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Correspondence author
O. O. Shynkarenko
oshynkarenko1503@gmail.com

O. O. Shynkarenko, O. V. Silagin

Vinnytsia National Technical University, Vinnytsia, Ukraine

MODELLING OF THE PROCESS OF CONTROLLING THE STATE OF A CLOSED AQUATIC ENVIRONMENT USING FUZZY LOGIC

In the state of significant development of aquaculture, the problem of managing the parameters of the aquatic environment becomes more urgent. Existing classic systems for controlling parameters of closed aquatic environments use strict models of dynamic control and are used for monitoring, control and regulation of those parameters. These models have a number of disadvantages related to the specifics of strict algorithmic control and the complexity of adequate models for growing living organisms. Such models require significant calculations related to solving differential equations and are bad in adaptation to uncommon changes of parameters due to external factors. In addition, such models are prone to fluctuations in parameter value changes in transient processes. The study emphasizes the importance of an adaptive control approach in aquatic biotechnical systems operating in unpredictable environments. The proposed model accounts for the uncertainty and incompleteness of information that arises during the monitoring of parameters such as temperature, oxygen level and other critical indicators. The implementation of such a system can reduce the risk of biological material loss and improve the efficiency of technological processes. The article also outlines the potential for using the model in conjunction with modern real-time data acquisition systems to improve control accuracy. To improve the control process, the use of a fuzzy logic apparatus is proposed. An improved model for controlling the state of closed aquatic environment based on the Mamdani method was created. A controller structure with a fuzzy logic inference module based on the transformation of input signal data into linguistic variables has been developed, which allows to avoid the solution of differential equations and transfer the solution of the problem to the system of logical rules activation. The work of the created model was tested and compared with the classic control system. The results of experimental testing confirm the effectiveness of the approach: the control error has been reduced, and the stabilization time after external disturbances has been shortened. The created model allows to adequately respond to changes in environmental indicators and avoids fluctuations in the value of the controlled parameter, which makes the system work more predictable and reliable. The prospects of using the developed model for combining the values of several input parameters for the formation of a logical conclusion are given.

Keywords: control model, fuzzy interference, aquaculture, linguistic variable.

Introduction

One of the areas of agriculture is aquaculture, which is the cultivation of aquatic organisms for the purpose of obtaining marketable products and their sale, artificial breeding or reproduction of aquatic bioresources, provision of recreational services, etc. A common approach to aquaculture is the use of aquariums. Designing and implementing effective control systems for aquariums is extremely important to ensure a healthy and stable environment for aquatic organisms. The main objective of aquarium research is to monitor, control and regulate their main parameters, such as water quality, temperature, light level, acidity and oxygen percentage, to provide the best conditions for the cultivation of aquatic organisms [1].

Among the problems that aquarium control systems must solve is the problem of the system's ability to adapt to atypical changes in the main parameters of a closed aquatic environment due to technical malfunctions or external factors, such as changes in the temperature of the room, excessive amounts of food or waste entering the water. In addition, different aquatic organisms require their own mode of operation of the closed aquatic environment and the appropriate response of the system to deviations from the norm. Therefore, the problem of solving the problems of controlling the parameters of a closed aquatic environment is relevant.

Traditional systems operate with clear sensor data based on pre-calculated mathematical models that may not take into account variable environmental conditions and incomplete input information. In addition, such systems are prone to an increase in the amplitude of fluctuations in parameter values [2]. If such errors and inaccuracies are taken into account, the number of mathematical calculations and the response time of the system increase significantly. To solve the problem of uncertainty and incompleteness of input data, as well as to get rid of excessive fluctuations during the operation of the control system, and to simplify the number of calculations, the use of a model based on fuzzy logic with the use of fuzzy linguistic variables and the mechanism of fuzzy logical inference can help.

The object of research is the process of controlling the parameters of a closed water environment.

The subject of research is algorithms and methods that provide the process of controlling the parameters of a closed water environment.

