FUZZY CONTROLLER FOR UNDERWATER REMOTELY OPERATED VEHICLE WHICH IS MOVING IN CONDITIONS OF ENVIRONMENT DISTURBANCE OCCURANCE

Andrzej Żak

Polish Naval Academy, Institute of Hydroacoustics
Smidowicza Street 69, 81-103 Gdynia, Poland
tel.: +48 58 6262868, fax: +48 58 6254846
e-mail: a.zak@amw.gdynia.pl

Abstract

Oceans fill two-third surface of the Earth and they are house for majority alive organisms of our planet. However human possibilities of cognition of this environment are very limited. To defeat these limitations lots of scientists dealing with exploration of depths, concentrates on unmanned, remote-controlled underwater vehicle. From seventieth years happened the development of unmanned underwater vehicles which currently administering all characteristic attribute of robot, and have the possibility of shifting and manipulation, ability of technical surroundings' observation, and sometimes are making independent decision in typical situations.

For control of all devices of robot responds the system of steering which holds supervision beginning from the propulsion and finishing on switching the video cameras and lighting. In robot's control system the functions of regulator in feedback the most often is realized by operator which is the onlooking working object on monitor installed in deck console. Nowadays more often automatic system of control is used, therefore in this paper such system will be proposed.

The main aim of paper is to introduce the results of research concentrated on controlling remotely operated underwater vehicle during movement in conditions of environment disturbance occurrence. Firstly the mathematical model of example ROV is briefly discussed. Next the environment disturbance and its taking into account in mathematical models is shortly described. Next the proposed control system which is using technology of fuzzy logic is presented. At the end the example results of research on stabilizing movements' parameters of ROV during environment disturbance occurrence, using ROV simulator were presented. The paper is finished by summary which include conclusions derive from results of research.

Keywords: *control, fuzzy logic, underwater remotely operated vehicle, modelling of environment disturbance*

1. Introduction

In automatics the simple and efficient solutions of any controls' problems are very worthfull. Watching at many of this problems from distance allow to see some not usual ideas of solution which are often very valued. Such features have fuzzy logic used in control systems. Fuzzy logic is expanding traditional binary logic and allows to describe physical phenomena in communicable for humans manner, simultaneously this description is understandable for machine's control system. This method is far resisting on measurements, environmental noises an even on parametric noises which is present in controlled object. The simplicity of designing fuzzy control systems which are working according to, defined based on expert knowledge, rule matrix go far towards rapid development and large popularity of this method.

Expansion of underwater technology is caused firstly by common in use of this technology, its economy effects and, in many cases, deficit of any other alternative technology which can be used to fulfil some of the tasks [4]. Mostly remotely operated underwater vehicles (ROV) are used in area of extract natural resources such as gas and oil. Because extract technology is touching the newest deposit of natural resources which are positioned on deepest area where exist strong environment disturbance it is necessary to discuss its influence on movement of remotely operated underwater vehicle. It must be noticed that dynamics of underwater vehicle is changing greatly in case of environment disturbance presents what makes time of underwater works much longer. That way possibility to stabilize movement's parameters of remotely operated underwater vehicle in conditions of environment disturbance occurrence is very important problem [1, 4, 6].

The object of the research is the remotely operated underwater vehicle „Ukwial" which is equipment of Polish navy ships. This underwater vehicle is used to recognition and mine disposal of underwater region. It is also used in search and rescue operation, object location and recovery, inspection of oceanotechnic's construction and underwater part of ships.

2. Mathematical model of underwater remotely operated vehicle

During analysis of movement of sailing objects with six degrees of freedom the two coordinate Cartesian systems are defined. The one of them is related with sailing object and is called the body-fixed reference system [2, 3]. This reference system is usually such configured that its origin is in the centre of gravity of object and axis cover with inertial axis of object. The movement of body-fixed reference system is described in coordinate system related with the Earth which is called the earth-fixed reference system (see Fig. 1). It is suggested that orientation of vehicle is described in body-fixed frame meanwhile angular and linear velocities should be described in earth-fixed frame. Magnitudes of movement are described according to SNAME notation [7] like it was presented on Tab. 1.

