning of decoupling multivariable controllers. *Automatica*, 43(9):1481–1494.

Mohd, A. b. A. (2015). *Model-Free Controller Design based on Simultaneous Perturbation Stochastic Approximation*. (Kyoto University).

Monje, C. A., Vinagre, B. M., Feliu, V., and Chen, Y. (2008). Tuning and auto-tuning of fractional order controllers for industry applications. *Control engineering practice*, 16(7):798–812.

Narayana, K. L., Kumar, V. N., Dhivya, M., and Raj, R. P. (2015). Application of ant colony optimization in tuning a pid controller to a conical tank. *Indian Journal of Science and Technology*, 8(S2):217–223.

Navalkar, S. T. and van Wingerden, J.-W. (2015). Iterative feedback tuning of an lpv feedforward controller for wind turbine load alleviation. *IFAC-PapersOnLine*, 48(26):207–212.

Ohnishi, Y., Kitagawa, H., Mori, S., Wakitani, S., and Yamamoto, T. (2013). Design of neural networks based frit pid controllers and its applications. *IFAC Proceedings Volumes*, 46(11):355–359.

Pandey, N. D. and Tiwari, D. P. (2017). Comparison between speed control dc motor using genetic algorithm and pso-pid algorithm. *International Journal of Electrical Engineering & Technology*, 8(1).

Park, H., Chwa, D., and Hong, K. (2007). A feedback linearization control of container cranes: Varying rope length. *International Journal of Control Automation and Systems*, 5(4):379.

Park, M.-S., Chwa, D., and Eom, M. (2014). Adaptive sliding-mode antisway control of uncertain overhead cranes with high-speed hoisting motion. *IEEE Transactions on Fuzzy Systems*, 22(5):1262–1271.

Parvat, B. and Patre, B. (2014). Design of smc with decoupler for multi-variable coupled tank process. In *India Conference (INDICON), 2014 Annual IEEE*, pages 1–5. IEEE.

Precup, R.-E., David, R.-C., Petriu, E. M., Preitl, S., and Radac, M.-B. (2011). Fuzzy control systems with reduced parametric sensitivity based on simulated annealing. *IEEE Transactions on industrial electronics*, 59(8):3049–3061.

Rayalla, R., Ambati, R. S., and Gara, B. U. (2019). An improved fractional filter fractional imc-pid controller design and analysis for enhanced performance of non-integer order plus time delay processes. *European Journal of Electrical Engineering*, 21(2):139–147.

Roman, R.-C., Radac, M.-B., Precup, R.-E., and Petriu, E. M. (2016). Data-driven model-free adaptive control tuned by virtual reference feedback tuning. *Acta Polytechnica Hungarica*, 13(1):83–96.

Saeki, M., Hamada, O., Wada, N., and Masubuchi, I. (2006). Pid gain tuning based on falsification using bandpass filters. In *2006 SICE-ICASE International Joint Conference*, pages 4032–4037. IEEE.

Safari, S., Ardehali, M., and Sirizi, M. (2013). Particle swarm optimization based fuzzy logic controller for autonomous green power energy system with hydrogen storage. *Energy conversion and management*, 65:41–49.

Safonov, M. G. and Tsao, T.-C. (1995). The unfalsified control concept: A direct path from experiment to controller. In *Feedback Control, Nonlinear Systems, and Complexity*, pages 196–214. Springer.

Sánchez-Peña, R., Colmegna, P., and Bianchi, F. (2015). Unfalsified control based on the h-infinity controller parameterisation. *International Journal of Systems Science*, 46(15):2820–2831.

Şen, M. A., Bakırcıoğlu, V., and Kalyoncu, M. (2016). Performances comparison of the bees algorithm and genetic algorithm for pid controller tuning. In *Proceedings of the 5th International Conference on Mechatronics and Control Engineering*, pages 126–130. ACM.

Shah, P. and Agashe, S. (2016). Review of fractional pid controller. *Mechatronics*, 38:29–41.

Sharma, M. K. and Kumar, A. (2015). Performance comparison of brain emotional learning-based intelligent controller (belbic) and pi controller for continually stirred tank heater (csth). In *Computational Advancement in Communication Circuits and Systems*, pages 293–301. Springer.

