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Selection of Method for Underwater Robot Control

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Abstract. Automatic control of motion of underwater robots, particularly along desired trajectory, requires application of proper controllers taking into account dynamics of the underwater robot and features of the marine environment.
In the paper the mathematical model of an underwater vehicle [2] and the architecture of designed control system [4] have been presented. Moreover, selected results of numerical analysis in the form of comparison of different course controllers have been provided.

Introduction

One of the main development directions of an underwater technology are robots, which are working under the surface of water. These unmanned vehicles enable exploration at bigger depths and in more hazardous conditions [3]. Correct execution of different underwater operations requires precise control of robot motion in underwater environment. Different control methods should be examined to find the most adequate method taking into consideration that underwater robot is an object of nonlinear dynamics and works in marine environment with different disturbances.
Control system of underwater robot motion consists of: supervisory unit and controllers working in *n* degrees of freedom. Here *n* depends on manoeuvre features of specific underwater robot. The paper undertakes problem of selection of controller structure to provide adequate response for desired values of motion parameters. For this aim different methods from classical PID control to fuzzy logic control have been examined [4-6].
There are different constructions of underwater vehicles (UV) in the world. There are also examples of UVs representing Polish technology. The most popular and simple construction of underwater vehicle is one based on a frame with a cubicoid shape (Fig. 1). The frame has often dimensions chosen in the way that a shape of an underwater vehicle is close to a cube. Driving system and additional equipment such as cameras, manipulators, lamps, etc. are mounted to the frame in the way that all elements are located inside the space of the frame. Driving systems of these underwater vehicles consist of propellers acting in horizontal and vertical surface. Most often 3 to 4 propellers are mounted in a vertical surface, what gives possibility to control linear motions in x_o and y_o axes (longitudinal and lateral axis of symmetry) and a rotational motion in z_o axis (vertical axis of symmetry). Additionally 1 to 2 propellers are usually mounted in a vertical surface. They are responsible for generating a driving force in z_o axis (in the case of 2 propellers, there is possibility of generating a moment of force in y_o axis). An example of this kind of construction is remotely operated vehicle Ukwial [5], which is equipment of a countermine warship (Fig. 1).

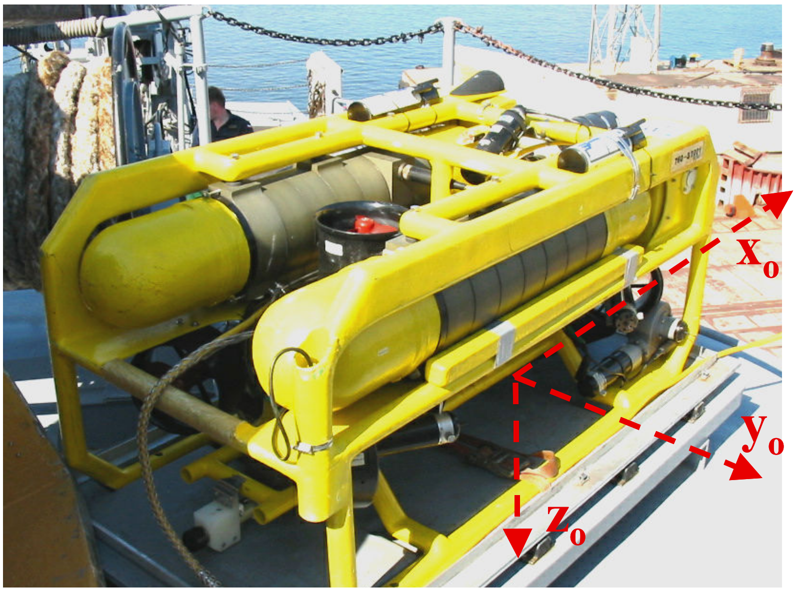

Fig. 1. Remotely operated vehicle Ukwial on board of countermine warship

Mathematical Model of Underwater Robot

To simulate movement of the underwater vehicle nonlinear model described in six degrees of freedom is used [2]. The mentioned motion is analyzed in two coordinate systems:
1. body-fixed coordinate system, which is movable,
2. earth-fixed coordinate system, which is immovable.

