Optimization of Control of Unmanned Underwater Vehicle in Collision Situation

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Abstract: - The paper presents a method used to set minimum-time control of unmanned underwater vehicles in a situation of collision with other underwater objects. It also includes the results of simulation study conducted with this method. Parallel closing of a unmanned underwater vehicle on to an encountered object was studied, i.e. a situation generating a critical case – collision of two underwater vehicles.

Keywords: underwater vehicle, control, anti-collisions systems.

1. Introduction

Unmanned underwater vehicles (UUV) have many applications in both the military and civilian domain. Military uses include surveillance and missions such as defusing mines. In the civilian domain UUVs are used extensively by the oil and gas extraction industries to install or repair equipment; they may complement, or in hazardous circumstances replace, teams of human divers. Applications for the scientific community include the use of UUVs to carry out sub-ocean observation missions over long distances.

As pointed out in [1], "mission drives design". The design of vehicle used will vary according to the range of tasks it is expected to realise:

- For the purposes of scientific observation the main criterion is that the vehicle should be able to cover large distances whilst performing monitoring tasks, without human intervention; i.e. be capable of operating autonomously. The vehicle may be deployed at great depths or near the surface, and may be required to cover large distances without human guidance, such as when passing beneath areas of polar ice.
- For assisting in oil and gas extraction, however, the vehicle may need to descend to great depths, but will probably be transported to the location on a surface vessel. It will be expected to provide a stable platform for the manipulators which perform maintenance work on sub-sea installations, and to be able to navigate its way very precisely through a complex underwater environment. The vehicle is typically controlled by a human pilot via an umbilical cable connection to the support vessel; this tether limits the depths to which vehicles can be deployed, and represents a potential hazard should the tether break or become fouled on some obstruction.

It would appear that people completely defer themselves oceans, but this is not true. Ocean element does not permit, within the next few days, to preclude in general the accidents on sea despite the apply the better and better technical and elements protected lives on sea. It's necessary to make decision in every time and every situation to limit accidents on see to minimum because the statistics are disturbing.

For these reasons unmanned underwater vehicles owners and designers are interested in problems of safe navigation and control. Therefore to increase the safety of navigation and reduce losses resulting from unexpected collisions UUVs have been equipped with a variety of systems which help people assess the situation and also make the right decision in case of danger to safety of navigation at sea. Such systems are referred to as collision avoidance systems. The problem of searching for effective methods to prevent UUVs from colliding has gained in significance with the increase in speed, size and number of underwater objects taking part in sea traffic. The development of sonar and then collision avoidance systems, which are used to assess risk of collision and simulate safe maneuvers, have contributed largely

to increasing safety in navigation. With progress in computer technologies and methods for optimization in collision avoidance systems, which can choose an optimum maneuver based on risk of collision indicator, have been developed. In the last years new tendencies in setting optimization tasks assessing solution to a collision-like situation not only according to safety of navigation but to economic aspect of control as well have appeared [4],[6],[7] and [8].

2. Formulating the problem

For further considerations it is assumed that movement UUV be realized in horizontal plane and the ship are not affected by any disturbances. For these assumptions the problem of optimum underwater vehicle control in a collision situation with a larger than one number of underwater objects can be formulated as follows:

- equations of own UUV movement with regard to speed are known and described in the form of differential equations:

$$\dot{\mathbf{X}}_0 = f_0(\mathbf{X_0}, \mathbf{U_0}) \tag{1}$$

where: $\mathbf{X_0}$ - state vector,

$\mathbf{U_0}$ - control vector.

- equations of two-sided constraints are noted as follows:

$$\frac{dD_j}{dt} = -V_0 \cos(N_j - \psi_0) + V_j \cos(N_j - \psi_j)$$

$$\frac{dN_j}{dt} = \frac{V_j[\sin\psi_j + \cos(N_j - \psi_j)\sin N_j]}{D_j \cos N_j} + \tag{2}$$

$$-\frac{V_0[\sin\psi_0 + \cos(N_j - \psi_0)\sin N_j]}{D_j \cos N_j}$$

- one-sided constraints are imposed on a UUV which result from technical limitations and limitations placed on the vector of UUV control $u^0 \in U^0$.
- UUV trajectory is preset as rectilinear by means of entering coordinates of successive points of turn (x, y) in a nonmoving rectangular coordinates system referred to earth.
- in speed frame known are equations of movement of encountered underwater objects and they are described by means of differential equations in form (1).
- in the general case own UUV is in a collision situation with encountered M-objects whose current positions in relation to own UUV are known, i.e. bearing N_j, distance D_j and current

parameters of movement speed V_j and course ψ_j.

