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AUTONOMOUS CONTROL OF THE UNDERWATER REMOTELY OPERATED VEHICLE IN COLLISION SITUATION WITH STATIONARY OBSTACLE

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ABSTRACT

The article considers the problem of autonomous control of the underwater remotely operated vehicle mini Remotely Operated Vehicle (ROV) in a collision situation with a stationary obstacle. The control of the collision avoidance process is presented as a synthesis of fuzzy proportional-differential controllers for the control of distance and orientation concerning the detected stationary obstacle. The control of the submergence depth of the underwater vehicle has been adopted as a separate control flow. A method to obtain the main motion parameters of the underwater vehicle relative to the detected stationary obstacle using a Laser-based Vision System (LVS) and a pressure sensor coupled to an Inertial Measurement Unit (IMU) is described and discussed. The result of computer implementation of the designed fuzzy controllers for collision avoidance is demonstrated in simulation tests and experiments carried out with the mini ROV in the test pool.

Keywords: underwater vehicle, mini-ROV, collision avoidance, stationary obstacles, fuzzy logic, laser-based vision system

INTRODUCTION

The rapid development of deep-sea technology is contributing to the development of increasingly well-equipped unmanned remotely operated and Autonomous Underwater Vehicles (AUV), which have the characteristics of mobile robots. Unmanned Underwater Vehicles (UUV) support the performance of many tasks in areas that are difficult for humans to access or during which there may be a risk to the operator's life. These tasks include mapping the depths of seas and oceans, identifying the areas of contaminated waters, or military applications such as destroying sea mines. Several works and programs related to the penetration of the seas and deep oceans are currently being implemented. An example is the European Research project of the Horizon 2020 framework named ENDURUNS, which includes new scientific solutions and advanced technologies that will allow exploration of the seabed of the seas and oceans, and coastal areas using underwater vehicles powered by renewable energy [24]. The range of planned or performed tasks continues to expand, which requires the development of new path planning algorithms depending on the vehicle mission. Once the path is planned, the control algorithms allow the UUV to follow the path, and if some constraints are encountered, the process of re-planning takes place to correct the previously determined path. The nonlinear dynamic properties of UUVs, the influence of forces acting in the marine environment, and variable parameters of the vehicles are the basic difficulties in designing control algorithms which will control the UUV motion along the path. For these purposes, adaptive or self-tuning controllers seem to be most suitable. Nevertheless, due to their simple implementation, classical proportional-integral-derivative (PID) control techniques are still used in UUVs [25]. The application of the sliding mode control method for controlling the movement of a formation of unmanned surface vehicles (USVs), coupled with their tracking, is presented in the paper [29]. The cooperative control of the formation of underactuated USVs takes into account the impact of disturbances in the marine environment. Connecting the USV dynamic model and the nonlinear disturbance observer makes it possible to compensate the impact of marine environment disturbances.

During an underwater mission along the path, it is important to maintain vehicle's safety, which includes, among other factors, avoiding collisions with obstacles. The problem of collision avoidance by vehicles has been discussed in a number of papers. The paper [26] presents a collision avoidance algorithm in emergency situations for Unmanned Surface Vehicles (USVs) based on a movement capability database. The algorithm aims to solve the problem as a last-chance maneuver, proposing to avoid a collision in an emergency situation through a sudden turning maneuver. In addition, in order to limit the maximum vehicle roll angle, a speed reduction is proposed during the

collision avoidance maneuver. Based on simulation studies, a database of USV maneuverability was created. The correctness of the proposed algorithm was tested by simulations in different scenarios. The application of artificial intelligence for trajectory planning of a ship in a collision situation is presented in the paper [27], where the collision avoidance algorithm is based on a hybrid genetic algorithm. The substance of this algorithm is a combination of the Multiple Population Genetic Algorithm (MPGA) and Nonlinear Programming, which makes it possible to define an optimal solution that determines ship's course changes corresponding to real maneuvers in a collision situation. An important practical problem for controlling the formation of autonomous unmanned surface vehicles is collision avoidance under real conditions. In the paper [28], this formation is depicted as a swarm moving in different configurations. The control of the autonomous swarm is based on a multilayer structure divided into three task layers. Particularly important is the second task layer, which is responsible for dispersing the swarm and avoiding obstacles and/or collisions within the swarm. The effectiveness of the proposed methodology was tested by numerical simulations of swarm movement, where the swarm behavior was studied for scenarios of avoiding the encountered static and moving objects.

Consequently, detecting an obstacle to avoid collision is one of the primary tasks of an AUV. The collision avoidance process uses the measurement data from sensors to assess the distance and orientation of the robot relative to the detected stationary obstacle. It is noteworthy here that the collision avoidance algorithms which are tasked with determining the safe trajectory of the vehicle have to take into account physical constraints and properties that allow executing appropriate maneuvers [1].