For the purpose of movement description, the notation of physical quantities according to SNAME (*The Society of Naval Architects and Marine Engineers*) was used [7].
The motion of an underwater vehicle is described by means of six equations of motion. The first 3 equations represent the translational motions, whereas the other three represent the rotational motions. The heave is the linear vertical (up/down) motion along z_o axis, the sway is the linear lateral (side-to-side) motion along y_o axis, and the surge is the linear longitudinal (front/back) motion along x_o axis. The roll is when the vehicle rotates about the longitudinal (front/back) axis, the pitch is when the vehicle rotates about the transverse (side-to-side) axis, and the yaw is when the vehicle rotates about the vertical (up-down) axis.
The mentioned above equations can be expressed in the following compact form:

$$\mathrm{M}\dot{\nu} + \mathrm{C}(\nu)\nu + \mathrm{D}(\nu)\nu + \mathrm{g}(\eta) + \mathrm{U}(\nu)\nu = \tau, \qquad (1)$$

where

$\nu=[u,v,w,p,q,r]$ is the body-fixed linear and angular velocity vector,
$\eta=[x,y,z,\phi,\theta,\psi]$ is the earth-fixed coordinates of position and Euler angles vector,
$\tau=[X,Y,Z,K,M,N]^T$ is the vector of forces and moments of force affecting underwater vehicle,
M is inertia matrix, which is equal to rigid-body inertia matrix $\mathrm{M_{RB}}$ and added mass inertia matrix $\mathrm{M_A}$,
C is a Coriolis and centripetal matrix, which is a sum of rigid-body $\mathrm{C_{RB}}$ and added mass $\mathrm{C_A}$ Coriolis and centripetal matrixes,
D is a hydrodynamic damping matrix,
g is a restoring force and moment matrix,
U is a damping matrix generated by a cable called umbilical cord.
Underwater vehicle could be supplied and controlled through the umbilical cord.
The nonlinear mathematical model of an underwater vehicle is considered in more detail in [2,4].

Control System of the Underwater Robot

The control system of the underwater vehicle Ukwial is designed in the way that it consists of 4 controllers of: a course, a displacement in x_o axis and a displacement in y_o axis, and a draught. These controllers are set in 4 degrees of freedom of the robot: moment of force N in z_o axis, force X in x_o axis, force Y in y_o axis and force Z in z_o axis (Fig. 2). Individual controllers receive desired values of controlled parameters such as desired course and desired coordinate x, y and z from the decision system. Current values of these parameters are received directly from measurement devices mounted on a board of the underwater vehicle [3].

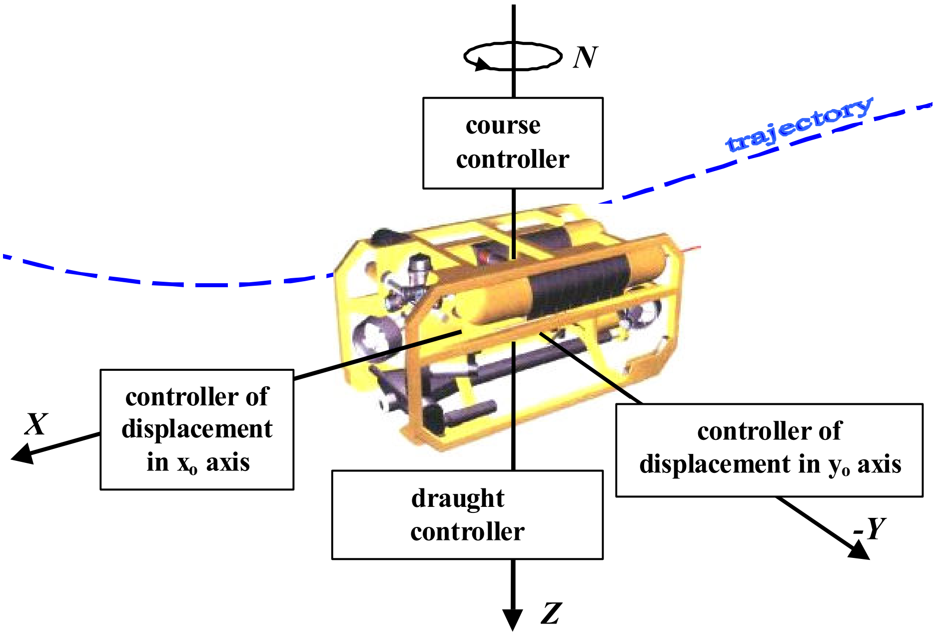

Fig. 2. Control system of underwater vehicle Ukwial

Different controllers were tested with the aim to obtain adequate control of the parameters Fig. 2): classical PD controllers, slide controllers and fuzzy controllers FPD based on fuzzy logic.

Classical Controller PD. Proportional-derivative (PD) action controllers are used to control objects, which are affected by big and rapid disturbances. The action of PD controller is described by equation in discrete form:

$$u(k) = K_P \cdot \left(e(k) + \frac{T_d}{T_p} \cdot \Delta e(k) \right). \tag{2}$$

Where $u(k)$ is a control signal in k step of simulation. Variable $e(k)$ is an error signal in k step of simulation, while $\Delta e(k)$ is a change of error signals in k step of simulation ($e(k)$–$e(k\text{-}1)$). Constant quantities are: K_p, T_d and T_p, where K_p is a gain factor, T_d is a constant of derivative action time and T_p is a sampling time.