Tab. 1. Notation using for describing movement of sailing objects

DOF	Name of movement	Forces and moments	Linear and angular velocity	Euler's positions and angles
1	surge (motion in the x-direction)	X	u	x
2	sway (motion in the y-direction)	Y	v	y
3	heave (motion in the z-direction)	Z	w	z
4	roll (rotation about the x axis)	K	p	ϕ
5	pitch (rotation about the y axis)	M	q	θ
6	yaw (rotation about the z axis)	N	r	ψ

Generally movement of underwater vehicle which has 6 dimension of freedom can be defined using following vectors:

$$\begin{aligned} \eta &= [x, y, z, \phi, \theta, \psi]^T, \\ \upsilon &= [u, v, w, p, q, r]^T, \\ \tau &= [X, Y, Z, K, M, N]^T. \end{aligned} \tag{1}$$

where:

η - vector which describe orientation in the earth-fixed reference frame,
υ - vector which describe velocities in the body-fixed reference frame,
τ - vector used for description of forces and moments which influence on vehicle.

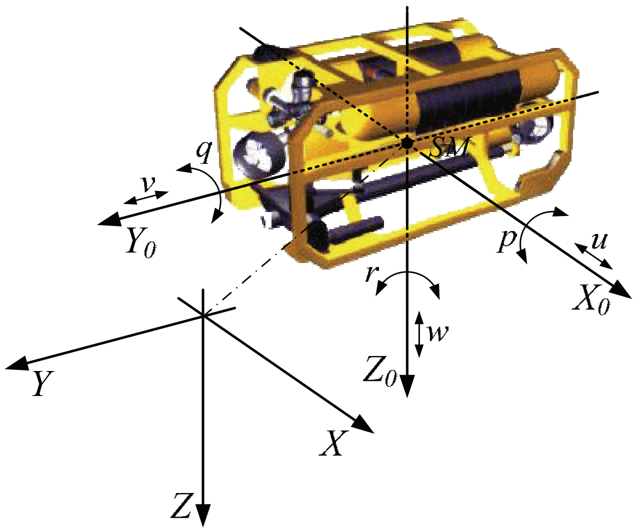

Fig. 1. The example of the influence of the number of thermal shocks on the deformation of the piston sample

The non-linear equations of underwater vehicle's movement treated as rigid body can be written as follows [2, 3, 8]:

$$\begin{aligned}
&m[\dot u-\upsilon r+\omega q-x_G(q^2+r^2)+y_G(pq-\dot r)+z_G(pr+\dot q)]=X\,,\\
&m[\dot\upsilon-\omega p+ur-y_G(r^2+p^2)+z_G(qr-\dot p)+x_G(qp+\dot r)]=Y\,,\\
&m[\dot\omega-uq+\upsilon p-z_G(p^2+q^2)+x_G(rp-\dot q)+y_G(rq+\dot p)]=Z\,,\\
&I_x\dot p+(I_x-I_y)qr-(\dot r+pq)I_{xz}+(r^2-q^2)I_{yz}+(pr-\dot q)I_{xy}\,,\\
&\qquad +m[y_G(\dot\omega-uq+\upsilon p)-z_G(\dot\upsilon-\omega p+ur)]=K\,,\\
&I_y\dot q+(I_x-I_z)rp-(\dot p+qr)I_{xy}+(p^2-r^2)I_{zx}+(qp-\dot r)I_{yz}\,,\\
&\qquad +m[z_G(\dot u-\upsilon r+\omega q)-x_G(\dot\omega-uq+\upsilon p)]=M\,,\\
&I_z\dot r+(I_y-I_x)pq-(\dot q+rp)I_{yz}+(q^2-p^2)I_{xy}+(rq-\dot p)I_{zx}\,,\\
&\qquad +m[x_G(\dot\upsilon-\omega p+ur)-y_G(\dot u-\upsilon r+\omega q)]=N\,,
\end{aligned} \tag{2}$$

where:

m - vehicle mass,

I_x, I_y, I_z - moments of inertia in relation to symmetry axis of vehicle,

x_G, y_G, z_G - co-ordinates of centre of gravity.