This paper presents the design and implementation of an algorithm for autonomous motion control of an underwater vehicle in a collision situation with a stationary obstacle, complemented with the results of simulation and experimental tests conducted on a real mini ROV - open-source Remotely Operated Vehicle (OpenROV Underwater Drone [17]). The measured results of distance, orientation, and submergence depth were used as input data for the control algorithm. The following measuring instruments and systems were used to obtain the measurement data: a Laser-based Vision System (LVS) with distance sensors, two laser pointers, a Full High-Definition (Full HD) vision camera, and a pressure sensor coupled to an Inertial Measurement Unit (IMU) [6]. These systems have been fitted by the producer as standard on the OpenROV (Fig. 1). For a detailed description of the underwater vehicle's configuration and equipment, see the OpenROV producer's specifications.

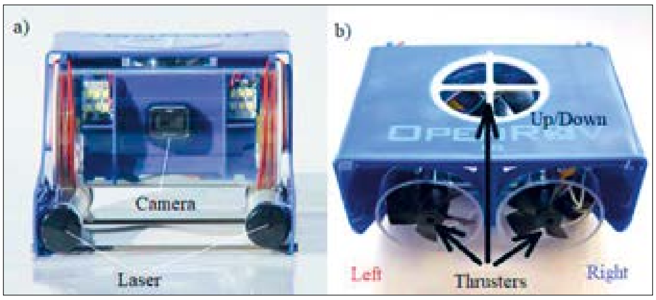

Fig. 1. ROV – OpenROV (Open-source Remotely Operated Vehicle): a) front b) back (OpenROV Underwater Drone [17])

To avoid collisions with stationary obstacles, an algorithm for autonomous control of the underwater vehicle has been developed. This algorithm makes use of a set of controllers to control the distance from a detected obstacle, and the position and submergence depth of the vehicle. The developed control regulators are based on the structure of a proportional-differential regulator using fuzzy logic – Fuzzy Proportional-Differential regulator (FPD). The FPD controllers with fuzzy data processing are simple to implement and allow control of the underwater vehicle's actuators. In fact, they are a proven control method in underwater navigation [8],[13],[14]. The FPD controllers of the course and submergence of an underwater vehicle for two degrees of freedom were presented in the paper [8]. The performed simulation studies and real tests have confirmed the effectiveness of using a FPD controller for automatic vehicle control, thus reducing the operator's task of guiding the vehicle along the set trajectory. In the paper [13], a comparison was made between a classical PID controller and a fuzzy controller in stabilizing the course of a vehicle in the marine environment. It was shown that the use of the fuzzy controller does not change the regulation times, while the scale of oscillations is significantly reduced compared to the classical PID. The authors of the article [14] proposed the application of fuzzy logic rules for autonomous navigation of an underwater vehicle and collision avoidance. Using this technology, a controller was developed and implemented in a real underwater vehicle equipped with a magnetometer and ultrasonic sensors. This controller includes the operation of two fuzzy logic blocks: the motion control block and the course correction block. In order to avoid collisions, the heuristics developed based on past experience was integrated into the fuzzy logic blocks, which significantly simplified the control algorithm. The presented concept of control in a collision and obstacle avoidance situation formed the basis for the development of the algorithm presented in this article. To determine the vehicle's position relative to the detected obstacle, an algorithm calculating the actual distance from the obstacle and orientation was implemented. This algorithm makes use of the data obtained from a Full HD wide-angle camera and two laser pointers being part of the LVS measurement system. The measuring devices were calibrated before the measurement.

The article is organized as follows: Chapter 2 presents in general the structure of the Remotely Operated Vehicle (ROV) and its dynamic properties, while Chapter 3 describes the method of determining the relative ROV position to a detected obstacle in a collision situation. Chapter 4 presents the architecture of fuzzy controllers and defines the problem of controlling an underwater vehicle in a collision situation. It also describes particular stages of designing the fuzzy controllers and the collision control algorithm. The results of simulation and experimental studies of mini ROV underwater vehicle control are discussed in Chapter 5, and the final conclusions are summarized in the last Chapter.

REMOTELY OPERATED VEHICLE (ROV) AND ITS DYNAMIC PROPERTIES

Remotely operated vehicles are used for scientific research, industrial work, as well as for military and other tasks. These vehicles have features of drones and mobile robots, including the ability to move in three-dimensional space, and to observe and scan the environment. An exemplary task executed by a ROV is the inventory of a hydrotechnical construction. In this case, the vehicle moves along a preset trajectory according to the inspection task [7] [20]. The ROV used for this task is usually constructed with a support frame, an external protective shell, buoyancy and ballast elements, and thrusters (Fig. 1). In addition, the vehicle is equipped with navigation and communication devices and controls, as well as with buoyancy, roll, and trim control subsystems, and visualization and hydroacoustic systems.