- an attempt is made to find such control for which the minimum distance $D^j_{\min}$ of closing on to j-th encountered object is larger than the safe distance D_b resulting from geometric dimensions of objects which are in the collision situation and from the dynamics of navigational situation, i.e. the control the condition $D_b \leq D^j_{\min}$ is met.
- in the process of searching for the control the optimization criterion is taken into account in the form of smallest loss of time which leads to the time-optimum control. Assuming the initial time for the maneuver as $t_0 = 0$ and $t_k = T^j_{D\min}$, the quality criterion can be formulated as follows:

$$I = \int_0^{T^j_{D\min}} dt \tag{5}$$

3. Solving the problem

The problem formulated above reduces to searching for the time optimum control affecting the UUV which allows for avoiding a collision with the encounter underwater objects. To solve this problem it is necessary to take into account the safe distance of closing on D_b (Fig. 1) in the kinematics model of the process. In this connection one of the constraint equations will be changed.
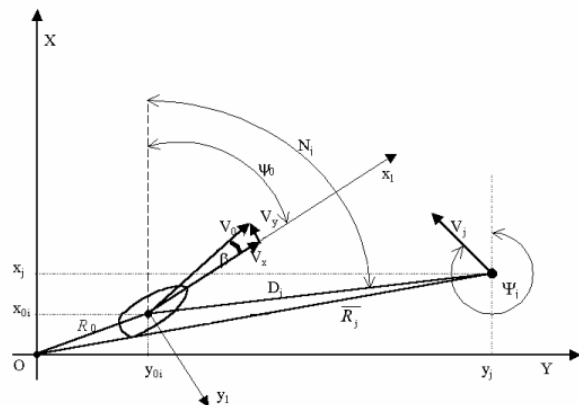

Fig .1 Kinematics relationships in complex movement with safe distance of passing taken into account.

It follows from Fig. 1 that in the case of passing the encountered underwater object ahead of its bow at a safe distance the dependence between bearing and safe distance can be noted as follows:

$$N_j^1 = N_j - \arcsin \frac{D_b}{D_j} \qquad (6)$$

whereas in the case of passing the encountered object behind its stern the dependence can be noted as follows:

$$N_j^2 = N_j + \arcsin \frac{D_b}{D_j} . \qquad (7)$$

These dependencies will be referred to as advanced bearing. Differentiating these equations in relation to time and substituting dependencies (2) obtained is the following:

$$\dot{N}_j^1 = f\left(D_j, N_j, V_0, \psi_0, V_j, \psi_j\right) \qquad (8)$$

$$\dot{N}_2^1 = f\left(D_j, N_j, V_0, \psi_0, V_j, \psi_j\right) \qquad (9)$$

The task is to find the minimum functionality (5) with conditions in the form of constraint equations (1), (3), (4), (8), (9). The function to minimize functionality (5) is searched for among variables $\mathbf{X_0}, D_j, \zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5 \quad N_j^1$ or N_j^2. For this purpose function $F\left(y, \dot{y}, t\right)$ formulated is in the form [2],[3],[5]:

$$F(\bullet) = 1 + \sum_{i=0}^{n} \lambda_i \, \varphi_i \qquad (10)$$

for which determined are the Euler-Lagrange equations [3],[5]:

$$\frac{\partial F}{\partial y_i} - \frac{d}{dt} \frac{\partial F}{\partial \dot{y}_i} = 0 \qquad (11)$$

The movement control of UUV is executed by means of changing its speed or course. For further considerations it will be assumed that the collision avoidance maneuver will be executed by changing the course of UUV. For this case it is assumed that V_D and n are constant and the limitations caused by change in the position of the fuel slat are not taken into account, thus the Euler-Lagrange equations are obtained for individual variables.

