An Ontological Model of Peltier Thermoelement Control based on a Fuzzy Digital Filter and a PID-controller

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Abstract

The ontological model of Peltier thermoelement control is presented in the article. It consists of a PID-controller, a fuzzy digital filter and an exponential moving average filter, implemented in software in the microcontroller. The ontological model calculates the voltage value, which is transmitted to the gate of the MOSFET-transistor. The field-effect transistor converts the applied voltage into a drain current signal, and this value is transmitted to the Peltier thermoelement. Voltage is removed from the Peltier thermoelement using thermistor, which is converted into a temperature value and limited from 25°C to 75°C. The technique for converting voltage to temperature is presented in the article. The temperature signal is transmitted to the input of the microcontroller. Also, a user-defined signal is fed to the input of the microcontroller, which must select the appropriate temperature value on the thermocouple. The fuzzy model, depending on the input signal, forms the coefficients of the exponential averaging filter. A limitation of the fuzzy method for calculating the coefficients used in the ontological model of thermoelement control is the use of triangular membership functions to describe the input variables. The experimental results presented in the article showed that when using a combination of a PID-controller, a fuzzy digital filter and an exponential moving average filter, the transient time during Peltier thermoelement control is reduced: overshoot reduced by 2.44%, achieved a 11.25% faster response time, and ensured 4.19% quicker stabilization.

Keywords

PID-controller, Peltier thermoelement ontology, Fuzzy logic, Fuzzy digital filter, Exponential moving average filter

1. Introduction

Systems with a PID-controller are often used in temperature control devices: a cutting tool cooling device [1], a device for regulating the temperature of a climatic chamber [2], a control system for electromechanical equipment [3], a temperature control system in a greenhouse [4], a controller for the performance and energy consumption of an industrial air conditioner [5], a control device for the air conditioning system of a car [6]. However, the PID-controller has two significant drawbacks: a large jump in the amplitude of the first harmonic of the output control signal (leading to a voltage jump that clearly accelerates the wear of the elements of the entire system) [7] and a long transient process time when the control signal goes to the specified values [8]. The third drawback of the PID-controller is the need to select the controlled coefficients Kp, Ki and Kd [9]. In one of the studies, this drawback was solved using a genetic method that allows for automatic selection of the controlled coefficients [10]. In [4], a neuro-fuzzy approach is used to solve the same drawback. In the study [2], scientists abandoned PID-control in favor of the Tsukamoto method. In this article, it is proposed to use a PID-controller modified using a combination of a fuzzy digital filter (FDF) and an exponential moving average filter (EMAF) [11] to control a Peltier thermoelement (PTE). FDF and EMAF allow to reduce the time of transient processes when controlling a PTE by reducing the jump in the amplitude of the first harmonic of the output control signal. With this approach, it is enough to set the controlled coefficients once and

The 2024 Sixth Doctoral Symposium on Intelligence Enabled Research (DoSIER 2024), November 28–29, 2024, Jalpaiguri, India
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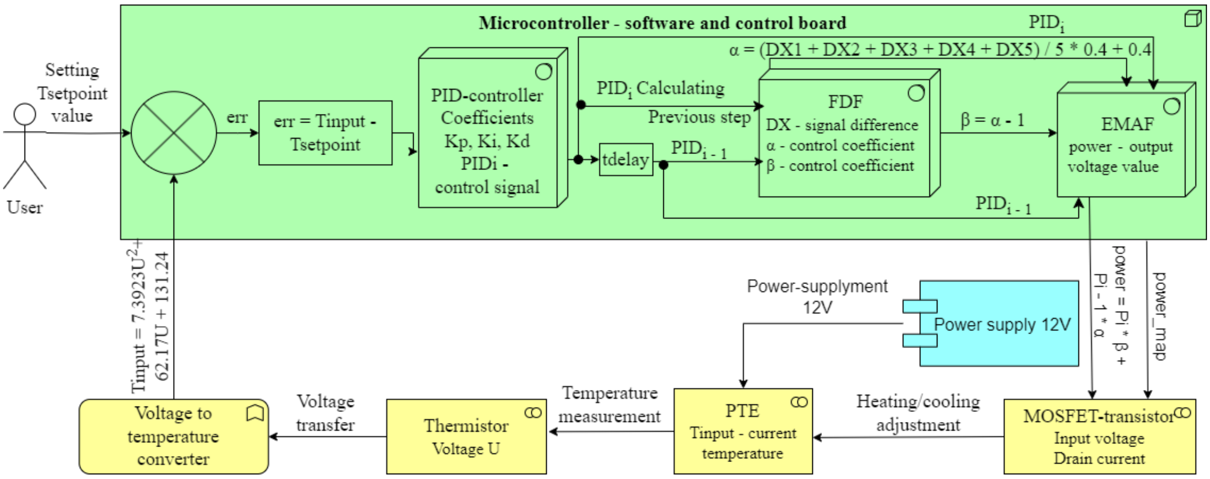