The general representation of equation of movement in body-fixed frame can be written as [2, 3, 8]:

$$M\dot v + C(v)v + D(v)v + g(\eta) = \tau\,, \tag{3}$$

where:

η - vector of state,

τ - vector of the input functions,

v - vector of velocities,

M - the matrix of vehicle masses and added water masses,

$C(v)$ - the matrix of centripetal and Coriolis forces,

$D(v)$ - the matrix of hydrodynamic dumping,

$g(\eta)$ - the matrix of restoring moments and forces.

The creating of mathematical model of underwater vehicle is the complex problem. It is difficult to delimitate or calculate many parameters, which has to be well-known to solve the equations of movement. It is possible to reduce the number of parameters making the certain assumptions related with vehicle's construction such as: the symmetry of vehicle in different surfaces, the position of centre of gravity and centre of uplift pressure, and suitable selection of reference system origin [2, 3, 8].

3. Environmental disturbance

To the basic environment's disturbances, which are considered at analysis of sailing objects belong: waviness, wind and underwater currents.

At examination of objects entirely plunged such underwater robots it is possible to omit influence of wind on object's model of object, meanwhile waviness matters only to the depth 10 meters. Assuming, that underwater works with usage of ROV are made on the depth greater than 10 meters (to this depth most underwater works is made by divers without necessity of using special equipment) this disturbance can be omitted hereinafter [2, 6, 9].

Current velocity can be written as sum of following velocity components:

$$V_c = V_t + V_{tw} + V_S + V_m + V_a + V_d \, , \tag{4}$$

where:

V_t - tidal component,

V_{tw} - component generated by local wind,

V_s - component generated by non-linear waves,

V_m - component from major ocean circulation,

V_a - component due to set-up phenomena and storm surges,

V_d - local density driver current components governed by strong density jumps in the upper ocean.

Let the vertical component z be measured positive downwards. Hence, the velocity profile of the tidal component can be written as follow [2, 9]:

$$V_t(z) = \begin{cases} V_t(0) \, , & for \quad 0 \le z \le d - 10 \, , \\ V_t(0)\log_{10}(1 + \dfrac{9z}{d-10}), & for \quad d - 10 < z < d \, , \end{cases} \tag{5}$$

where:

$V_t(0)$ - the surface Speer of the tidal,

d - the water depth (greater than 10 meters).

The component generated by the local wind is written as [2, 9]:

$$V_{tw}(z) = \begin{cases} V_{tw}(0)\dfrac{d_0 - z}{d_0}, & for \quad 0 \le z \le d_0 \, , \\ 0 \, , & for \quad z > d_0 \, , \end{cases} \tag{6}$$

where d_0 is the reference depth for the wind-generated current usually taken to be 50 m.

It can be shown that V_{tw} can be approximated as:

$$V_{tw}(0) = 0.02 V_{10} \, , \tag{7}$$

where V_{10} is the wind velocity, measured 10 m above sea level.

Component generated by nonlinear waves are the 2nd-order wave disturbance or so-called wave drift forces and can be treated as an additional current component. The contribution to the drift resulting from the irrotational properties of the wave can be written as [9]:

$$V_s(z) = \sum_{i=1}^{N} \frac{4\pi^2 A_i^2}{T_i \lambda_i} \exp(-4\pi \frac{z}{\lambda_i}) \, , \tag{8}$$

where:

A - the wave high,

T - the time period between next waves,
λ - the wave length.

Forces and moments induced by water currents are taken into consideration in equations of dynamics of movement at assumption that the equations of movement can be represented in terms of relative velocities [2, 3, 9]:

$$v_r = v - v_c \,, \tag{9}$$

where $v_c = [u_c, v_c, \omega_c, 0,0,0]^T$ is the vector of irrotational velocities of currents in body-fixed reference frame.

Let the earth-fixed current velocity vector be denoted by: $[u_c^E, v_c^E, \omega_c^E]$. From that we can calculate the body-fixed component using Euler's theory. Let's assume that the velocity of current in body-fixed frame is constant or at least slowly-varying such that fulfils [2, 3, 9]:

$$\dot{v}_c = 0 \quad \Rightarrow \quad \dot{v}_r = \dot{v} \,, \tag{10}$$

Hence, the nonlinear relative equations of motion (2) take the form [2, 3, 9]:

$$M\dot{v} + C(v_r)v_r + D(v_r)v_r + g(\eta) = \tau \,, \tag{11}$$

The earth-fixed current velocity components (u_c^E, v_c^E, w_c^E) can be related to V_c by defining two angles: α (angle of attack) and β (sideslip angle), describing the orientation of V_c about the *X* and *Y* axis respectively (see figure 1), what can be written as:

$$\begin{aligned} u_c^E &= V_c \cos\alpha \cos\beta \,, \\ v_c^E &= V_c \sin\beta , \\ w_c^E &= V_c \sin\alpha \cos\beta . \end{aligned} \tag{12}$$