The best way to solve the Euler-Lagrange equations is to begin with equations (10), (11) which have alternative solutions. The solutions offer two boundary values:

$u_\alpha = 0$ as well as $u_\alpha = -1$

and $\qquad (12)$

$u_\alpha = 0$ as well as $u_\alpha = 1$

Depending on the sign of initial angular speed of advanced bearing this solution can be noted as follows:

$$u_\alpha = sign \frac{dN_j^{1,2}}{dt} \qquad (13)$$

Due to the fact that it is only the sign of angular velocity of advanced bearing it is enough to treat (8) or (9) as switching function $\delta(t)$

$$\delta(t) = f\left(D_j, N_j, V_0, \psi_0, V_j, \psi_j\right) \qquad (14)$$

where D_j, N_j, ψ_0 can be derived from (2), (8) and coupling relationships (4).

The solution for control in the general form can be noted as follows:

$$u_\alpha = sign\,\delta(t)\left[H\left(t - t_0\right) - H\left(t - t_p\right)\right] \qquad (15)$$

Dependence (15) embraces two solutions $u_\alpha = sign\,\delta(t)$ for $t \in \left(t_0, t_p\right)$ and $u_\alpha = 0$ for $t \geq t_p$, but t_p is equal to $\delta(t) = 0$. The change in direction of UUV movement requires a control impulse which can be calculated from (4), substituting control (14), and taking into account the technical limitations. Appointed the angle contained among longitudinal axis the UUV and applied force to his centre of gravity so as to achieve the parallel closing with the point of safe passing. UUVs course ensuring parallel closing on can be calculated from (8) or (9), the second, and the third equations from the set of equations (1). This way the duration time of control impulse executing time-optimum control is calculated.

4. The simulation study

The simulating model was created on basis the real parameters of underwater vehicle "UKWIAL" which was designed in Poland by team from University of Gdansk.
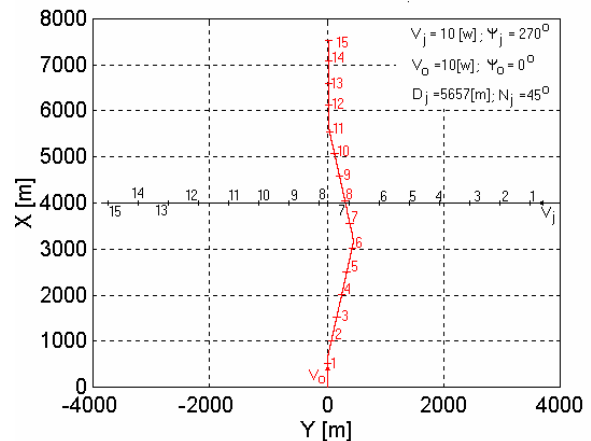

Fig. 2 Trajectories of encountered object and own UUV in collision situation

Basic technical parameters of this vehicle are:
- working depth: 200 m;
- vehicle's mass: 175 kg;
- equipment: two TV cameras; sweeping sonar; sonic finder; magnetic and electronic compass; electrolytical inclination gauge;

- quantity of thruster: 6, 4 in horizontal and 2 in perpendicularplane;
- force of individual thrusters: 220 N;
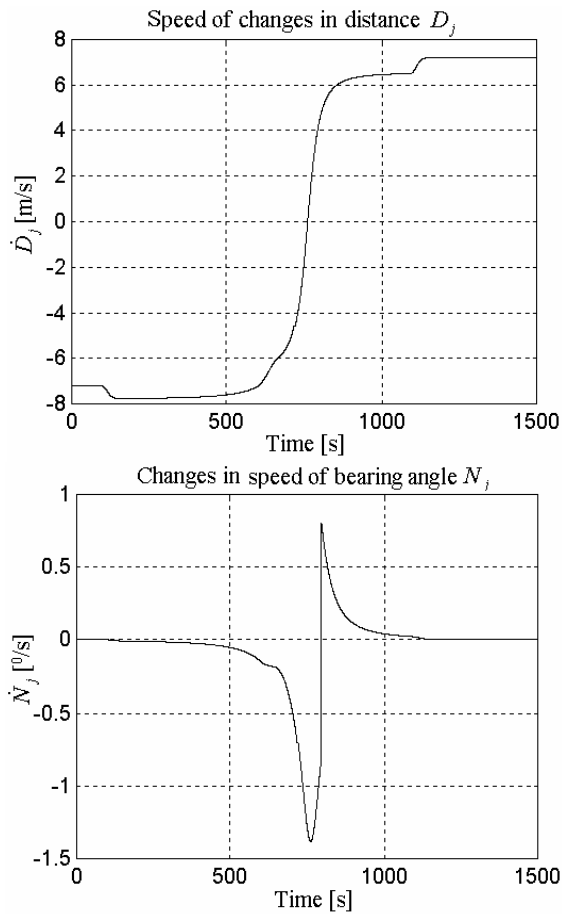- maximum forward speed: 1,5 m / s.