Figure 1: The ontological model of PTE control

not change them. Thus, all the main problems of the PID-controller are eliminated at once. At present, there are already modifications of the PID-controller using fuzzy logic blocks [6], [10], [12]. There are also exponential averaging modifications [9], but the combination used in this article is presented for the first time.

2. Methodological basis of the ontological model of Peltier thermoelement control

The Ontological Model of Peltier Thermoelement Control (OMPTC) allows to organize the structure of the system and describe the interaction of its components. OMPTC is represented as the following formula:

$$O_m = \left\langle \overset{10}{\underset{i=1}{O_c}},\ \overset{21}{\underset{j=1}{O_a}},\ \overset{18}{\underset{k=1}{O_r}}, \right\rangle \tag{1}$$

where O_c is the ontology of concepts, O_a is the ontology of attributes, O_r is the ontology of relations [13].

The graphical representation of the ontological model is shown in Fig.1.

A list of elements is used to describe the process of TE control, such as a MOSFET-transistor, PTE, thermistor, power supply and microcontroller (MC), in which the following are software implemented: comparison unit, PID-controller, FDF, EMAF; voltage converter, indicating their attributes and interrelations. The list of elements is summarized in Table 1.

The structure of the computational processes for controlling the PTE is presented as a two-level system in Fig.2. This structure allows to reduce the time of transient processes and reduce the jump in the amplitude of the first harmonic of the output control signal of the PID-controller. The first level includes the following computational processes: converting the thermistor voltage into temperature; calculating the PIDi control signal using the PID-controller; smoothing this signal using the FDF based on fuzzification of input data and the area ratio defuzzification method, forming the optimal voltage for the MOSFET-gate using the EMAF.

The second level of the system is designed to control the intensity of cooling or heating of the PTE. It includes the following computational processes: regulating the PTE power using the MOSFET-transistor, measuring the temperature on the PTE using the thermistor, transmitting the voltage by the thermistor to the voltage converter.

At the initial stage of the OMTC operation, data is received from the thermistor. For this purpose, it is necessary to calculate the temperature value Tinput based on the dependence of the voltages at

Table 1
Specification of concepts of the OMPTC

Concepts O_c	**Attributes** O_a	**Relationships** O_r
PTE O_{c_1}	PTE type (Peltier element) O_{a_1}	Controlled by the drain current of the MOSFET transistor O_{r_1}, the temperature is measured by the thermistor O_{r_2}.
	Power O_{a_2}	
	Efficiency O_{a_3}	
Thermistor O_{c_2}	Temperature O_{a_4}	Measures the temperature of the PTE O_{r_3}. Transmits temperature data to the voltage converter O_{r_4}.
	Resistance O_{a_5}	
MC O_{c_3}	Clock frequency O_{a_6}	Controls the PID-controller and the MOSFET-transistor O_{r_5}. Connected to the zero bus O_{r_6}.
	Memory capacity O_{a_7}	
User O_{c_4}	*Setpoint* O_{a_8}	Sets the specified value O_{r_7}. The value goes to the comparison block O_{r_8}.
Comparison block O_{c_5}	*Tinput* O_{a_9}	Receives data from the voltage converter and the set value O_{r_9}. Gives a signal about the need for regulation $O_{r_{10}}$.
	Tsetpoint $O_{a_{10}}$	
PID-controller O_{c_6}	Coefficient K_p $O_{a_{11}}$	Receives power data after a signal about the need for regulation $O_{r_{11}}$. Calculates the control signal for the FDF $O_{r_{12}}$.
	Coefficient K_i $O_{a_{12}}$	
	Coefficient K_d $O_{a_{13}}$	
	dt $O_{a_{14}}$	
	Output PID$_i$ $O_{a_{15}}$	
FDF O_{c_7}	α $O_{a_{16}}$	Processes the control signal of the PID-controller using a smoothing algorithm $O_{r_{13}}$.
	β $O_{a_{17}}$	
EMAF O_{c_8}	Output value power $O_{a_{18}}$	From the signal coming from the FDF, it forms an output signal and transmits it to the MOSFET-transistor $O_{r_{14}}$.
MOSFET-transistor O_{c_9}	Current $O_{a_{19}}$	Receives control signal from EMAF controller $O_{r_{15}}$. Connected to zero bus $O_{r_{16}}$.
	Voltage $O_{a_{20}}$	
Power supply $O_{c_{10}}$	Voltage $O_{a_{21}}$	Connected to the 12V TE $O_{r_{17}}$, zero bus $O_{r_{18}}$.