Purpose of research is to reduce the amplitude of oscillations of the error signal in the process of controlling the parameters of a closed water environment.

To achieve this goal, the following main *research objectives* have been defined:

- to study the subject area of controlling the parameters of a closed water environment;
- to create a model of a fuzzy module for controlling the parameters of a closed water environment;
- to implement the model of the fuzzy module with modern software tools;
- to test the correctness of controlling the parameters of a closed water environment by the implemented fuzzy module;
- to consider the possibilities of expanding and prospects for the development of the model of a fuzzy module for controlling the parameters of a closed water environment.

Materials and methods of research. The study uses modeling and analysis methods to develop a controller based on fuzzy logic and compares it with a PID controller. The fuzzy logic methods were used to build a control system, as well as error analysis based on the calculation of the output signal deviation amplitude. Data structures, namely dictionaries, lists, and arrays, were used to implement the algorithms [6, 7].

The study was carried out using the Python programming language [8] in the Jupyter Notebook environment [9]. The scikit-fuzzy library [10] was used to develop the fuzzy controller. The results were visualized using the matplotlib library [11]. Numerical calculations were performed using the numpy library [12]. The modeling of dynamic systems was carried out using simulation methods for analyzing the behavior of a controlled object [13].

Analysis of recent research and publications. Regulation of the parameters of a closed water environment is carried out by changing the operating modes of the pump of the closed water environment, changing the lighting modes using a system of sensors that collect information about the main parameters of the closed water environment and a system of controllers that will change the operating modes of the main components of the closed water environment. This may be a situation in which an object needs to be heated, cooled, or both consistently in response to environmental changes.

Traditionally, automatic control is associated with defining differential equations that describe it quantitatively in accordance with the laws of physics, thermodynamics, and electromagnetism. Defining differential equations requires a deep understanding of the processes occurring in the object of management (in the case of the research topic, the water environment). At the same time, a person is able to manage such objects without defining and solving equations. A human trait is the ability to learn and evaluate objects of observation in natural language - low temperature, large error, sufficient illumination etc. The ability to formalize such expressions is provided by the use of fuzzy variables and fuzzy sets.

The use of fuzzy logic compared to classical systems has a number of advantages and disadvantages. The advantage of the classical system is the availability of a model that adequately and fully describes the dynamics of the system, which allows for no additional model adjustment. However, it is difficult to obtain differential equations that adequately describe the dynamics of the system, taking into account nonlinear factors of influence. A fuzzy model does not require the development of differential equations. The system model is described in the form of linguistic variables and rules. However, the process of setting up a linguistic model is mandatory [3].

The use of fuzzy logic in the process of water environment management is covered in scientific papers.

For example, paper [1] considers the possibility of using fuzzy logic to assess the condition of fish based on temperature, dissolved oxygen, and water conductivity. These parameters are converted into fuzzy variables and processed by the controller based on fuzzy logic inference. The resulting value is converted from a fuzzy variable back to a clear value that can be interpreted in the further process of managing the water environment.

In paper [4], a similar fuzzy inference mechanism to the previous one is considered, which in the context of the work performs the function of regulating the speed of the filter pump to ensure the improvement of water quality. The input parameters for the fuzzy inference system are the turbidity of the water and its acidity, which are obtained as a result of measurements of the corresponding sensors. Such a system brings the required indicator to the desired level evenly over time. However, this may not be enough in every situation. If the temperature drops by a significant amount, direct human intervention will be required, as the control system will not be able to adequately respond to such a change in indicators and will not have time to bring the indicators to the desired level within the required time period, which can lead to the death of living organisms in the aquatic environment. A closed-loop controller can solve this problem.