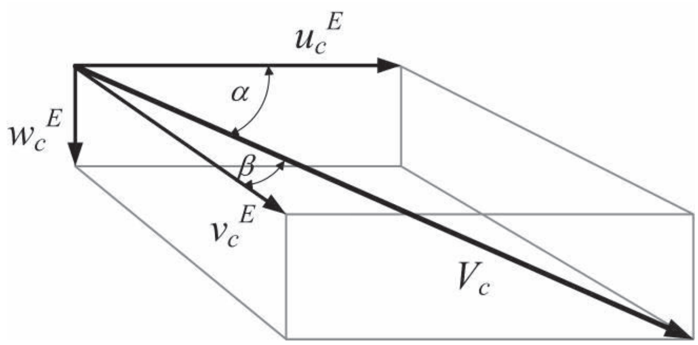

Fig. 2. Orientation of average current velocity with earth-fixed frame

For computer simulations the average current velocity can be generated by using a 1st-order Gauss-Markov process. For instance $V_c(t)$ can be described by the following differential equation [2]:

$$\dot{V}_c + \mu_0 V_c(t) = \omega(t) \,, \tag{13}$$

where:
$\omega(t)$ - a zero mean Gaussian white noise,
$\mu_0 \geq 0$ - a constant.

Usually it is sufficient to choose $\mu_0 = 0$ which simple corresponds to a random walk that is time integration of white noise. This process must be limited such that $V_{\min} \leq V_c(t) \leq V_{\max}$ in order to simulate realistic ocean currents.

4. Fuzzy controller

One of the typical practical applications on fuzzy logic is in projection of control systems. In most cases to control object is used controller which is processing the error of regulation to the control signal according to its characteristic. Such system can be generally presented as it is shown on Fig. 3.

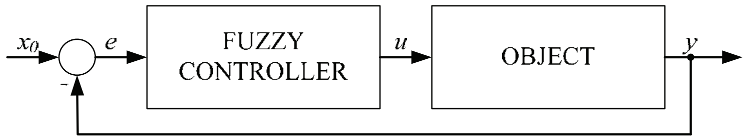

Fig. 3. Control system with fuzzy controller

The structure of typical fuzzy controller was presented as block diagram on Fig. 4.

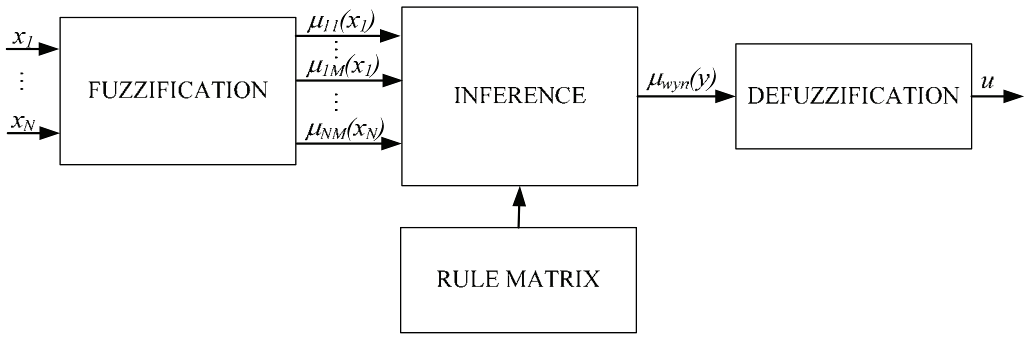

Fig. 4. Structure of example fuzzy controller

The fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets [5]. The membership function is used to associate a grade to each linguistic term. Therefore before fuzzification process take place the membership functions must be qualitative defined (type of function) as well as quantify defined (values of parameters of functions). Both type of function and values of its parameters have much influence on whole system precision.