the analog output of the thermistor, using a formula based on polynomial regression [14], which is obtained empirically:

$$T_{input} = 7.39 \times U^2 + 62.17 \times U + 131.24, \tag{2}$$

where U is the voltage at the analog input of the MC.

Thus, according to Eq.2, the MC calculates the temperature of the PTE using information coming from the thermistor, which is fixed on the surface of the PTE.

PID-controller is used to control the thermoelement, ensuring that the set temperature is maintained. For this purpose, a controlled signal is calculated, the task of which is to reduce the difference between the temperature set by the user $T_{setpoint}$ and the actual T_{input} received from the thermistor in the MC:

$$err = T_{setpoint} - T_{input} \rightarrow min. \tag{3}$$

The coefficients proportional K_p, integrating K_i, differentiating K_d, integration step dt have specific values and do not need to be calculated. Thus, the following signal is generated at the output of the PID-controller [15]:

$$PID_i = err \times K_p + err \times dt \times K_i + \frac{(err_i - err_{i-1}) \times K_d}{dt}. \tag{4}$$

From the control signal of the PID-controller PID_i, a delay signal PID_{i-1} is formed, determined after a specified time interval t_{delay}. Both signals are transmitted to the FDF for further smoothing using a fuzzy rule base.

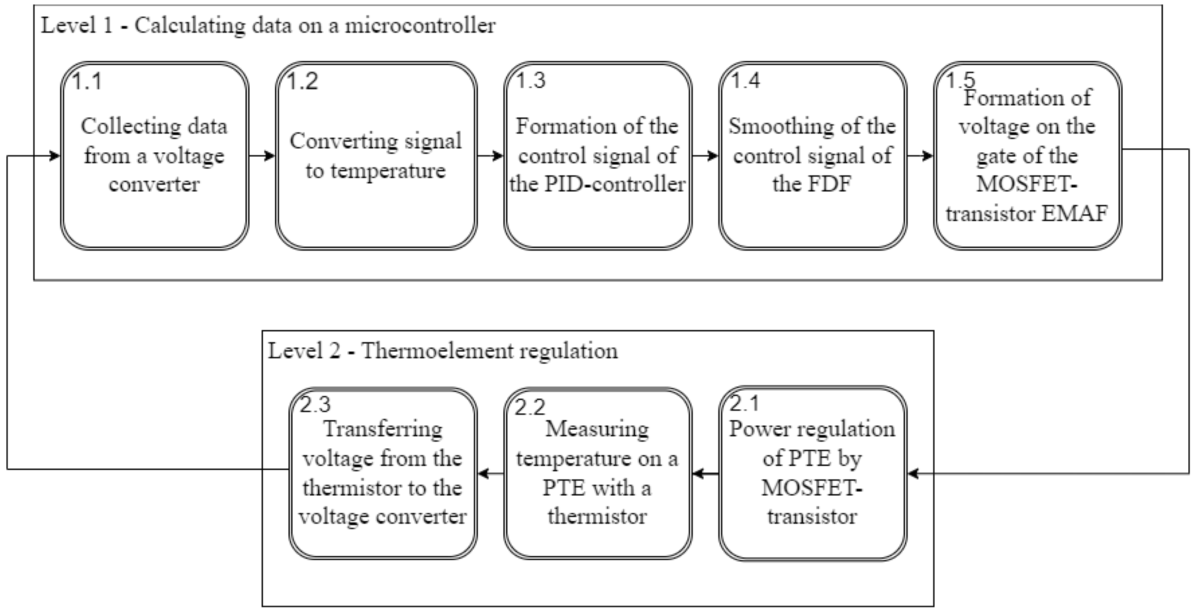

Figure 2: The structure of computational processes in a two-level PTE control system