Fig. 3 Speed of changes in distance and changes in speed of bearing angle during anti-collision maneuver.

A dangerous navigational situation was simulated for relative speed $D_j < 0$ and speed in change of bearing angle $N_j = 0$, i.e. for a critical case of parallel closing on. The solution to the collision situation was searched for with the assumption that that the object encountered did not make any maneuvers and was moving rectilinearly at a constant speed. For this situation calculated was a time-optimum control determining the safe trajectory for own UUV. The research into controlling UUV movement was carried out by means of changing the course during the maneuver of safe passing behind the stern of the encountered object for a safe distance $D_b = 25[m]$ and $D_b = 50[m]$. For this maneuver calculated were: trajectories of the encountered object and own UUV, distribution of its state coordinates, control signals and solutions to constraint equations. The results of simulation

research investigations are presented in the figures bellow. The control signal and force on rudder is calculated for time-optimum control.
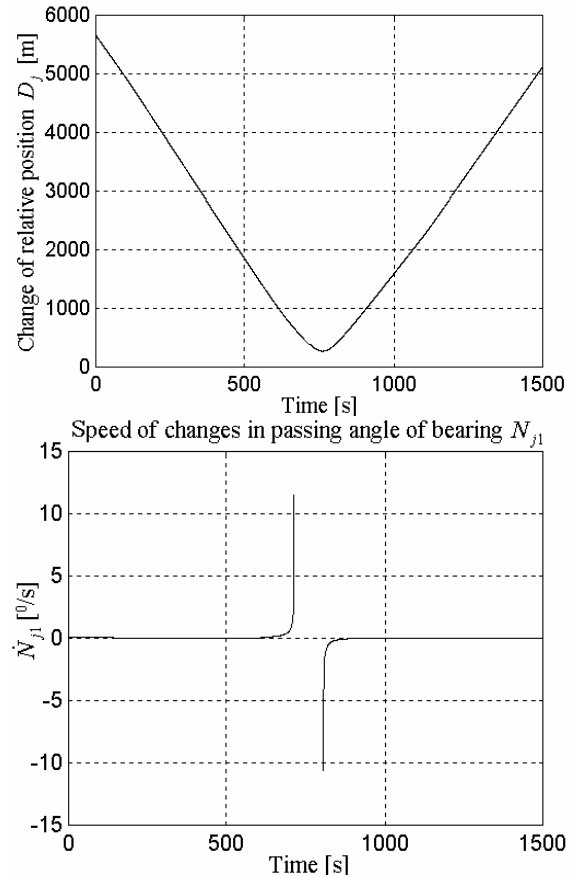

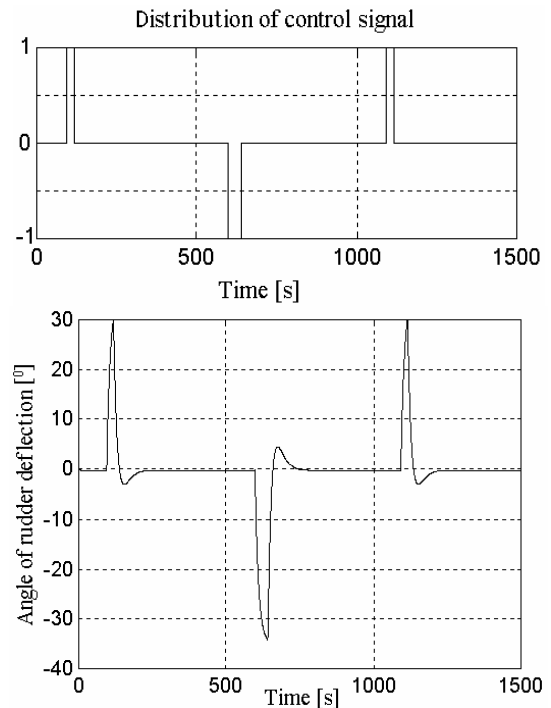Fig. 4 Changes of relative position D_j and speed of changes in passing angle of bearing