The core section of a fuzzy system is that part, which combines the facts obtained from the fuzzification with the rule base and conducts the fuzzy reasoning process [5]. This is called a fuzzy inference machine. To make possible calculations of inference the rule matrix must be defined. Such rule matrix consists of logical rules which describe causality-results dependencies between input and output membership functions. Basis on defined rules and values of premises' fulfil the values of membership function for conclusions of each rules is calculated.

As a result of applying the previous steps, one obtains a fuzzy set from the reasoning process that describes, for each possible value, how reasonable it is to use this particular value [5]. In other words, for every possible value, one gets a grade of membership that describes to what extent this value is reasonable to use. Using a fuzzy system as a controller, one wants to transform this fuzzy information into a single value that will actually be applied. This transformation from a fuzzy set to a crisp number is called a defuzzification. It is not a unique operation as different approaches are possible. The most important ones for control are: centre of gravity method, centre of singleton method, maximum methods, margin properties of the centroid methods.

5. Results of researches

Basis on mathematics equitation presented in previous chapter the model of underwater remotely operated vehicle was worked out. These models along with model o underwater currents which influence on underwater vehicle become the simulation environment for next researches. Next using theory of fuzzy logic the fuzzy controller was build. Its task was to stabilize the underwater vehicle course basis on information about difference between desired course and actual course φ and angular velocity dφ/dt around the normal axis of vehicle. Created controller has the structure presented on Fig. 4. Membership functions for controller input were presented on Fig. 5.

Inference process was calculated according to matrix rules which was created basis on expert experience and has been presented in Tab. 2. In table there are following denote: LN – large negative, MN – medium negative, SN – small negative, Z – zero, SP – small positive, MP – medium positive, LP – large positive.

Defuzzification process is calculated according to centre of gravity method using output membership functions presented on Fig. 6.

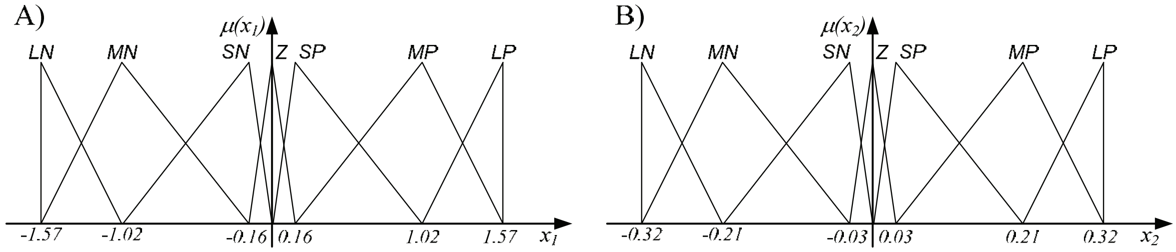

Fig. 5. Membership function a) for first input (difference between desired course and actual course of vehicle), b) fo second input (rotational velocity of vehicle around its normal axis)

Tab. 2. Rule matrix of fuzzy controller

		φ						
		LN	MN	SN	Z	SP	MP	LP
dφ/dt	LN	LP	LP	MP	MP	MN	MN	LN
	MN	LP	MP	SP	SP	SN	SN	MN
	SN	MP	SP	SP	Z	Z	Z	SN
	Z	LP	MP	SP	Z	SN	MN	LN
	SP	SP	Z	Z	Z	SN	SN	MN
	MP	MP	SP	SP	SN	SN	MN	LN
	LP	LP	MP	MP	MN	MN	LN	LN

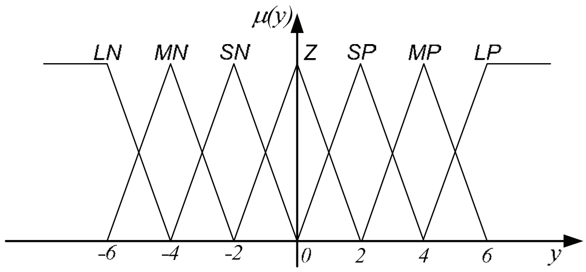

Fig. 6. Membership function used in defuzzification process

The researches were conducted in worked out simulation environment. The virtual underwater remotely operated vehicle has task to recognize the area of operation (searching of dangerous objects). Firstly the task was performed in environment without disturbance and next using the same control in environment with underwater currents occurrence. Below on the figures were presented chosen results of research. Gray colour means movement of vehicle in environment without disturbance, black colour means movement in environment with underwater current occurrence. Underwater current parameters such as speed and course were changed according to presented on Fig. 7. More over the obtained results of using fuzzy controller were compared with results obtained during deployment of classical PID controller [10] what was shown on Fig. 8.