There are two main types of controllers – open-loop and closed-loop. An open-loop controller performs the control function without taking into account the actual output of the parameter being controlled. Closed-loop controllers constantly measure the output value of the parameter and adjust changes to maintain the desired value of the parameter. The key element of a controller is an algorithm or device that decides how to continue its work and how much power to output to change the parameter. There are several control mechanisms - it is worth noting the on/off controller and proportional-integral-differential (PID) controller. The latter is based on the sum of three terms, consisting of the difference between the input signal and the feedback signal, the integral of the mismatch signal, and the derivative of the mismatch signal. The PID controller provides higher calculation accuracy and allows to directly control the output signal. The main disadvantages of this controller are an increase in the number of calculations, increased amplification of the high-frequency components of the error signal, and the possibility of signals of greater amplitude [3].

The above problems can be solved by using a fuzzy logic mechanism that allows replacing a purely formal description of specific temperature values and error values with linguistic variables, which in turn can be used to form a base of logical rules, thereby making it possible to activate the formed rules based on error values and changes in the error value at the previous discrete time point to form a conclusion about the optimal behavior of the system at the next discrete time point.

Research results and their discussion

The structure of the PID controller shown in Fig. 1 should be considered.

The controller receives the desired value of the parameter. This is the value that the controller must maintain during its operation. The summator calculates the error value, which is usually obtained as the difference between the desired temperature and the output signal. The error is provided to the controller, which makes calculations based on the error value in three components – proportional, integral and derivative. The generated signal is transmitted to the control element that directly affects the parameter (heater to change the temperature, pump to purify water, etc.). The result of the operation directly affects the value of the controlled parameter. This new value is provided back to the input to determine a new error value [2, 5].

Thus, the input parameters of the system such as the desired parameter value and the error can be determined. In addition to these parameters, the value of the error change (first derivative) should also be taken into account, which will allow for more accurate adjustment of the controller output. The result is the effort to be performed by the control element.

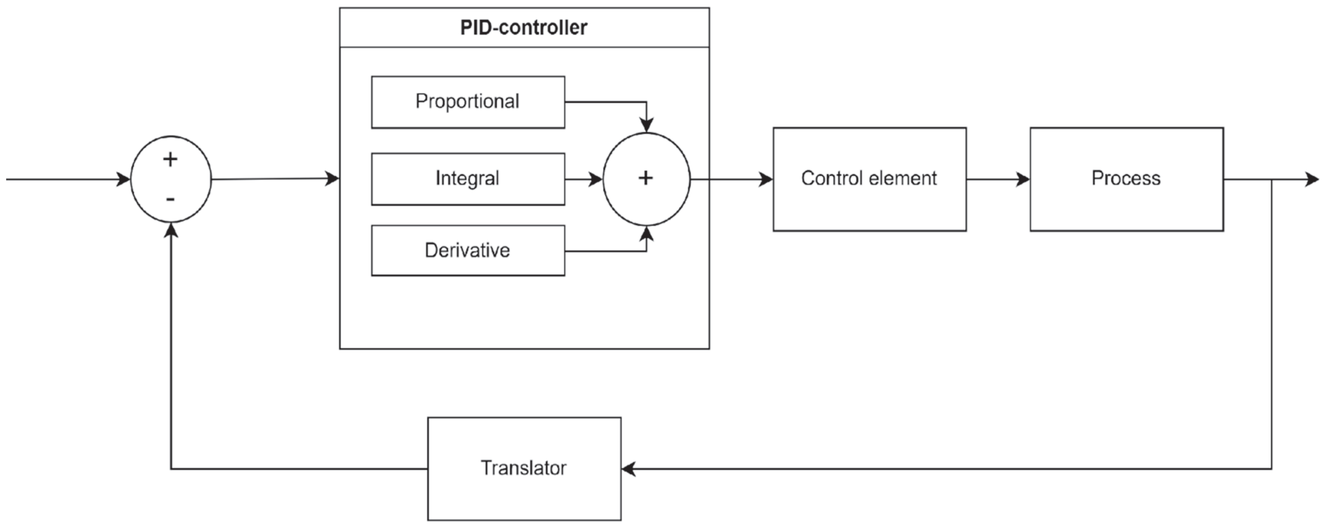

Fig. 1. General structure of PID controller

The disadvantages of the PID controller approach are the need for more calculations and the need to create a complex mathematical model. Under conditions of uncertainty, unpredictable fluctuations in input parameters, a strict mathematical model tends to increase the amplitude of error fluctuations during the time of system stabilization. The use of fuzzy logic can simplify the formalization and editing of a set of rules during system operation. In addition, the use of fuzzy variables can reduce fluctuations in the transient states of the system.