For determination of values of constant quantities it is necessary to correct action of controller. For this purpose different methods could be used. In the paper a classical Ziegler-Nichols method was applied. For selected course controller the following values of constant quantities were received: $K_p = 19$, $T_d = 260$ ms and $T_p = 55$ ms.

Slide Controller. Controllers working in slide mode are used in control of nonlinear objects [8], for example underwater vehicles. Their principle of operation is based on changing a sign of the function $s(t)$ depending on its location to switching surface $s(t) = 0$. The principle could be described by means of the following equation:

$$u(t) = k \cdot sat\left(\frac{s(t)}{\phi_{wg}}\right) + u_{eq}, \tag{3}$$

where,
$u(t)$ is a control signal and k is a maximal value of a control signal,
$s(t)$ is a switching function equal to $s(t) = e(t) + \lambda \cdot \dot{e}(t)$, where λ is a constant value,
u_{eq} is a equivalent quantity of slide control,
ϕ_{wg} is a thickness of a boundary layer [8].
Slide controller tuning was performed in the empirical way with the aid of direct control quality indexes. For selected course controller the following values of parameters were received: k = 80, λ = 0.3 and ϕ_{wg} = 90.
Stability of the tuned controller was tested by simulation for several values of desired course: 10°, 20°, 45°, 60°, 90° in the presence of affecting sea current with maximal velocity 1 m/s.
Fuzzy Controller FPD. For the control of nonlinear objects operating in an environment with large and rapid disturbances, artificial intelligence methods are used more often, in particular fuzzy logic method. Using of fuzzy logic in data processing provides possibilities of nonlinear system development, which is robust to environmental disturbances [1].
Using fuzzy logic method for PD control depends on selection: a number, a type and parameters of membership functions of input and output variables. Moreover, fuzzy inference rules, which create base of rules, should be designed and tuned [1]. Fuzzy proportional-derivative action controller has a structure presented in Fig. 3. Parameter p could be adequately a course angle or a coordinate x, y, or z.

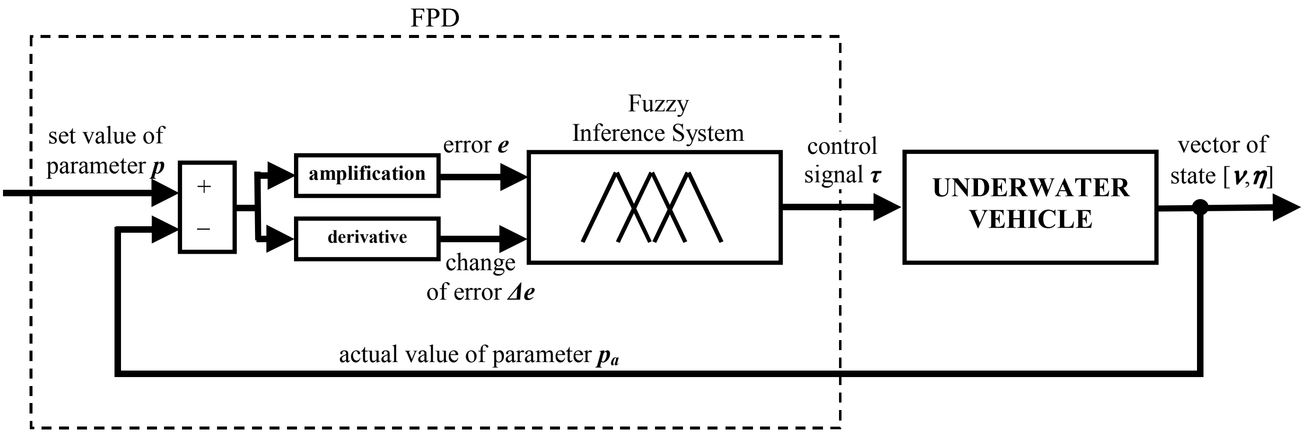

Fig. 3. Structure of fuzzy proportional-derivative controller

For FPD control of course angle simple Sugeno type fuzzy inference system was accepted, which was used in earlier research [4]:
1) 3 fuzzy sets with external trapezoidal membership functions and internal triangular membership function for input signals: error (intersection points of functions equal to [–0,2; 0.5] and [0,2; 0,5] and change of error (intersection points of functions equal to [–0,07; 0,3] and [0,07; 0,3]),
2) 5 singletons for output signal - moment of force M (with coordinate equal to: -1, -0,65, 0, 0,65 and 1).

Amplification factors for normalized membership functions were tuned with the aid of simulation and were evaluated with direct control quality indexes. Following values of amplification factors were obtained: 180° for error signal, 30° for change in error signal and 42 N for control signal.
Settings of fuzzy system can be tuned by artificial neural network, which can be considered as modern computational system processing data similar to process in a human brain. Neural network learns required behavior of unidentified object on the basis of training data, which conclude values of input and response function of this object. In this case, a neuro-fuzzy controller is created.

