Automated safe control of a Self-propelled Mine Counter Charge in an underwater environment

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Abstract

The operation of a Self-propelled Mine Counter Charge (SMCC) in an underwater environment is exposed to disturbances of its movement. The main disturbances in this kind of environment are sea currents. Another difficulty in SMCC operation, particularly with automated control, is the nonlinear dynamics of the torpedo-shaped body of the SMCC.

In this paper the automatic control system of a SMCC, called Gluptak, is presented, which can support the execution of a counter mine mission. Additionally, two control methods have been be presented that can interact with the sea current influence in the case of a lack of sea current measurement on board the SMCC. For the purpose of Gluptak's control, the use of classical PD and artificial intelligence controllers have been considered, particularly with fuzzy data processing.

A mathematical model of the SMCC and selected results of the numerical research are presented.
Keywords: underwater vehicle, counter mine mission, automatic control, fuzzy logic.

1 Introduction

One of the main development directions of military underwater technology is that of robots, which are used to identify and destroy naval mines. Using these unmanned vehicles enables exploration at greater depths and in more hazardous conditions.

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The Polish implementation of this technology is the Self-propelled Mine Counter Charge (SMCC), Głuptak (fig. 1). It was designed in the Underwater Technology Department of Gdańsk University of Technology. The SMCC is a disposable unit, remotely operated and powered from on-board. It is shaped like a torpedo (fig. 1). It carries mine disposal equipment to the detected and classified target. While the target is identified by vehicle sonar and TV cameras (fig. 1), this equipment is used to initiate the mine explosive [3].

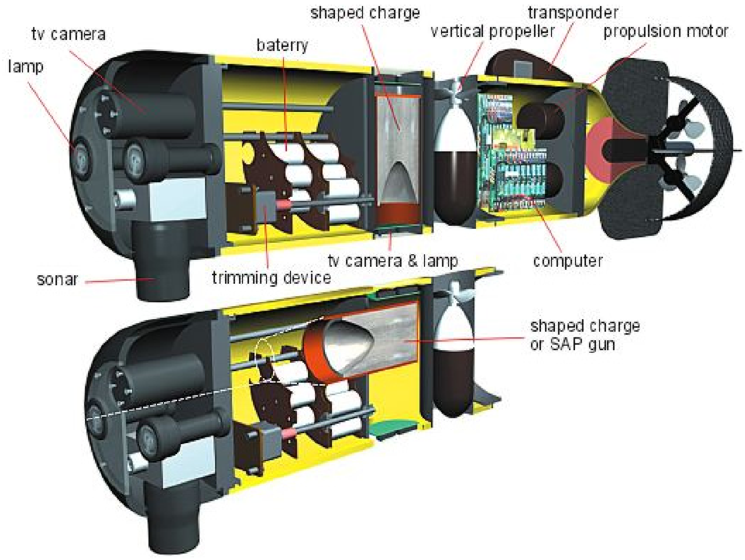

Figure 1: Principal components of SMCC Gluptak.

SMCC Gluptak has a specific propulsion system, consisting of: four, 3-blade screw propellers in the horizontal plane and a single 3-blade screw propeller in a tunnel in a vertical plane. Each thruster is electrically driven and has 50 W power. The propulsion system enables the underwater vehicle to move in water with a maximal speed of 3 m/s and allows the control of the SMCC's movement in four degrees of freedom (two translation motions: in the longitudinal axis of symmetry x_o and the vertical axis of symmetry z_o, and two rotations around the lateral axis of symmetry y_o and around the z_o axis).

2 Mathematical model

For the purpose of Gluptak's movement simulation, a nonlinear model in six degrees of freedom has been accepted [1], where movement is analysed in two coordinate systems:

1) the body-fixed coordinate system $x_o y_o z_o$, which is movable,
2) the earth-fixed coordinate system xyz, which is immovable.

While for the aim of movement description, notation of physical quantities according to SNAME (*The Society of Naval Architects and Marine Engineers*) has been accepted [2].

SMCC Gluptak's movement is described with the assistance of six equations of motion, where the three first equations represent the translations and the last three equations represent the rotations (in three axes of symmetry: longitudinal x_o, lateral y_o and vertical z_o). These six equations can be expressed in a compact form [1] as:

$$\mathrm{M}\dot{\nu} + \mathrm{C}(\nu)\nu + \mathrm{D}(\nu)\nu + \mathrm{g}(\eta) = \tau . \tag{1}$$

Here $\nu=[u,v,w,p,q,r]$ 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 and $\tau=[X,Y,Z,K,M,N]^T$ is the vector of forces and moments of force influenced underwater vehicle. M is an inertia matrix, which is equal to a rigid-body inertia matrix M_{RB} and an added mass inertia matrix M_A. C is a Coriolis and centripetal matrix, which is the sum of a rigid-body and an added mass Coriolis and centripetal matrixes. D is a hydrodynamic damping matrix and g is a restoring forces and moments matrix.