Taking into account the listed disadvantages of the PID controller and the potential advantages of using a fuzzy logic apparatus, we will replace the PID controller with a fuzzy inference module. To solve the problem, the Mamdani algorithm was chosen, which is a fuzzy inference algorithm based on a knowledge base (rules). The Mamdani method is a fuzzy inference system (FIS). A FIS is a system that uses fuzzy set theory to map inputs (functions in the case of fuzzy classification) to outputs (classes in the case of fuzzy classification). Each stage is executed sequentially, and each subsequent stage receives as input the values obtained as a result of the previous one [6, 7].

Data preparation for the algorithm is carried out by means of fuzzification – the transformation of clear input data into fuzzy variables. The resulting fuzzy variables activate sub-conclusions based on the rule base, and the accumulated conclusion is defuzzified, i. e., converted into a clear output value of the force for the control element. All other components of the controller remain unchanged. Let's take as a basis the structure of the controller with the fuzzy inference module shown in Fig. 2 for further implementation of the model.

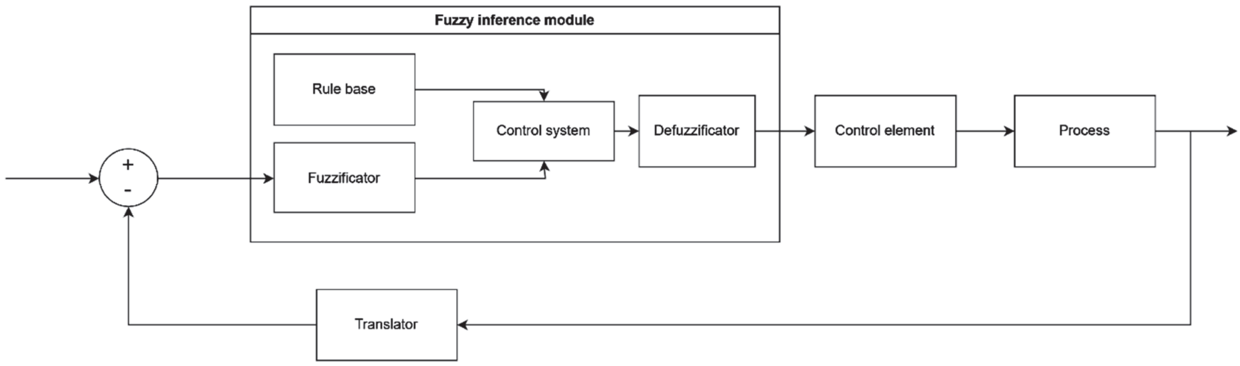

Fig. 2. General structure of controller with fuzzy inference module

To demonstrate and implement a controller with a fuzzy logic inference module, the control of the water environment's temperature was chosen. Accordingly, the task of the controller is to heat or cool the water to the desired value. A separate informal requirement is to minimize possible temperature fluctuations from the desired value to ensure stable conditions for living organisms, as well as smooth heating or cooling to avoid sudden temperature changes.

The input parameters of the controller are the desired temperature value and the current error value. The parameter of the error change relative to the previous measurement is also used to form a logical conclusion. Taking into account the degree of error change can help to avoid additional fluctuations and a sharp increase or decrease in the output commitment of the control element. To implement the fuzzy inference module, we chose the scikit-fuzzy package, a set of tools for working with the fuzzy logic apparatus for the Python programming language. The package simplifies the creation of fuzzy variables, the formation of terms, the formation of a rule base, and the process of defuzzification [10].