Results of Numerical Research

Fig. 4 presents comparison of 3 control methods: classical PD, slide control and fuzzy FPD.

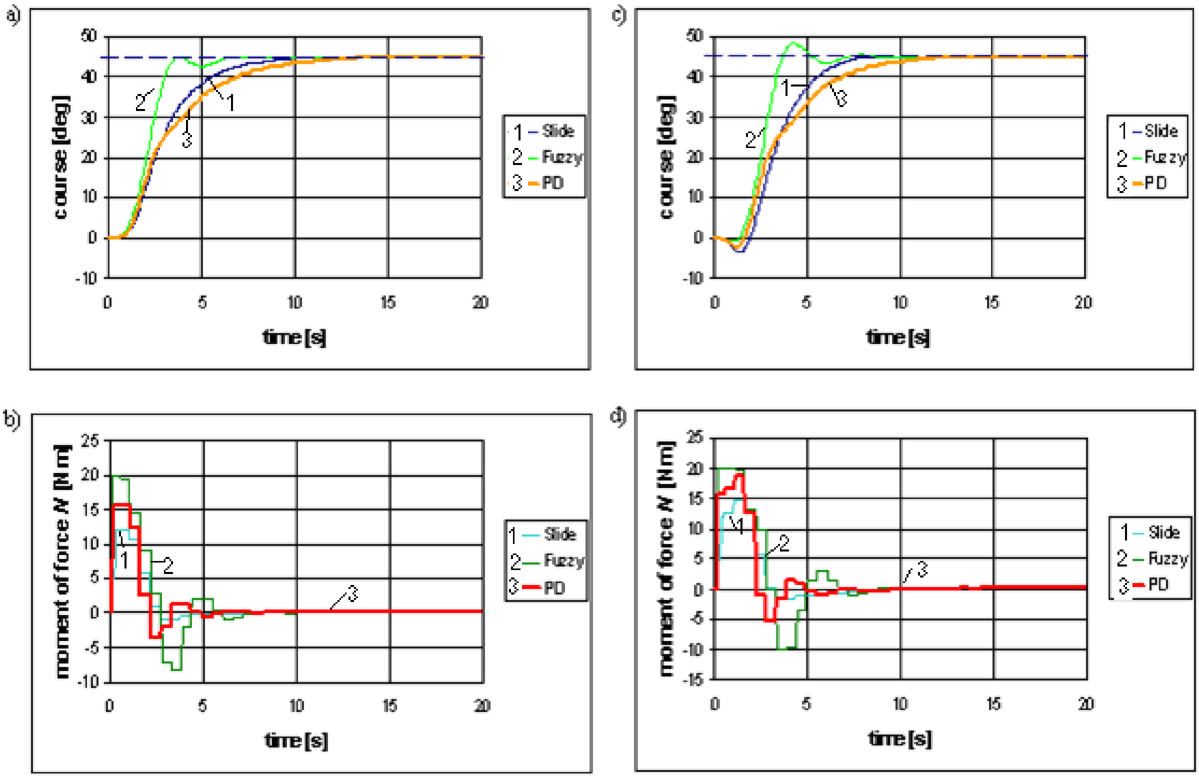

Fig. 4. Comparison of 3 control methods: classical PD, fuzzy FPD and slide mode control based on course control of underwater robot Ukwial without a) b) and with c) d) affecting sea current with velocity 1 m/s and direction 90°.

To evaluate the quality of tested controllers, the following direct control quality indexes were used:
1) t_n – rise time, defined as time to achieve 90% expected change of setting parameter (since beginning value to set value),
2) t_r – setting time, defined as time to achieve value of setting parameter, which changes (e.g. oscillates) less than 5% total change of setting parameter,
3) M_r – first overshoot value, characterizing oscillation of response.

Obtained values of direct control quality indexes for 3 different controllers have been presented in Table 1.

Table 1. Direct control quality indexes for 3 course controllers

Control quality indexes	**without sea current**			**sea current (velocity 1 m/s and direction 90°)**		
	Classical PD	Slide controller	Fuzzy FPD	Classical PD	Slide controller	Fuzzy FPD
t_n [s]	7.36	5.77	3.08	7.31	5.72	3.41
t_r [s]	9.26	7.09	3.30	8.85	6.54	4.73
M_r [deg]	–	–	–	–	–	3.36

Summary

The best direct control quality indexes were received for fuzzy FPD controller (Table 1), which are characterized by a nonlinear control surface and high robustness to environment disturbances [1,4]. On the other hand, the fuzzy control is characterized by oscillation of response, particularly under effect of sea current. More smoothed curves were obtained for slide course controller and even

classical PD controller.
Controllers based on fuzzy logic method should be used in order to obtain fast-operating control system of the underwater robot.

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