Autonomous Underwater Robot Fuzzy Motion Control System for Operation under Parametric Uncertainties

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Abstract. The paper describes the design of a fuzzy motion control system of an autonomous underwater vehicle. A mathematical model of the underwater vehicle is synthesized. A fuzzy regulator for controlling the depth of immersion AUV is designed. The quality of control for step control, harmonic control, as well as various types of exogenous disturbances is investigated. The comparison of the functioning quality of the designed fuzzy controller with the PD controller is made. It is shown that the designed fuzzy controller provides a higher quality of control compared to the PD controller. The proposed fuzzy controller provides high quality control of the plant under uncertainties.

Keywords: maritime, controller, fuzzy, AUV, function/

DOI 10.14357/20718632210106

1. Introduction

Underwater robotics objects operate in difficult conditions of underwater navigation. Modern automatic movement control systems of autonomous underwater vehicles (AUV) should provide increased accuracy of AUV's controlled movement along a given path, achieving maximum speed, optimal control in complex hydrometeorological conditions, under the influence of various kinds of disturbances.

In addition, the peculiarity of working under water is the presence of external and internal (parametric) disturbances. These disturbances have a significant impact on the operation of robotic objects under water and on the robot's performance of its tasks. Therefore, the development and application of new approaches to the synthesis of automatic control systems for underwater objects are required. These perturbations are difficult, and in most cases impossible to measure, so the AUV motion control process takes place under conditions of uncertainty.

In practice, situations also often arise when the parameters of the AUV itself are unknown or their accuracy is not high enough to build adequate mathematical models. In this regard, there is also an uncertainty in the design and operational parameters of the AUV.

These features of the operation of underwater robots determine the search for new non-traditional approaches to solving the problems of controlling their movement. A review of the scientific and technical literature on control systems shows that the main direction of further development of the theory of synthesis of automatic control systems for autonomous underwater robots in the conditions of uncertainty of their parameters and environmental characteristics is the use of artificial intelligence elements – fuzzy regulators (Marir, Chadli, 2019).

2. Description of the problem

When solving the problems of navigation, orientation and motion control of underwater robots and vehicles, various coordinate systems are used (Sun and Chen, 2016). This is due to the difference in tasks, as well as the fact that the structure and form of the equations substantially depend on the choice of coordinate system.

The choice of coordinate systems is predetermined by the method known in mechanics of dividing the complex motion of a body into translational with some point taken as a pole, rotational (spherical) relative to this pole. The study of translational motion is reduced to determining the motion of the pole, for which the basic fixed coordinate system is sufficient. Rotational motion in the general case can be determined in the coordinate system with respect to which the body moves with one fixed point.

AUV motion analysis will be carried out in a coordinate system stationary relative to the Earth whose origin at the initial moment of time coincides with the center of mass of the robot. The coordinate system x-y, rigidly connected with the robot, is chosen as follows. The origin is placed in the center of mass, the y axis is located in the diametrical plane and directed towards the nose of the robot so that, in its natural position, the axis coincides with the horizon (the y axis is the longitudinal axis of the robot). The x axis should coincide with the line of intersection of the main planes of the robot and have a direction up from the center of displacement.

Next, we consider the movement of an underwater vehicle in an unlimited reservoir of finite depth, filled with an ideal incompressible non-heat-conducting stratified fluid with a viscosity effect. Viscosity is taken into account in the sense of the presence of the Stokes drag force. It is assumed that each layer has its own density, which is considered to be known in advance.

AUV performs plane-parallel movement. At the initial time, the apparatus rests at a given depth. Each given layer of the medium in which the apparatus moves has a constant density. Layer densities may vary. Layers can exhibit rectilinear uniform motion along the x axis. At this stage, we assume that the velocities and directions of motion of the layers are given (Fig. 1).

Obviously, the solution can be obtained as the sum of the solutions at intervals corresponding to the layers of the medium. That is, first of all, the problem for one layer should be solved.