According to the Mamdani method, the conclusion is formed on the basis of implication rules. Implication expresses the statement that if one statement is true, then the other is also true. The parts of the rule are antecedent and consequent – parts of a statement that form "if – then" rules, which are essentially rules for implicating fuzzy variables, for example, for two input parameters:

$$\mu C'^{(z)} = min(\, min\,(\mu A^{(x)}, \mu B^{(y)}), \mu C^{(z)}) \,, \tag{1.1}$$

where $\mu A^{(x)}$ – the degree of input value x membership in the fuzzy set A; $\mu B^{(y)}$ – the degree of input value y membership in the fuzzy set B; $\mu C^{(z)}$– the degree of membership of the output term C; $\mu C'^{(z)}$ – implication result, the set of the rule result [6].

Let's define the linguistic factor variables and the sets on which they are defined based on the input and output parameters:

– temperature_error [–50; 51] – error relative to the desired value;
– temperature_delta [–10; 10] – change in error compared to the previous measurement moment;
– temperature_adjustment [–50; 51] – the proportional duty transferred to the control element.

The terms of each of the factors are formalized in the form of the same type of fuzzy sets based on a linguistic assessment of the factor value:

– nb – negative big;
– ns – negative small;
– ze – close to the zero;
– ps – positive small;
– pb – positive big.

The breakdown by the degree of deviation allows you to make more accurate and adequate decisions about the further operation of the control. Similarly, accepting the error value as close to zero can reduce the number of fluctuations in the degree of commitment of the control element.

For each term, we need to describe membership functions. Based on them, we can assign the appropriate semantics to each new value of the linguistic variable by forming a fuzzy set. Membership functions are formed automatically using the automf() method from the scikit-fuzzy package [10] on a certain universal set defined for each linguistic variable and shown in Fig. 3.

A set of rules has been formed that make up the causal hierarchy within the fuzzy inference module. A fragment of the rule base is presented in the form of products that reflect the activation of the term "nb" of the factor "temperature_adjustment":

– IF (temperature _error = «nb») AND (temperature_delta = «nb») THEN temperature_adjustment = «nb».
– IF (temperature _error = «nb») AND (temperature_delta = «ns») THEN temperature_adjustment = «nb».
– IF (temperature _error = «ns») AND (temperature_delta = «nb») THEN temperature_adjustment = «nb».

Rules based on the conjunction of input values of this type are generated for each term of the output parameter. Together, these rules form the rule base for decision making by the control module.

On the basis of the formed rule base, it is possible to build a knowledge matrix, which is presented in Table 1.