Shukla, D. M. and Panchal, B. (2017). Power electronics converters and wind turbine. *IJEDR*, 5(2):1199–1205.

Shukor, N. S. A., Ahmad, M. A., and Tumari, M. Z. M. (2017). Data-driven pid tuning based on safe experimentation dynamics for control of liquid slosh. In *2017 IEEE 8th Control and System Graduate Research Colloquium (ICSGRC)*, pages 62–66. IEEE.

Sitti, M., Menciassi, A., Ijspeert, A. J., Low, K. H., and Kim, S. (2013). Survey and introduction to the focused section on bio-inspired mechatronics. *IEEE/ASME Transactions on Mechatronics*, 18(2):409–418.

Son, D. and Choi, H. (2018). Iterative feedback tuning of the proportional-integral-differential control of flow over a circular cylinder. *IEEE Transactions on Control Systems Technology*, 27(4):1385–1396.

Åström, K. and Hägglund, T. (2001). The future of pid control. *Control Engineering Practice*, 9(11):1163 – 1175.

Tanaka, Y., Azuma, S.-i., and Sugie, T. (2015). Simultaneous perturbation stochastic approximation with norm-limited update vector. *Asian Journal of Control*, 17(6):2083–2090.

Timmis, J. and Neal, M. (2003). Artificial homeostasis: integrating biologically inspired computing. *Technical Report UWA-DCS-03-043, University of Wales, Aberystwyth.*

Twin Rotor, M. (1998). System advanced teaching manual 1 (33-007-4m5). *Feedback Instruments Ltd, Crowborough, UK.*

Ünal, M., Erdal, H., and Topuz, V. (2012). Trajectory tracking performance comparison between genetic algorithm and ant colony optimization for pid controller tuning on pressure process. *Computer Applications in Engineering Education*, 20(3):518–528.

Varshney, T., Varshney, R., and Singh, N. (2018). A dpso-based nn-pid controller for mimo systems. In *Ambient Communications and Computer Systems*, pages 535–551. Springer.

Wakitani, S., Nishida, K., Nakamoto, M., and Yamamoto, T. (2013). Design of a data-driven pid controller using operating data. *IFAC Proceedings Volumes*, 46(11):587–592.

Wang, X., Zhang, G., Neri, F., Jiang, T., Zhao, J., Gheorghe, M., Ipate, F., and Lefticaru, R. (2016). Design and implementation of membrane controllers for trajectory tracking of nonholonomic wheeled mobile robots. *Integrated Computer-Aided Engineering*, 23(1):15–30.

Waugh, A. and Grant, A. (2014). Anatomy and physiology in health and illness. *Elsevier Health Sciences*, 10th Edition:212–215.

Weng, Y. and Gao, X. (2017). Data-driven sliding mode control of unknown mimo nonlinear discrete-time systems with moving pid sliding surface. *Journal of the Franklin Institute*, 354(15):6463–6502.

Yamamoto, T., Takao, K., and Yamada, T. (2009). Design of a data-driven pid controller. *IEEE Transactions on Control Systems Technology*, 17(1):29–39.

Ye, Y., Yin, C.-B., Gong, Y., and Zhou, J.-j. (2017). Position control of nonlinear hydraulic system using an improved pso based pid controller. *Mechanical Systems and Signal Processing*, 83:241–259.

Zhang, T., Jin, Y., Ding, Y., and Hao, K. (2015). A cytokine network-inspired cooperative control system for multi-stage stretching processes in fiber production. *Soft Computing*, 19(6):1523–1540.

Zhao, J., Lin, C.-M., and Chao, F. (2019). Wavelet fuzzy brain emotional learning control system design for mimo uncertain nonlinear systems. *Frontiers in Neuroscience*, 12:918.

Zhu, D., Zhao, Y., and Yan, M. (2012). A bio-inspired neurodynamics based backstepping path-following control of an auv with ocean current. *I. J. Robotics and Automation*, 27.

Zribi, A., Chtourou, M., and Djemel, M. (2018). A new pid neural network controller design for nonlinear processes. *Journal of Circuits, Systems and Computers*, 27(04):1850065.