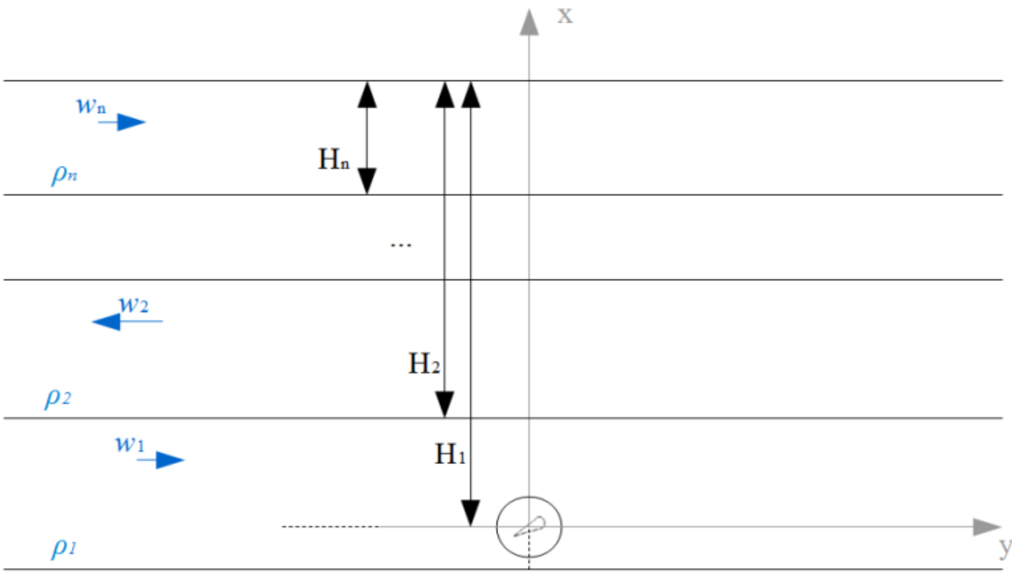

Fig. 1. Structure of a stratified continuous medium

3. Mathematical model

The underwater vehicle under consideration is a spherical body. The body has two wings of finite wingspan (Fig. 2). The trajectory of the object is the trajectory of the center of the ball.

Let the wings of the object are thin with a large elongation, and their shape minimizes the inductive resistance force.

The following forces act on the underwater vehicle (Fig. 3): F_{arch} – buoyant or Archimedean force; F_g – gravity; the total drag force (Sokolov, Zhilenkov, Nyrkov & Chernyi, 2017)

$$F_{drag}^{(j)} = C_X^{(j)} S^{(j)} \frac{\rho v^2}{2},$$

where $j=1$ for ball and $j=2$ for wings; lifting force

$$F_{lift} = \rho v^2 S \frac{k\alpha}{1+\mu_0};$$

force of inductive resistance

$$F_i = \frac{\rho}{2} v^2 S \frac{\mu_0}{2k} \left(\frac{2k\alpha}{1+\mu_0} \right)^2 .$$

The equations of motion of an autonomous underwater vehicle in projections on the x and y axis can be represented as follows:

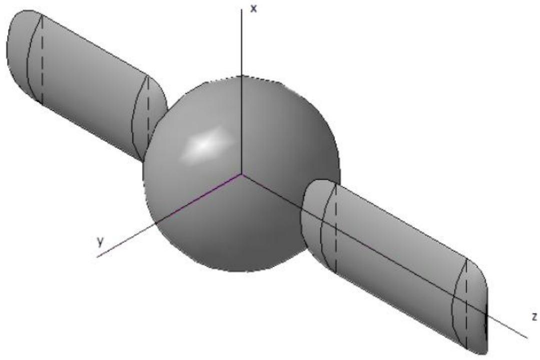

Fig. 2. The underwater vehicle under consideration

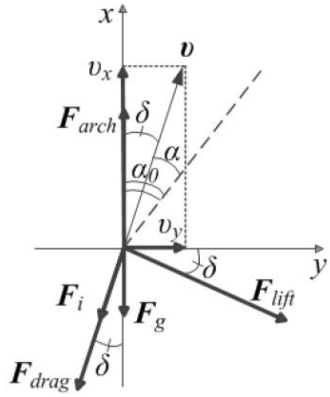

Fig. 3. Illustration of the hydrodynamic forces acting on the ball-wing system

$$\begin{cases} \left(m + \frac{2}{3}\rho\pi R^3 \right) \frac{d^2 x}{dt^2} = F_{arch} - 2F_i \cos\delta - \left(F_{drag}^{(1)} + 2F_{drag}^{(2)} \right) \cos\delta - 2F_{lift} \sin\delta - F_g, \\ \left(m + \frac{2}{3}\rho\pi R^3 \right) \frac{d^2 y}{dt^2} = -2F_i \sin\delta - \left(F_{drag}^{(1)} + 2F_{drag}^{(2)} \right) \sin\delta - 2F_{lift} \cos\delta. \end{cases} \quad (1)$$

Let's make an assumption about a small angle of attack. This assumption ensures the smallness of δ, therefore, we have $\sin\delta \approx \delta,\ \cos\delta \approx 1$.