The ROV is connected with the surface vehicle via a cable used to supply the unit with electricity, transmit the measurement data, and control the unit's movement with a manipulator [1]. Depending on the scope of work, it is additionally equipped with specialized apparatus which requires appropriate control algorithms. However, compared to mobile robots, the control of an underwater vehicle is hampered by the marine environment and the presence of hydrostatic pressure, as well as by optical limitations preventing precise object identification, which include image attenuation, refraction, laser beam scattering, and increased image distortion. Also, communication problems occur in the marine environment due to the attenuation of high-frequency waves which prevents the use of Global Positioning System (GPS) navigation systems, Wi-Fi, and Bluetooth wireless communication. In addition, the hull of the vehicle is affected by hydrodynamic interference such as underwater currents, wave action, and wind. Moreover, at great depths, changes in density, temperature, and salinity of the water must be taken into account [5].

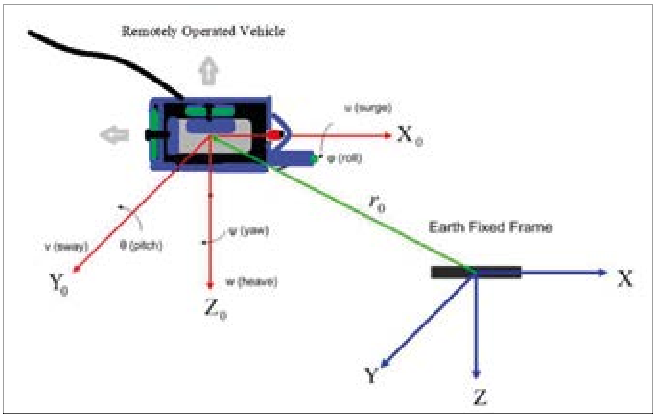

Fig. 2. BFF and ECEF coordinate systems for ROV [6]

In several scientific papers [4],[8],[9],[13], a general mathematical model of the underwater vehicle is presented as a set of equations of its motion, in matrix form developed by T. Fossen [10],[11],[12]. For the purpose of simulation studies, this model has the following form:

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

where:

- ν – vector of linear and angular velocities,
- M – matrix of vehicle masses,
- $C(\nu)$ – matrix of Coriolis centrifugal and centripetal forces,
- $D(\nu)$ – hydrodynamic resistance matrix,
- $g(\eta)$ – matrix of moments and restoring forces,
- $U(\nu)$ – matrix of damping generated by the connecting cable,
- τ – vector of forces and moments influencing the vehicle.

Model (1) is universal, as it takes into account the influence of both internal disturbances, created by changing the distribution of vehicle masses, and environmental disturbances, such as underwater currents, wave action, and wind. The influence of wind can be ignored when evaluating the dynamics of movement of a vehicle fully submerged in water. Moreover, the wave action is only relevant at depths of up to 10 m. In most design solutions for mini ROVs, the interference caused by the connecting cable is negligible, and in autonomous vehicles of Autonomous Underwater Vehicle (AUV) type, due to the absence of a cable, this interference does not exist at all. However, at great depths, it is necessary to take into account other constraints of the marine environment such as changes in water density, temperature, salinity, etc. which change the dynamic and control properties of the object [5].

The difficulties associated with remote and autonomous control of an ROV arise directly from the marine environment. Autonomous control of a deep-sea vehicle requires determining a large number of parameters of the equations of motion of this object. Most of these parameters are selected experimentally by performing a series of tests under various environmental conditions in both laboratory pools and real conditions in the deep sea. However, by making assumptions based on the design of ROVs and taking into account the characteristics of the marine environment at a given submersion depth treated as operational, the model of this object can be significantly reduced [5].

The development of control algorithms for an underwater vehicle requires determining basic parameters of its motion - position and speed. The position vector of the marine vehicle (2) refers to the Earth-centered, Earth-fixed (ECEF) coordinate system, while the velocity vector (3), related to the motion of the object itself, is given in the Body Fixed Frame (BFF) system [6]:

$$\eta = [x\ y\ z\ \varphi\ \theta\ \psi]^T \tag{2}$$

$$v = [u\ v\ w\ p\ q\ r]^T \tag{3}$$

where:

x, y, z – linear coordinates - position of the marine vehicle,
$\varphi\ \theta\ \psi$ – angular Euler coordinates - orientation of the marine vehicle,
u, v, w – linear velocities along the X_0, Y_0, Z_0 axes,
p, q, r – angular velocities about the X_0, Y_0, Z_0. axes.