After making the assumption that SMCC has three planes of symmetry, it moves with small speed in a viscous liquid and a movable coordinate system calculates the vehicle's centre of gravity, obtained with a specific form of matrixes with nonzero values of the diagonal's elements [1]. According to [5], these elements were calculated on the basis of the geometrical parameters of SMCC Gluptak.

Coriolis and centripetal matrixes were omitted because of the small numerical values that are unimportant in computer simulation.

3 Architecture of the control system

The automated control system of SMCC Gluptak consists of (fig. 2):

1) a supervisory control unit, which is responsible for setting values of the movement's parameters and turning on and off individual controllers at proper moments,
2) four controllers of: course, trim, translation and draught, which are generating an adequate control signal (fig. 2).

Because the hydrodynamic damping in the y_o and z_o axes is almost 10 times bigger than in the x_o axis, and there being about four times more thrust in the x_o axis than in the z_o axis, the draught's controller is useless in practise.

As there is a lack of information about the sea current's influence on the underwater vehicle, it has been assumed that the SMCC should approach its aim with a constant velocity of 0,5 m/s. Therefore, the controller of the translation controls translational velocity is relative to the target of the mission. The value of the velocity is obtained from an underwater trackpoint system, which is used to navigate below the surface of the water.

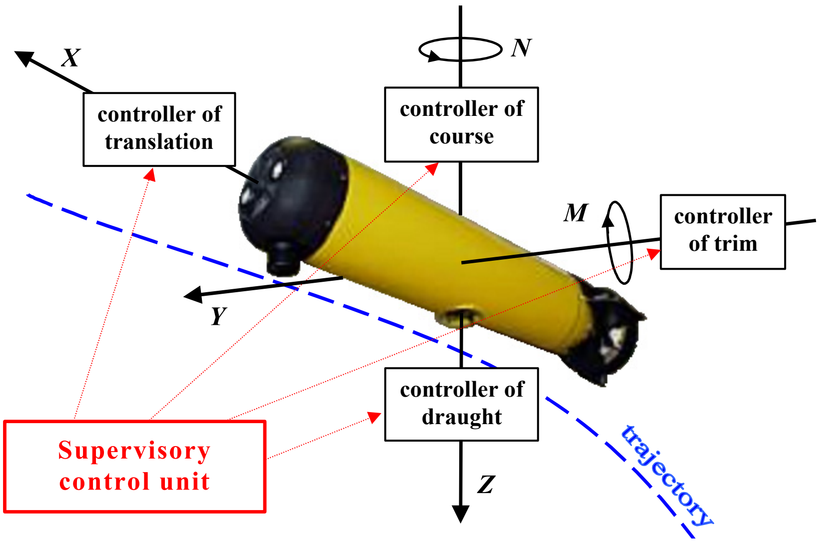

Figure 2: Architecture of the automated control system of SMCC Gluptak.

The controller of translation is a classical proportional-derivative-integral action controller PID, the action of which in discrete time is based on the simple equation:

$$u_n = k_p \cdot \varepsilon_n + k_i \cdot \sum \varepsilon_n + k_d \cdot \Delta\varepsilon_n . \tag{2}$$

Here u_n is the control signal, ε_n is the control error, $\sum\varepsilon_n$ is the sum of recent errors in n instant of time and $\Delta\varepsilon_n$ is the derived change in error in n instant of time. k_p, k_i and k_d are amplification factors adequately of the proportional, the integral and the derivative elements.

All the controller's settings were tuned in an experimental way with assistance of direct control quantity indexes, such as the rise time, the setting time and the value of the first overshoot. For the accepted step of the control, equal to 1/18 s, the following amplification factors have been received: $k_p = 55$, $k_i = 0{,}1$ and $k_d = 21$.

For the purpose of the courses and trims control two types of proportional-derivative action controllers have been used:

1) classical PD,
2) based on fuzzy logic method FPD [5].

An action of classical PD controller in discrete time is based on the simple equation:

$$u_n = k_p \cdot \varepsilon_n + k_d \cdot \Delta\varepsilon_n . \tag{3}$$

Here u_n is the control signal, ε_n is the control error and $\Delta\varepsilon_n$ is the derived change in error in n instant of time. k_p and k_d are amplification factors adequately of the proportional and the derivative elements.

All of the controller's settings were tuned in an experimental way with the assistance of direct control quantity indexes, such as the rise time, the setting time and the value of the first overshoot. For the accepted step of the control, equal to 1/18 s, the following amplification factors have been received: $k_p = 2{,}9$ and $k_d = 256$.