After replacing the variables:

$$x = z_1, \quad \dot{x} = \dot{z}_1 = z_2,$$
$$y = z_3, \quad \dot{y} = \dot{z}_3 = z_4.$$

we get a system of differential equations of the first order:

$$\begin{cases} \dot{z}_1 = z_2, \\ \dot{z}_2 \cdot b_0 = b_1 - (b_2 \cdot \alpha^2 + b_3 + 2b_4) \cdot z_2 \cdot \sqrt{z_2^2 + z_4^2} - 2b_5 \cdot \alpha \cdot z_4 \cdot \sqrt{z_2^2 + z_4^2}, \\ \dot{z}_3 = z_4, \\ \dot{z}_4 = -(b_2 \cdot \alpha^2 + b_3 + 2b_4) \cdot z_4 \cdot \sqrt{z_2^2 + z_4^2} + 2b_5 \cdot \alpha \cdot z_2 \cdot \sqrt{z_2^2 + z_4^2}, \end{cases} \quad (2)$$

where $b_0 = m + \frac{2}{3}\rho\pi R^3$, $b_1 = \rho g V - mg$, $b_2 = \rho S_{kp} \frac{2k\mu_0}{(1+\mu_0)^2}$, $b_3 = c_{0\_spsh} \frac{\rho\pi R^2}{2}$, $b_4 = c_{0\_w} \frac{\rho S_w}{2}$, $b_5 = \rho S_{kp} \frac{k}{1+\mu_0}$.

The movement of the apparatus to follow a given trajectory is controlled by changing the angle of attack α .

A numerical solution for model (2) can be obtained using the fourth-order Runge-Kutta method, for example.

4. Synthesis of a fuzzy controller to stabilize the depth of an underwater robot

Based on a comparison of methods for constructing a fuzzy controller (Muraleedharan, Osadciw, 2006), we formulate a method for the synthesis of the AUV depth stabilization controller.

Linguistic variables are qualitatively characterized by term sets, chosen as follows: negative large (NL), negative small (NS) zero (Z), positive small (PS), positive large (PL), which are described on the universal set, membership functions depth and linear vertical velocity. To describe the input variable V, we divide the range of its values into three subsets: negative (N) zero (Z) positive (P).

The output linguistic variable T is the traction force in vertical direction. It has the following terms: negative strong (NL), negative average (N), negative small (NS), zero (Z), positive small (PS), positive average (P), positive strong (PL). Membership function options are shown in Fig. 4.

After determining the number of terms of each linguistic variable and the distribution of membership functions, fuzzy rules are formed. These rules are created based on the experience of an expert who expresses in a formal language possible combinations of control variables (Zhilenkov & Chernyi, 2019). For fuzzy inference, a fuzzy model of the Sugeno type is used, where each rule is of the following type: IF “h is x” AND “V is y”, THEN “T is z”. Here x, y are the subsets of input variables, z is the subset of the output variable. The set of rules is given in Table 1.

Using the Fuzzy Logic Toolbox application package in the MATLAB interactive system, a fuzzy inference surface is obtained that displays the operation of the controller (Fig. 5).

5. Simulation results

The fuzzy control system was simulated using the Matlab package. Fig. 6 shows a test model that includes the plant and the actual fuzzy controller, as well as an observer. Figures 7 – 8 show graphs of the dependence of depth on time when controlling the PD controller and when controlling a fuzzy controller.

Formally, it was stated above that in the depth control channel the perturbation is of a wave nature. However, taking into account the possibilities of transferring the fuzzy control structure to other coordinates, modeling was performed with disturbances of different form and nature.

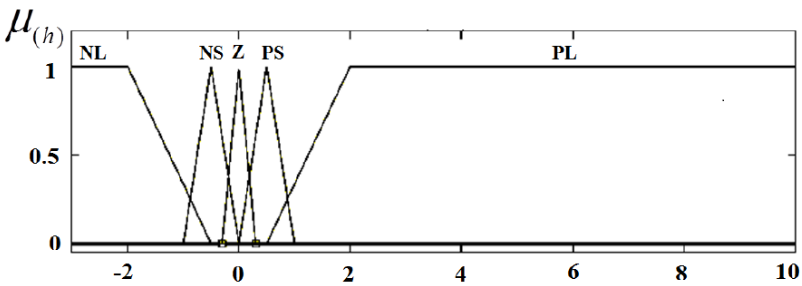

Fig. 4. Membership functions of the terms of linguistic variables of a fuzzy controller