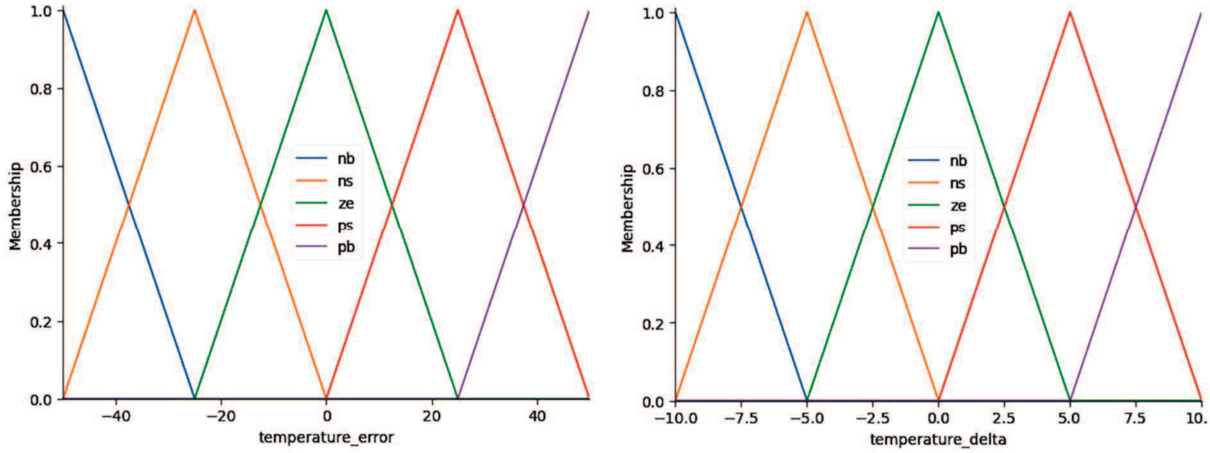

Fig. 3. Graphic representation of “temperature_error” and “temperature_delta” linguistic variables membership functions

Table 1. Knowledge matrix for temperature control by fuzzy inference module

temperature_error/ temperature_delta	nb	ns	ze	ps	pb
nb	NB	NB	NS	NS	ZE
ns	NB	NS	NS	ZE	PS
ze	NS	NS	ZE	PS	PS
ps	NS	ZE	PS	PS	PB
pb	ZE	PS	PS	PB	PB

Based on the formed knowledge base, a three-dimensional decision surface of the control module can be built. Such a representation allows to better reflect the influence of input parameters on the formation of the controller output. To build the three-dimensional decision surface shown in Fig. 4, it is necessary to calculate for each possible discrete value of the input parameters on universal sets of linguistic variables.

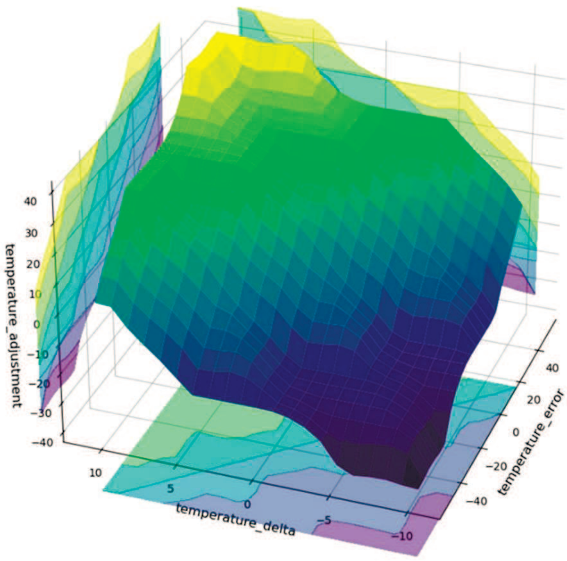

Fig. 4. Graphic representation of a decisions surface of fuzzy inference module

The work of the developed module and the PID controller in the same model of the environment were tested – the desired temperature value is 25 conventional units, the temperature in the environment at the beginning of operation and measurements is 20 conventional units, the measurement is carried out for 300 iterations, or an analogue of 300 discrete moments of time during which the indicators were recorded, as shown in the graphical representation of the results in Fig. 5.

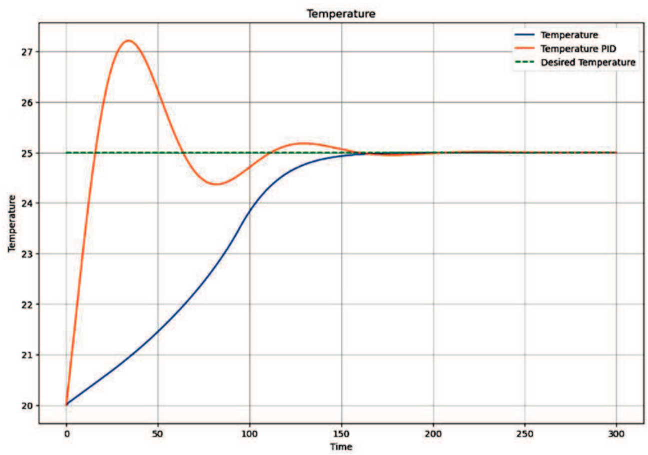

Fig. 5. Graphic representation of the test results of fuzzy inference module and PID controller