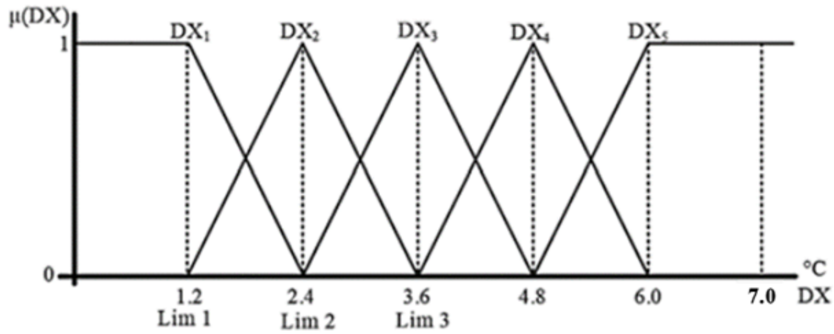

Figure 3: Input membership functions, where the labels Lim_1, Lim_2, Lim_3 are designated for the second membership function DX_2

After the PID-controller generates the control signal, it is necessary to smooth it to eliminate sharp jumps and reduce the load on the MOSFET-transistor. For this purpose, a FDF is used, which eliminates high-frequency interference in the signal. The EMAF signal smoothing formula is formulated as follows:

$$DX = PID_i - PID_{i-1}. \tag{5}$$

where PID_i is the current signal of the PID-controller, PID_{i-1} is the delay signal determined after a specified time interval dt.

Transform the variable DX (see Eq.5) into a linguistic variable with terms DX = DX1, DX2, DX3, DX4, DX5. The core of the input linguistic variable is the range of values from 0.0 to 7.0. The graph of the input membership function is shown in Fig.3.

The output linguistic variable is the control coefficient α, consisting of five terms: M1, M2, M3, M4, M5, which is set by a proportional value in the range from 40% to 80% [0.4; 0.8] of its maximum value [17]. The bases of the input membership functions (see Eqs.6-8) and fuzzy rules (see Eqs.9-13) are presented below:

$$\mu(DX)_1 = \begin{cases} 1, & \text{if } DX > 0 \text{ and } DX < Lim_1 \\ \frac{Lim_2 - DX}{Lim_2 - Lim_1}, & \text{if } DX > Lim_1 \text{ and } DX < Lim_2 \\ 0, & \text{else;} \end{cases} \tag{6}$$

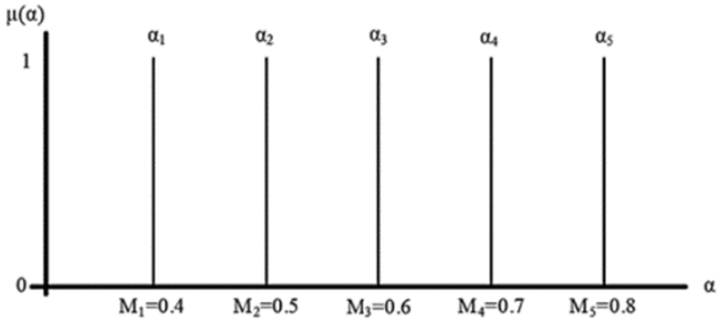

Figure 4: Output membership functions

$$\mu(DX)_{2,3,4} = \begin{cases} \frac{DX-Lim_1}{Lim_2-Lim_1}, & \text{if } DX > Lim_1 \text{ and } DX < Lim_2 \\ \frac{Lim_3-DX}{Lim_3-Lim_2}, & \text{if } DX > Lim_2 \text{ and } DX < Lim_3 \\ 0, & \text{else;} \end{cases} \tag{7}$$

$$\mu(DX)_5 = \begin{cases} \frac{DX-Lim_1}{Lim_2-Lim_1}, & \text{if } DX > Lim_1 \text{ and } DX < Lim_2 \\ 1, & \text{if } DX > Lim_2 \text{ and } DX < Lim_3 \\ 0, & \text{else;} \end{cases} \tag{8}$$

$$IF\ \ DX_1\ \ THEN\ \ M_1 \tag{9}$$

$$IF\ \ DX_2\ \ THEN\ \ M_2 \tag{10}$$

$$IF\ \ DX_3\ \ THEN\ \ M_3 \tag{11}$$

$$IF\ \ DX_4\ \ THEN\ \ M_4 \tag{12}$$

$$IF\ \ DX_5\ \ THEN\ \ M_5 \tag{13}$$

The graph of the output membership function is shown in Figure 4.
The control coefficient α is calculated using the following formula:

$$\alpha = \frac{\sum_{i=1}^{5} DX_i - M_i}{\sum_{i=1}^{5} DX_i}. \tag{14}$$

Calculating the β coefficient:

$$\beta = 1 - \alpha. \tag{15}$$

The coefficient β is necessary for the final calculation of the output voltage value from EMAF U_g. The U_g value is calculated according to the following form:

$$U_g = PID_{i-1} \times \alpha + PID_i \times \beta. \tag{16}$$

After calculating the voltage Ug, it is converted into a range suitable for the eight-bit DAC at the output of the MC (Arduino) [16]:

$$power_{map} = U_g \times 100/255. \tag{17}$$

The output voltage Ug after processing by the EMAF is transferred to the drain of the MOSFET-transistor, which is used to switch the power of the PTE [17].

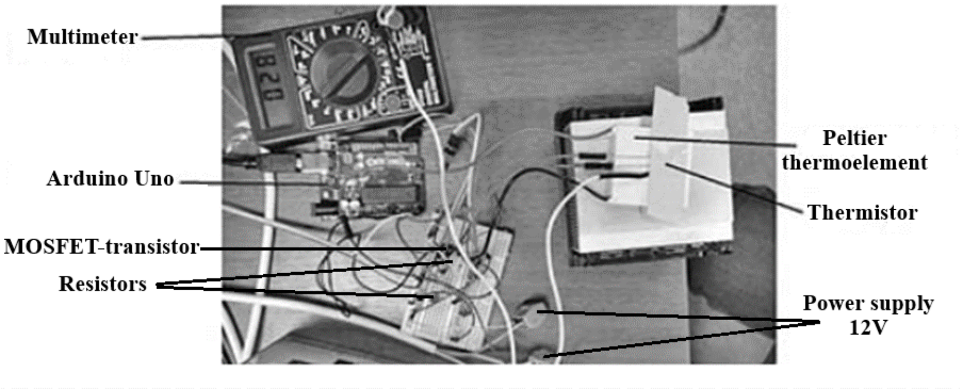

Figure 5: The experimental setup OMPTC with FDF

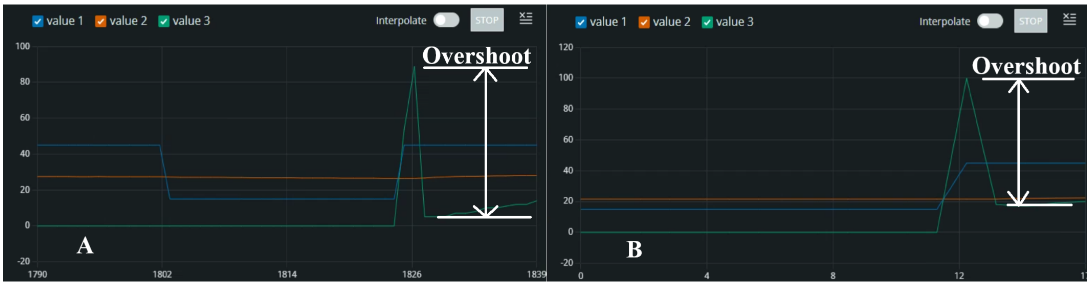

Figure 6: OMPTC reaction when user set $T_{setpoint}$: A is default PID-regulator, B is PID-regulator with FDF and EMAF

3. Experimental research

The characteristics of the OMPTC were determined by conducting experimental studies. The experimental setup of the control system with software-implemented FDF, EMAF and PID-regulator is shown in Fig.5.

The objective of the experiment was to compare the performance of the OMPTC system using the default PID-regulator against the enhanced PID-regulator with FDF and EMAF. During the experiment, the user set a target temperature of $T_{setpoint}$ = 45°C, represented by the value1 signal (blue). This signal remained constant over time, indicating that the system was maintaining the desired temperature.

Signal value2 (orange) represents the current measured temperature T_{input} from the PTE obtained via a thermistor. When value1 changes, the control system adjusts the PTE temperature to approach the target value, demonstrating effective regulation.