6. Summary

Fuzzy control allows to easy project regulators for nonlinear objects, especially in case when character of nonlinearity impedes its description using analytic methods. According to the possibility of control's algorithm implementation the fuzzy regulators belongs to computer (microprocessor) methods of control. It can be pointed following features of fuzzy control:

- allows to describe the problem in natural human language basis on expert know-how (analysis dependencies between input and output data), what makes it easy to understand,
- it allow to model nonlinear dependencies with large complexity, where analytic description is hard or event not possible,
- allows to use adaptive technique of parameter calculations basis on set of learning data (ANFIS - Adaptive Neuro-Fuzzy Inference Systems),
- characterize by robustness and hard on not precision data,
- pleadable to parallel calculations,
- it can be integrated with classical methods of controls.

Basis on simulation researches, which chosen results were presented above, it can be said that using fuzzy controller for stabilization underwater remotely operated vehicle's course which is moving in environment with disturbance occurrence, gives satisfy results. It must be pointed that in spite of small difference between vehicle's course on which the ocean current has influence and this one which is moving in environment without disturbance, the trajectory of both vehicles differ a lot. It follows that underwater current cause drift of vehicle according to its powerful and way of flooding in.

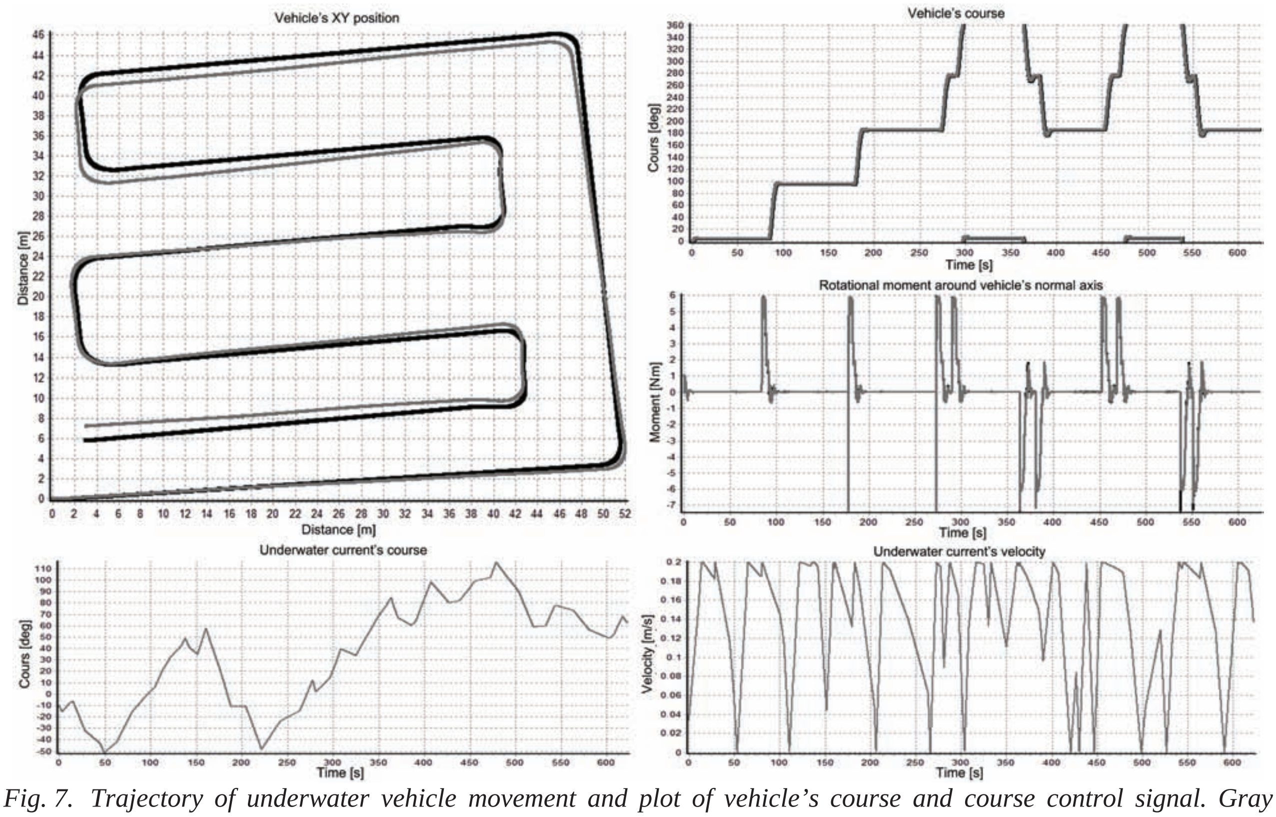