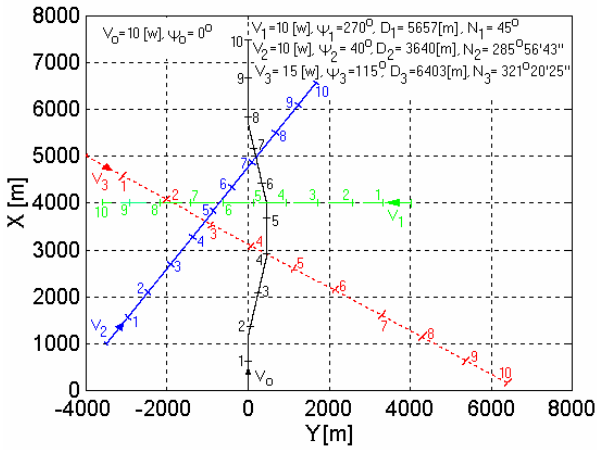Fig. 5 Trajectories of control signal and angle of rudder deflection

Fig. 6 Trajectories of encountered object and own UUV
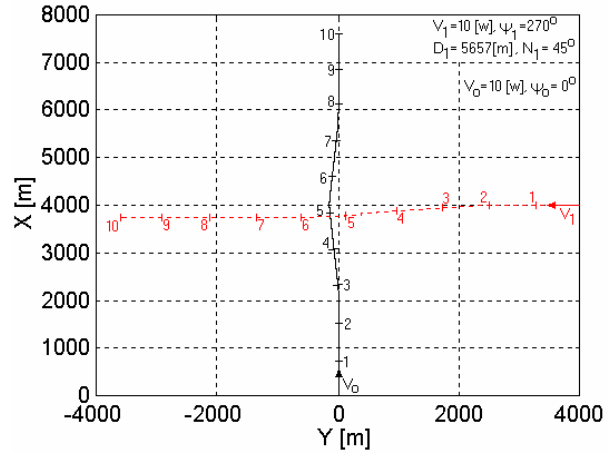in collision situation

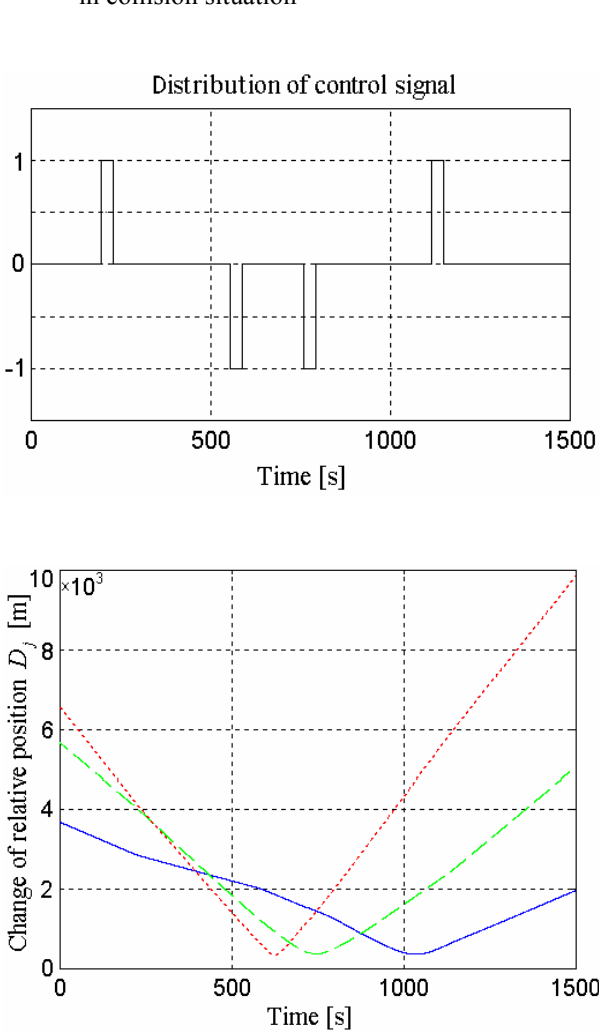Fig. 7 Trajectories of control signal and change of
relative position between encounter and UUV