Signal value3 (green): This is the control signal representing the voltage $power_{map}$ applied from MC (Arduino) to the MOSFET-transistor. The MOSFET-transistor regulates the power supplied to the PTE. The sharp spikes and subsequent drops in this signal indicate the process of power regulation to minimize the deviation from the target temperature. The behavior of the default PID-regulator and the enhanced PID-regulator (with FDF and EMAF) is shown in Figs.6-8:

The results of the experiment are summarized in Table 2.

Table 2
OMPTC default PID-regulator and FDF EMAF PID-regulator comparison

Characteristics	default PID-regulator	FDF and EMAF PID-regulator
Overshoot reduction	82	80
Response time	1:20	1:11
Stabilization time	5:34	5:20

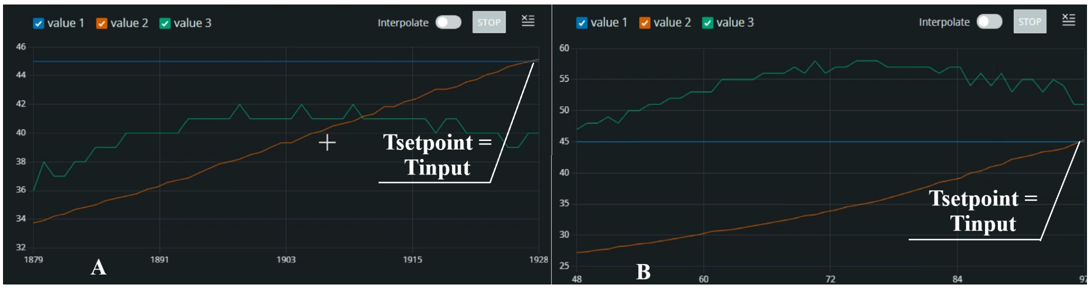

Figure 7: T_{input} equal $T_{setpiont}$ moment: A is default PID-regulator, B is PID-regulator with FDF and EMAF

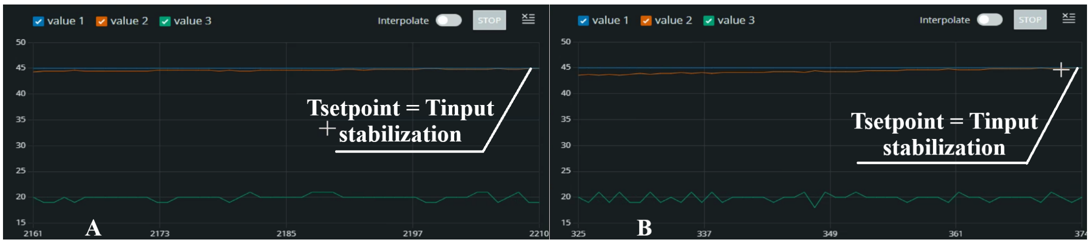

Figure 8: Convergence of $T_{setpoint}$ and T_{input} at the end of PID-adjustment: A is default PID-regulator, B is PID-regulator with FDF and EMAF

4. Conclusion

The experiment aimed to compare the performance of the OMPTC system with a default PID-regulator against the OMPTC system enhanced with FDF and EMAF in terms of temperature control and stabilization. Based on the results, the FDF and EMAF PID-regulator demonstrated better performance across all key indicators: it reduces overshoot by 2.44%, achieves a 11.25% faster response time, and ensures 4.19% quicker stabilization.

5. Acknowledgments

The work was prepared as part of the implementation of the RSF project No. 24-21-00055. The authors are grateful to the Foundation for their support.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References

[1] M. V. Bobyr, A. S. Yakushev, A. A. Dorodnykh, Fuzzy devices for cooling the cutting tool of the cnc machine implemented on fpga, Measurement 152 (2020). doi:10.1016/j.measurement.2019.107378.

[2] A. K. Putra, T. Rahmawati, P. A. Tetraputra, S. Misra, Comparing temperature and humidity control using pid and fuzzy logic in a climatic chamber, Jurnal Teknokes 17 (2024) 117–120. doi:10.35882/teknokes.v17i2.493.

[3] S. M. Yesaulov, O. F. Babicheva, M. Khvorost, M. Naidonov, Application of fuzzy logic in the control system of electromechanical equipment, Municipal economy of cities 6 (2023). doi:10.33042/2522-1809-2023-6-180-33-42.