The action of FPD controllers is based on the fuzzy inference (fig. 3). Use of fuzzy inference in FPD controllers depends on the selection: number, type and position parameters of the membership function of the input and output variables and fuzzy inference rules, which create a base of rules.

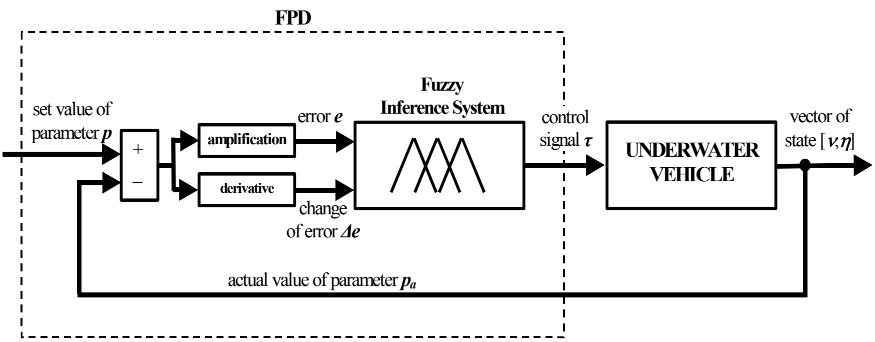

Figure 3: Block diagram of the fuzzy proportional-derivative controller FPD.

For the purpose of the FPD control of trim and course, a simple structure of the fuzzy inference system has been accepted, which was used in earlier research [4]:

1) three fuzzy sets with external trapezoidal membership functions and internal triangular membership functions 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) five singletons for output signal – moment of force M (with coordinates equal to: -1, -0,65, 0, 0,65 and 1).

Amplification factors for normalized membership functions were tuned with the assistance of the simulation of the mathematical model and were evaluated with the assistance of direct indexes. The following values of amplification factors have been received: 90° for the error signal, 3° for the change in error signal and 4,5 N for the control signal.

4 Strategy of approach to target the SMCC mission

During the process of designing the approach strategy to a mission target carried out by Gluptak, the following factors should be taken into consideration:

1) the torpedo-shaped body of the SMCC, where the only efficient direction of travel is translational movement in the x_o axis,

2) the potential possibility of control in four degrees of freedom reduced to three degrees of freedom (proper draught should be carried out by adequate trim and forward movement),
3) the specific construction of a control cable called the umbilical cord in the form of a thin optical waveguide unrolling from a spool (this type of cable generates almost neutral resistance of movement, but it has limited length and the speed of its unrolling depends on the trajectory of the SMCC and the action of the sea current).

Because of the presented factors, it has been assumed that the SMCC should take a starting position relative to the target of the mission in the way that the eventual sea current will act on it in its x_o axis and on the contrary of its translational velocity vector. In this case, the underwater vehicle will move forward along a line close to a straight line and its cable will unroll backwards to prevent eventual damage of the cable by the underwater vehicle's thrusters.

In the case of sea current action, the effect of an underwater vehicle pushing aside could be observed. When the SMCC is equipped with a sea current measuring device there is no problem with interaction. In this case the virtual aim of the mission should be calculated, which will take into consideration the direction and velocity value of the sea current.

In the case of a lack of sea current measurement on the board the SMCC, correction of the set value of controlled variables should be executed. For the purpose of interacting with the sea current two control methods have been developed:

1) continuous updating of the set value of the controlled variable (if an underwater vehicle is pushed aside by the sea current, then a new set value of the controlled variable is calculated),
2) correction of the set value of the controlled variable on the basis of bearing (after achieving set values of the controlled variable bearing in the horizontal or the vertical surface is calculated; changes of bearing in time indicate the sea current action, which gives the possibility of correcting the set value of the controlled variable).

The second correction method was based on the simple equation:

$$p_n = p_{n-1} + k_b \cdot \Delta b_n \,. \tag{4}$$

Here p_n is the set value of the controlled variable in n instant of time, $p_{n\text{-}1}$ is the set value of the controlled variable in n-1 instant of time, k_b is the gain factor and Δb_n is the error of bearing in n instant of time.

5 Numerical research

Computer simulation was realized in the Windows/Matlab environment. Simulation was executed with the influence of the sea current with the following parameters: specified velocity V_c and direction of affecting α_c. With the aim of the tested controllers evaluation, direct control quantity indexes have been used.