Fig. 7. Trajectory of underwater vehicle movement and plot of vehicle's course and course control signal. Gray colour means movement of vehicle in environment without disturbance, black colour means movement of vehicle in environment with underwater current influence on vehicle (presented on chart)

During researches it was checked the difference in vehicle course stabilization in environment of disturbance occurrence using classical PID controller [10] (which parameters were calculated using Tyreus-Luyben method), and fuzzy controller. As it was shown on charts the time of regulations in both cases were similar but PID controller cause formation of many oscillations. Changing parameters of PID controller such as minimize the number of oscillations cause times of regulation prolongation [10]. More over oscillations which were present during using of PID controller are undesirable from the realizing underwater task point of view.

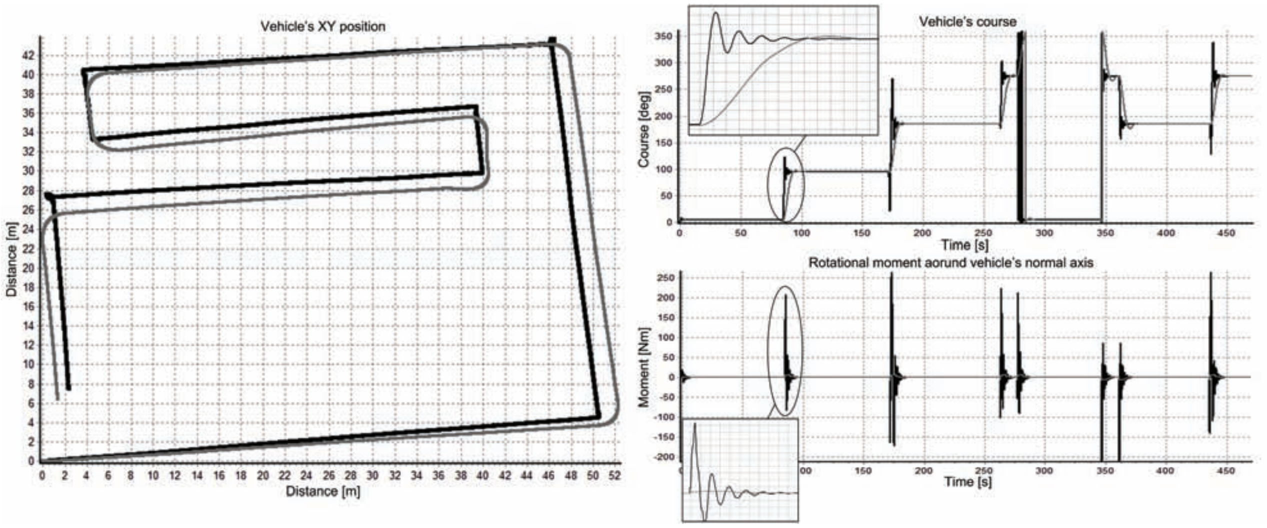

Fig. 8. Trajectory of underwater vehicle movement and plot of vehicle's course and vehicles rotational moment - course control signal. Vehicle is moving in environment with disturbance occurrence such as ocean current which flow with velocity of 0.12 m/s and course of 30 deg. Gray colour means movement using classical PID controller and black colour means using fuzzy controller

The results of researches allows to work out the control algorithm which may be used to precision tracking of underwater vehicle along the trajectory in environment where the disturbance occurrence. This problem will be next researched. More over the usefulness of neuro-controller will be investigated in next works.

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