[4] M. Outanoute, A. Selmani, H. Oubehar, A. Snoussi, M. Guerbaoui, A. Ed-Dahhak, A. Lachhab, B. Bouchikhi, Self tuning fuzzy-pid controller in real time greenhouse temperature control,

in: B. Bachir (Ed.), Proceedings of the Third International Conference on Optimization and Applications (ICOA 2017), Meknes Morocco, 2017.
[5] L. Barelli, G. Bidini, R. Arce, Fuzzy logic regulator for the performance improvement and the energy consumption reduction of an industrial chiller, in: Proceedings of the ASME 2003 International Mechanical Engineering Congress and Exposition, volume 2, ASME, 2008, pp. 1218–1221. doi:10.1115/IMECE2003-41910.
[6] A. U. Yakubu, S. Xiong, Q. Jiang, Z. Zhao, Z. Wu, H. Wang, X. Ye, H. Wangsen, Fuzzy-based thermal management control analysis of vehicle air conditioning system, International Journal of Hydrogen Energy 77 (2024). doi:10.1016/j.ijhydene.2024.06.030.
[7] A. Leva, M. Zamuner, Model parametrisation and rule selection for problem-tailored pid autotuning, IFAC-PapersOnLine 58 (2024) 43–48. doi:10.1016/j.ifacol.2024.08.008.
[8] S. J. Bassi, E. D. Gbenga, A. Abidemi, D. Oyewola, B. K. Mohammed, Metaheuristic algorithms for pid controller parameters tuning: Review, approaches and open problems, Heliyon 8 (2022). doi:10.1016/j.heliyon.2022.e09399.
[9] L. Keviczky, C. Bányász, Adaptive iterative method to improve the robustness of pid regulators, IFAC-PapersOnLine 55 (2022) 149–155. doi:10.1016/j.ifacol.2022.07.303.
[10] R. K. Signe, F. B. Motto, Fuzzy-pid controller based sliding-mode for suppressing low frequency oscillations of the synchronous generator, Heliyon 10 (2024). doi:10.1016/j.heliyon.2024.e35035.
[11] Z. Ma, T. Pan, J. Tian, Deep reinforcement learning optimized double exponentially weighted moving average controller for chemical mechanical polishing processes, Chemical Engineering Research and Design 197 (2023) 419–433. doi:10.1016/j.cherd.2023.07.049.
[12] W. Xian, Q. Qi, W. Liu, Y. Liu, D. Li, Y. Wang, Control of quadrotor robot via optimized nonlinear type-2 fuzzy fractional pid with fractional filter: Theory and experiment, Aerospace Science and Technology 151 (2024). doi:10.1016/j.ast.2024.109286.
[13] A. Grebeshkov, R. Shebalov, S. Gorshkov, O. Mushtak, Ontological modelling of enterprises: technologies and methods, 1st ed., TriniData LLC and Ural Federal University, Yekaterinburg Russia, 2019.
[14] M. V. Bobyr, N. A. Milostnaya, V. A. Bulatnikov, The fuzzy filter based on the method of areas' ratio, Applied Soft Computing 117 (2022). doi:10.1016/j.asoc.2022.108449.
[15] M. Bobyr, V. Titov, A. Belyaev, Fuzzy system of distribution of braking forces on the engines of a mobile robot, in: Proceedings of the MATEC Web of Conferences, volume 79, MATEC Web of Conferences, EDP Sciences, Les Ulis France, 2016, pp. 3–7. doi:10.1051/matecconf/20167901052.
[16] A. Jalahi, M. Linke, C. Weltzien, P. Mahajan, Developing an arduino-based control system for temperature-dependent gas modification in a fruit storage container, Computers and Electronics in Agriculture 198 (2022). doi:10.1016/j.compag.2022.107126.
[17] F. Loche-Moinet, L. Theolier, E. Woirgard, Electro-thermo-mechanical modelling of a sic mosfet transistor under non-destructive short-circuit, Microelectronics Reliability 150 (2023). doi:10.1016/j.microrel.2023.115143.
[18] E. van Krieken, E. Acar, F. van Harmelen, Analyzing differentiable fuzzy logic operators, Artificial Intelligence 302 (2022). doi:10.1016/j.artint.2021.103602.
[19] M. Bobyr, A. E. Arkhipov, S. Emelyanov, N. Milostnaya, A method for creating a depth map based on a three-level fuzzy model, Engineering Applications of Artificial Intelligence 117 (2023). doi:10.1016/j.engappai.2022.105629.