From the test results, it is seen that both controllers reached the desired temperature value of 25 conventional units in a relatively similar period of time. However, the curve of temperature change during the operation of the PID controller has a significant amplitude of oscillations before reaching the desired result. The controller based on the fuzzy inference module formed a smoother temperature change curve, reducing the control element’s commitment with a smaller temperature error. For quantitative comparison, Table 2 of the output temperature and error values for the fuzzy logic inference module and the PID controller was formed.

Table 2. Temperature and temperature error measurements results for fuzzy inference module and PID controller

No.	PID t	PID delta	Fuzzy t	Fuzzy delta
1	20	5	20	5
10	23.34945	1.65055	20.28074	4.71926
20	25.94027	–0.94027	20.54765	4.45235
30	27.12388	–2.12388	20.82337	4.17663
40	27.03321	–2.03321	21.12465	3.87535
50	26.22185	–1.22185	21.45438	3.54562
60	25.28612	–0.28612	21.81783	3.18217
70	24.62546	0.37454	22.22268	2.77732
80	24.37385	0.62615	22.68177	2.31823
90	24.45821	0.54179	23.22056	1.77944
100	24.71005	0.28995	23.83621	1.16379
110	24.96722	0.03278	24.28694	0.71306
120	25.13170	–0.13170	24.58204	0.41796
130	25.18002	–0.18002	24.76372	0.23628
140	25.14154	–0.14154	24.86980	0.13020
150	25.06602	–0.06602	24.92958	0.07042
160	24.99670	0.00330	24.96236	0.03764
170	24.95688	0.04312	24.98002	0.01998
180	24.94938	0.05062	24.98944	0.01056
190	24.96380	0.03620	24.99442	0.00558
200	24.98583	0.01417	24.99706	0.00294
210	25.00415	–0.00415	24.99845	0.00155
220	25.01346	–0.01346	24.99918	0.00082
230	25.01395	–0.01395	24.99957	0.00043
240	25.00904	–0.00904	24.99977	0.00023
250	25.00277	–0.00277	24.99988	0.00012
260	24.99802	0.00198	24.99994	0.00006
270	24.99595	0.00405	24.99997	0.00003
280	24.99623	0.00377	24.99998	0.00002
290	24.99780	0.00220	24.99999	0.00001
300	24.99939	0.00061	24.99999	0.00001

From the measurement results, it can be seen that the largest deviations from the desired value after its achievement during the operation of the PID controller are -2.1238 conventional units and 0.6261 conventional units, respectively. As a result of the operation of the fuzzy inference module, the obtained value does not exceed the desired value and the corresponding oscillation amplitudes are not recorded, which indicates the correctness of the module's operation, the fulfillment of the tasks set before the study and the achievement of the work goal, namely, reducing the amplitude of error oscillations.

Discussion of research results. The problem of controlling the parameters of a closed aquatic environment has received various solution proposals, including both traditional and fuzzy control methods. Traditional methods require completeness of input data and more complex calculations in the process of model design, while fuzzy methods do not take into account the dynamics of changes in the error value to adequately respond to changes in the aquatic environment.

Thus, based on the results of the work performed, the following scientific novelty and practical significance of the research results can be formulated.

The scientific novelty of the research is that for the first time a model of a fuzzy module for controlling the parameters of a closed water environment based on the Mamdani method was developed, taking into account the dynamics of changes in the error signal; a fuzzy module for controlling the parameters of a closed water environment was developed; an acceptable test result of the implemented fuzzy module was obtained.

The practical significance of the research results is a significantly reduced amplitude of the error signal oscillations compared to traditional means of controlling the parameters of a closed water environment.

The developed model can be used to integrate with sensors and controls of a closed water environment, provided that the membership functions of linguistic variables are pre-tuned and the rule base is expanded.