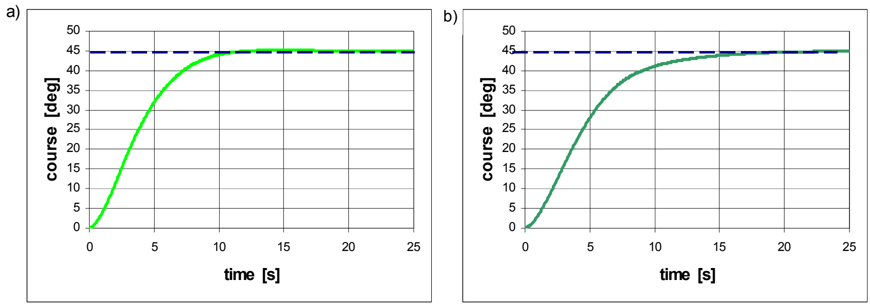

Figure 4: Simulation results of course's control: a) based on fuzzy logic method FPD, b) classical PD.

At the beginning of the action of the course's controllers: classical PD and the based on fuzzy logic method (FPD) have been compared (fig. 4). The setting time for the PD controller is almost 40% bigger (12,26 s) than the setting time for the FPD controller (8,74 s). Moreover, fuzzy logic methods are more robust for the nonlinearity of the object and the influence of disturbances [4]. Because of the accepted approximation of the SMCC in the form of a cylinder, received results of numerical researches for the trim controllers are similar to the presented results for the course controllers.

Then the action of the whole automated control system on the horizontal surface XY has been examined (fig. 5). The main task of the automatically controlled SMCC Głuptak was to reach a target. Additionally, it had to move along as close to a straight line as possible. This condition is very important in an underwater environment with many obstacles, especially during carrying out of a counter mine mission.

Moreover, the comparison of the two control methods has been executed in the presence of affecting sea currents from different directions (fig. 5). As we can observe, the second method (correction of the set value of the controlled variable on the base of bearing) is better than the first one (continuous updating of the set value of the controlled variable). The use of an added bearing signal gives possibilities to move along a safer trajectory closer to a straight line.

6 Conclusion

In general, the received results of the executed numerical research confirmed that the automated control system of the SMCC Głuptak can be successfully used to steer this underwater vehicle along a desired trajectory, especially along a line to the target of a counter mine mission.

In particular, it should be underlined that the introduction of an added bearing signal in the control system gives indirect information about the affects of the sea current, which is very significant in the case of a lack of this type of information

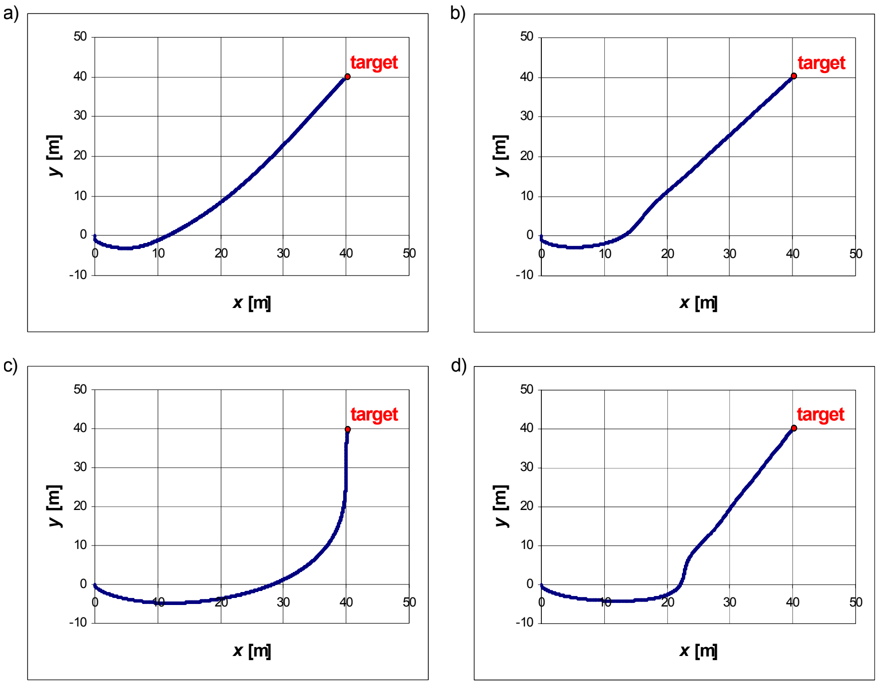

Figure 5: Automated control of the SMCC Gluptak to the target using methods: a) c) continuous updating of set value, b) d) correction of set value on the base of bearing in environment with affecting sea current: a) b) $V_c = 1$m/s, $\alpha_c = 60°$, c) d) $V_c = 1$m/s, $\alpha_c = 90$.

on board an underwater vehicle. The correction of the set value of the controlled variable on the basis of bearing enables the approach to a target to be along a safer trajectory than continuous updating of the set value of the controlled variables.

In addition, the controller based on the fuzzy logic method (FPD) enables better and faster regulation of trim and course angle than a classical PD controller.

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