Fig. 8 Trajectories of maneuvered, encountered object
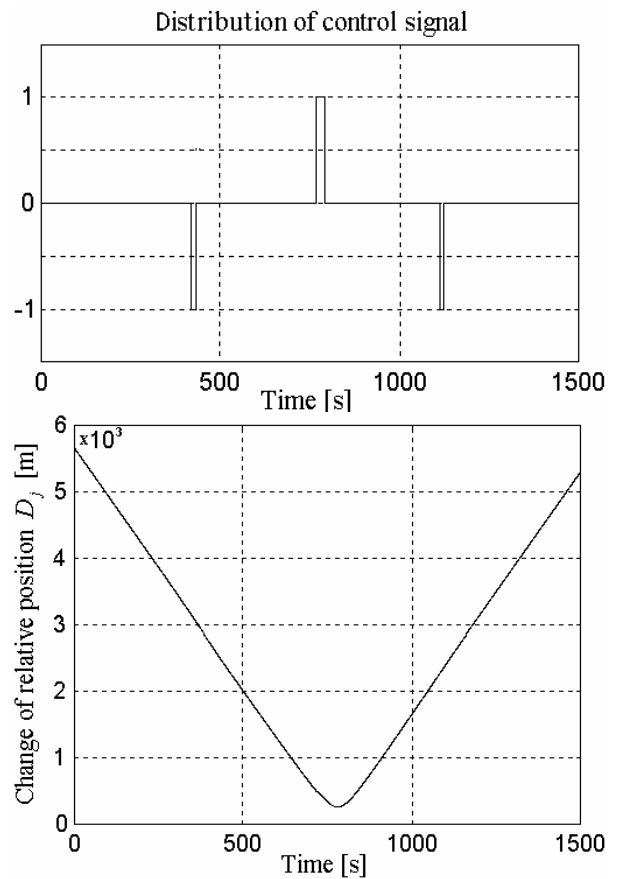and own UUV in collision situation

Fig. 9 Trajectories of control signal and change of
relative position between encounter and UUV

5. Conclusion

The solution to problem of avoiding collision at see formulated in this way is time-optimum control of own ship. The programs for time-optimum control have never been used in dealing with collision avoidance problems. In these problems the parallel closing on to an encountered object generates a dangerous situation, thus appropriate control has to be executed to avoid it.

However, formulating the problem with constraint equations with regard to advanced bearing angle $N_{j1,2}$ dependent on safe distance of closing on D_b time-optimum control programs can be used to solve collision situations at underwater area. Boundary process of time-optimum control, i.e. parallel closing on, is possible only for such angles for which the condition of parallel closing on is met as early as at time t_0. This obviously occurs when angular speed of observation line is $\dot{N}_j = 0$. In the case of employing the method presented to avoid a collision at see and calculate the time-optimum control there is always a possibility of executing this control, since for the danger-posing object angular speed of observation line is $\dot{N}_j = 0$, which means that parallel closing on occurs. Then the task for controls is to obtain $\dot{N}_j \neq 0$ and to zero the speed of advanced observation line $N_{j1,2}$ at the moment of switching control, i.e. for $t = t_p$. At this moment both switching functions are cleared. Further control is executed with use of the peculiar controls $u_1 = 0, u_2 = 0$. It realizes the so called parallel closing on to advanced point, whose position is determined by the safe distance of passing D_b determined for given hydrodynamics and navigational conditions.

The distribution of time-optimum control is rectangular and belongs to the ideal control, whereas the time to lead own ship to parallel closing on to advanced point depends mainly on maneuverability of own UUV, the initial value of angular speed of observation line and the value of safe distance of closing on D_b.

From the research results presented follows that the objects were closing on parallely, therefore they are critical cases where $\dot{N}_j = 0$ and $\dot{D}_j < 0$. After the collision avoidance maneuver, in accordance with the calculated time-optimum control, the angular speed of closing on becomes different from zero ($\dot{N}_j \neq 0$), whereas the speed of advanced observation line becomes zero ($\dot{N}_{j1,2} = 0$), thus there occurs the case where own ship parally closes on to the advance point determined by value D_b. The trajectory which ensures passing the encountered object at a safe distance is achieved by the UUV within short time because the maneuvers executed are weak maneuvers, i.e. change in course is made within small range.

The moment the encountered object has been passed there occur change in speed sign of advanced observation line $N_{j1,2}$ and in the speed of closing on D_j, and the encountered object becomes a safe object. At this time the control signal is sent, bringing the UUV onto preset trajectory. This signal has an opposite value to the signal calculated for the collision avoidance maneuver and its duration time is twice as long. Such signal causes the UUV to turn and close on to the preset trajectory along which she had been moving before the collision situation occurred.

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