This approach can be combined with a decision-making approach based on the error values of several related parameters. Such an approach would require a more complex and larger rule base, but the complexity of calculations would not increase in this case. Accordingly, without loss of performance, there is a prospect of increasing the accuracy and adequacy of the model's response and allocating the resources of several control elements for optimal use. In addition, it is possible to use the control module in terms of monitoring the state of the aquatic environment to connect additional resources in case of critical deviations from the desired values, which can prevent the death of aquatic organisms.

Conclusions

The purpose of research, specifically reducing the amplitude of the error signal fluctuations in the process of controlling the parameters of a closed aquatic environments, has been achieved. Compared to the traditional closed-loop controller, the use of a fuzzy module makes it possible to avoid the fluctuations of the error signal after reaching the target value of the parameters.

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О. О. Шинкаренко, О. В. Сілагін
Вінницький національний технічний університет, м. Вінниця, Україна

МОДЕЛЮВАННЯ ПРОЦЕСУ УПРАВЛІННЯ СТАНОМ ЗАМКНЕНОГО ВОДНОГО СЕРЕДОВИЩА ЗАСОБАМИ НЕЧІТКОЇ ЛОГІКИ

Із розвитком аквакультури стає все актуальнішою проблема управління параметрами водного середовища. Класичні системи управління параметрами замкненого водного середовища, що використовують чіткі моделі динамічного управління і застосовуються для моніторингу, контролю і регулювання цих параметрів, мають певні недоліки, пов'язані зі специфікою чіткого алгоритмічного управління та складністю адекватних моделей умов для вирощування живих організмів. Такі моделі потребують громіздких розрахунків для розв'язання диференційних рівнянь, а також погано адаптуються до нетипових змін параметрів у зв'язку із зовнішніми чинниками. Крім того, такі моделі схильні до виникнення коливань значень параметрів у перехідних процесах. Дослідження акцентує на важливості адаптивного підходу до управління в умовах водних біотехнічних систем, які функціонують у непередбачуваному середовищі. Запропонована модель дає змогу враховувати нечіткість і неповноту інформації, що виникає під час контролю параметрів, зокрема температури, рівня кисню та інших критичних показників. Упровадження такої системи може знизити ризики загибелі біологічного матеріалу та підвищити ефективність технологічного процесу. У статті також окреслено потенціал використання моделі разом із сучасними системами збирання даних, що працюють у режимі реального часу, для удосконалення контролю. Для покращення управління запропоновано використання апарату нечіткої логіки. Створена покращена модель управління станом замкненого водного середовища на основі методу Мамдані. Розроблено структуру контролера із модулем нечіткого логічного висновку, основаного на перетворенні вхідних даних сигналів на лінгвістичні змінні, що дає змогу уникнути розв'язання диференційних рівнянь та перенести вирішення проблеми на систему активації логічних правил. Виконано тестування роботи створеної моделі та порівняння її із класичною системою управління. Результати експериментального тестування підтверджують ефективність підходу: знижено похибку регулювання параметрів, а також зменшено тривалість стабілізації після зовнішніх збурень. Створена модель дає змогу адекватно реагувати на зміну показників середовища та уникає коливань значень параметрів, якими управляють, що забезпечує передбачуванішу та надійнішу роботу системи. Наведено перспективи використання розробленої моделі для поєднання значень декількох вхідних параметрів для формування логічного висновку.

Ключові слова: модель контролю, нечітке виведення, аквакультура, лінгвістична змінна.

Інформація про авторів:
Шинкаренко Олег Олександрович, аспірант, кафедра комп'ютерних наук. **Email:** oshynkarenko1503@gmail.com; https://orcid.org/0009-0007-9225-9747
Сілагін Олексій Віталійович, канд. техн. наук, доцент, кафедра комп'ютерних наук. **Email:** avsilagin@vntu.edu.ua; https://orcid.org/0009-0006-0089-4800

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