Table 1. The base of the rules of the fuzzy controller

		h				
		NL	NS	Z	PS	PL
V	N	NS	Z	PS	P	PL
	Z	NL	NS	Z	PS	PL
	P	NL	N	NS	Z	PS

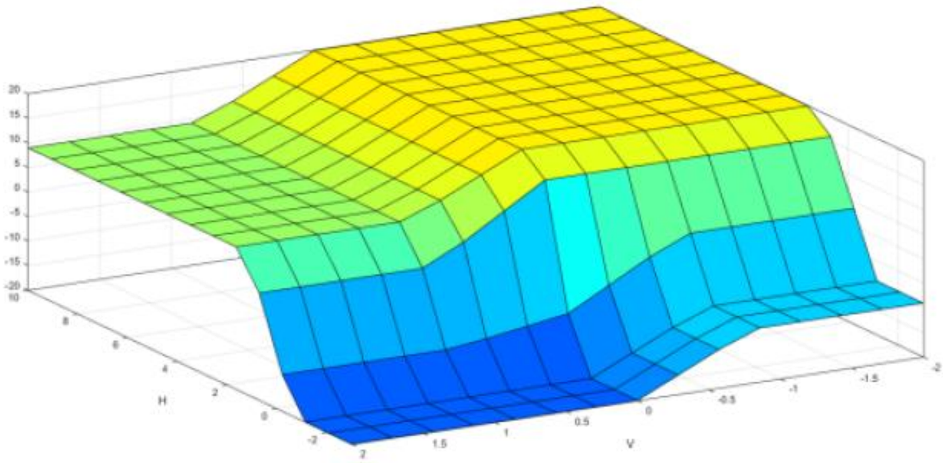

Fig. 5. The surface of the fuzzy controller

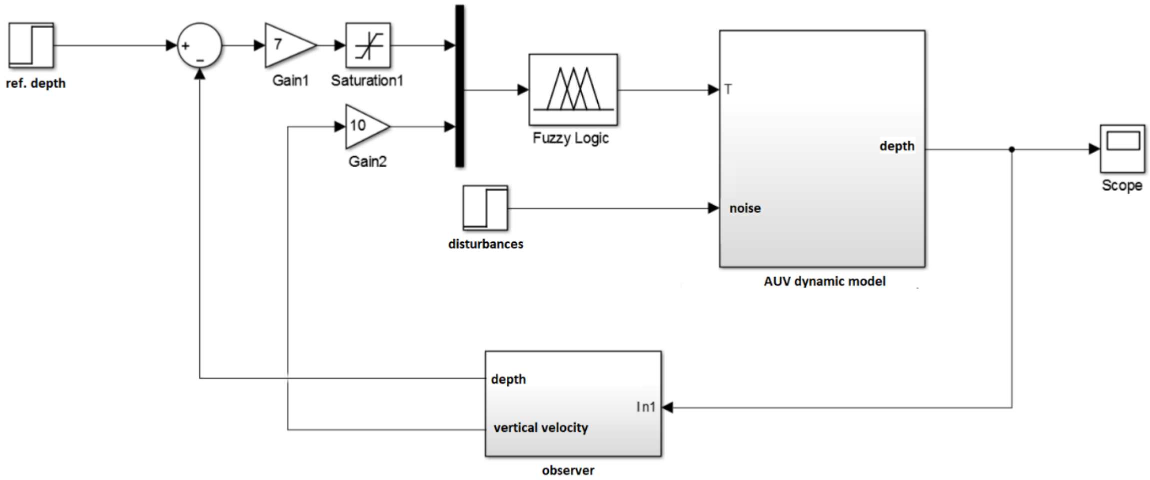

Fig. 6. Simulation of an underwater robot in a Matlab environment

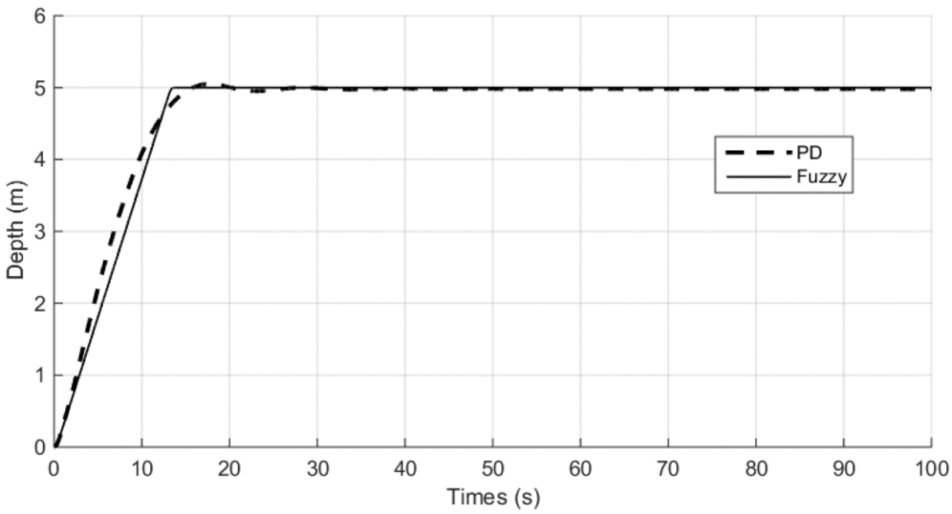

Fig. 7. Graph of the given and the current depth of the AUV versus time without noise or external disturbances

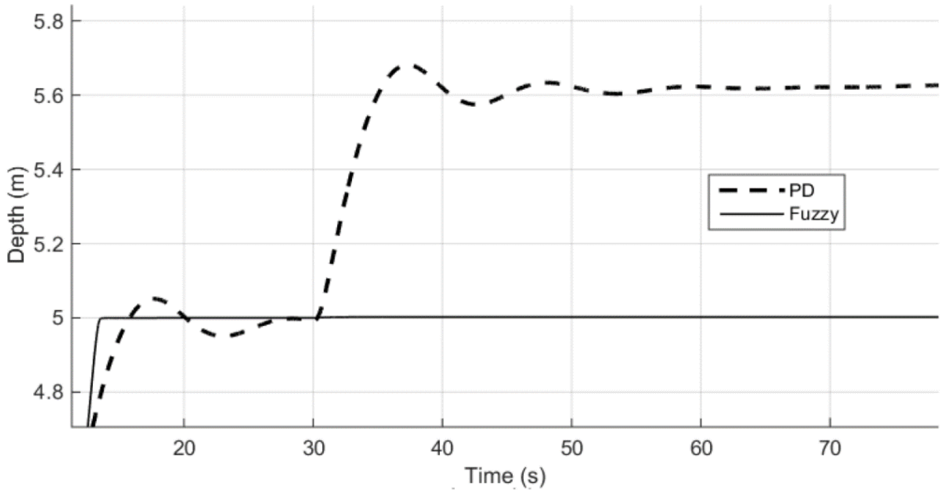

Fig. 8. Graph of the given and the current depth of the AUV versus time with constant exogenous disturbance

The simulation results show that the fuzzy controller is not inferior in quality to the PD controller, has less overshoot, works better in conditions of random and harmonic disturbances. In addition, setting the coefficients of the optimal PD controller is a time-consuming operation, and setting the fuzzy controller is simpler.

The developed mathematical models can be used to solve the problems of synthesis of fuzzy controllers, increasing efficiency, avoiding the inaccuracy or uncertainty of our knowledge about plant when synthesizing it's model.

The use of fuzzy logic methods for the synthesis of control laws of modern automatic control systems, consisting of a set of various underwater robots, can increase the reliability of the operation of underwater hydraulic structures in difficult or extreme conditions due to periodic monitoring of their condition.

6. The study of the efficiency of the fuzzy control system with a stepwise change in the depth of immersion AUV

The simulation showed the effective use of a fuzzy controller (FC) of the proposed structure for stabilization at depth. We will now establish the possibilities for the effective operation of the FC for operating cases when the new value of the given depth is such that the AUV does not have time to develop the maximum vertical speedF.

It's obvious that

$$h = h_a + h_s + h_b,$$

where h_a, h_s, h_b – the path of acceleration, steady motion and braking of AUV, respectively.

Then the minimum value of the change in the depth $h_{\min}$ of AUV, at which the considered FC's work efficiently, is defined as the sum

$$h_{\min} = h_a + h_b.$$

For a specific AUV with known values of mass, hydrodynamic drag coefficient, and characteristics of a moving device, the value $h_{\min} = const$.

For $h < h_{\min}$, applying the FC with the dependencies synthesized above for the coefficients k_1 and k_2 is ineffective. For example, let the new value of the given depth $h = 1m$. Fig. 8 shows the operation of the FC, the coefficients k_1 and k_2 of which correspond to a depth of 10 meters, and in Fig. 8, the operation of the FC with the coefficients k_1 =1.01 and k_2 =12, specially tuned to change the depth by 1 meter.

Obviously, for each value of $h < h_{\min}$, it is necessary to determine new values of the coefficients k_1 and k_2, which complicates the synthesis of FC and limits its application.

Studies have also shown that a similar conclusion can be made regarding the other FC options discussed above.

Thus, along with the fundamental possibility of achieving high quality control of the FC with

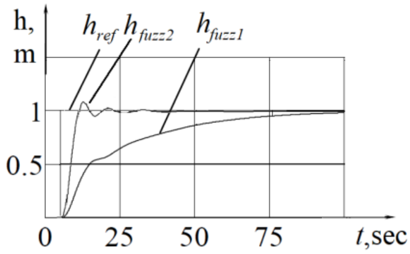

Fig.9. Control of the vertical movement of the AUV when changing the depth by 1 m

Table 2. Dependence of scale factors on harmonic input signal

k_1	0,64	0,61	0,61	0,62	0,61	0,62
k_2	10	20	30	40	50	60
n_1	3	4	5	6	6	7
ε_1, m·s	130,0	129,7	129,7	129,6	129,7	129,7
n_2	1	1	2	2	2	2
$h_{e\max}$, m	1,00	0,60	0,42	0,33	0,27	0,23
ε_2, m·s	56,0	29,1	19,6	14,92	12,10	10,22

Table 3 - The values of the coefficients of the PD controller

k_1, V/m	200	150	100	90	80	70	60
k_2, V/m	2000	1500	1000	900	700	500	420
ε_1, m·s	153,8	153,9	154,0	154,0	148,1	141,6	141,2
k_1, V/m	40	35	30	25	20	15	10
k_2, V/m	280	250	210	180	150	120	80
ε_1, m·s	141,3	141,9	141,4	142,3	143,7	146,3	147,4

a harmonic input signal, the incompatibility of the coefficients k_1 and k_2 of FC was also found in the automatic control of vertical movement for stepwise and harmonic input signals. This means that each of the above modes requires a separate synthesis of FC coefficients, which limits the application of such a regulator in practice.

Studies of the other FC options discussed above showed even lower accuracy with a harmonic input signal and the need for appropriate adjustment of the coefficients.

7. Comparative analysis of the performance of a fuzzy control system and a system with PD controller

To compare the results with traditional control systems, a proportional differential (PD) controller was synthesized, in which the control signal is calculated by the formula [7-8]:

$$u = k_1 h_e + k_2 h_e'.$$

Since the model of the control object contains quadratic dependencies, it is impossible to perform the Laplace transform and obtain the transfer function of the control object. In this regard, the coefficients k_1 and k_2 were determined experimentally. The experimental results are shown in Table 3, and the best characteristics that were obtained with coefficients k_1 = 60, k_2 = 420 are shown in Fig. 10.

As the simulation showed [10], the PD controller shows slightly worse results compared to the best results obtained when controlling a fuzzy controller. Thus, the total error ε is almost 9% larger, and the transition process time is 43% larger. For the harmonic input signal, the following quantitative characteristics of control quality were obtained: $\varepsilon = 6.5\,\text{m}\cdot\text{s}$, maximum error

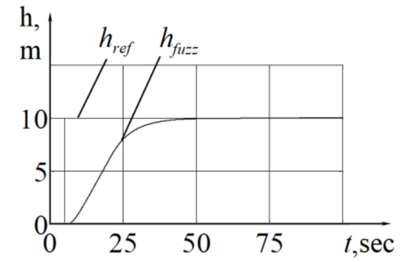

Fig. 10. The transition process of stepwise changes in the depth of the AUV with PD-regulator: a graph of changes in depth

$h_{e\max} = 0.1$ m, which almost does not differ from the adjusted FC.

8. Conclusions

The paper presents mathematical models of the basic integration of a computing system. Cases of component modeling are analyzed. Applied algorithmic approaches for the transient. Transitions for processing streaming signals based on the PD controller have been implemented.

This study provided the design of a fuzzy motion control system of an autonomous underwater vehicle.

- A mathematical model of the underwater vehicle is synthesized.
- A fuzzy regulator for controlling the depth of immersion AUV is designed.
- The quality of control for step control, harmonic control, as well as various types of exogenous disturbances is investigated.
- The comparison of the functioning quality of the designed fuzzy controller with the PD controller is made.

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