The most important parameter for orientation in space is the vehicle rotation about the vertical axis *OZ* (parameter ψ-heading, referred to as orientation). Other parameters (roll about the *OX*-axis and pitch about the *OY*-axis) are of little importance for navigation since ROVs are designed to remain vertical. Due to this principle of ROV design, the orientation and angular velocities associated with the *OX* and *OY* axes are statically steady and equal to zero. Given this assumption, the position and velocity can be defined as vectors (4) and (5), respectively:

$$\eta = [x\ y\ z\ \psi]^T \tag{4},$$

$$v = [u\ v\ w\ r]^T \tag{5}$$

which allows considering the underwater vehicle with four Degrees of Freedom (4 DOF). Consequently, only 4 equations of motion can be considered in detail in the model [6].

DETERMINING ROV POSITION RELATIVE TO AN OBSTACLE IN COLLISION SITUATION

In most situations faced by an underwater vehicle [14] [30], the inputs to the collision avoidance algorithm are the *x, y* position, and ψ orientation of the vehicle relative to the detected obstacle - a stationary object. In this case, the position of the stationary object can be considered as the reference system for the ROV. The values of *x, y,* and ψ parameters relative to the stationary object are measured by the LVS system, which consists of one wide-angle Full HD camera and two laser pointers directed parallel to the camera axis (Fig. 1a). These two laser pointers produce a focused beam of high intensity, which is visible in the camera's field of view. Knowing the distances L_1 and L_2 of the laser pointers from the stationary obstacle (Fig. 3) and the distance d_H between the laser pointers, the distance d and the orientation ψ of the vehicle relative to the detected obstacle is calculated.

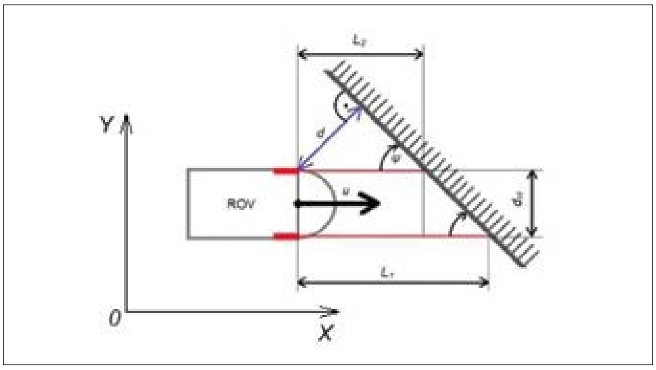

Fig. 3. Measuring position x and orientation ψ relative to a stationary obstacle

The data provided by the LVS system is determined using a triangulation technique based on the following relationships (6-10) [6],[16]:

$$x = (L_1 + \frac{L_2 - L_1}{2}) \cos(\psi) \tag{6}$$

$$y = \frac{(s_x - x_0)x}{a_x \cos(\psi)} + [L_1 + \tan(\psi)\,\frac{d_H}{2}] \sin(\psi) \tag{7}$$

$$z = \frac{(s_y - y_0)x}{a_y \cos(\psi)} \tag{8}$$

$$\psi = \frac{\pi}{2} - arctan2(d_H, L_1 - L_2) \tag{9}$$

$$d = \min(L_1, L_2) *\sin(\psi) \tag{10}$$

where:

d – distance from the obstacle,
L_1, L_2 – distances of laser indicators from the obstacle,
d_H - – distance between laser pointers,
$C(x_0, y_0)$ – coordinates of the image center (Fig. 4. a, b),
$S(s_x, s_y)$ - – coordinates of the laser beam on the image plane (Fig. 4. b),
a_x, a_y – focal length of the camera.

Laser indicators, as vehicle equipment components, return the distances L_1, L_2 to the obstacle along the x-axis, and the orientation about the yaw angle z-axis. To find the coordinates (s_x, s_y) of the laser beam, the acquired camera image is analyzed [30]. The adopted method of analysis consists in segmenting the image into areas that fulfill the condition of laser dots (quadrant III and IV - Fig. 4. b, segmentation with mask - Fig. 4. c). The next step is noise removal, done by defocusing the image with a Gauss filter and applying thresholding with specific brightness thresholds for each channel of the RGB model [18]. The result is the image shown in Fig. 4. d, which transforms the laser beams into "black dots." These points are tracked using the Blob Detection algorithm presented in [19]. After processing the image, the Blob Detection algorithm locates the laser dots and determines their centers of gravity (Fig. 5), which represent the position (s_x, s_y) of the beam on the image plane.

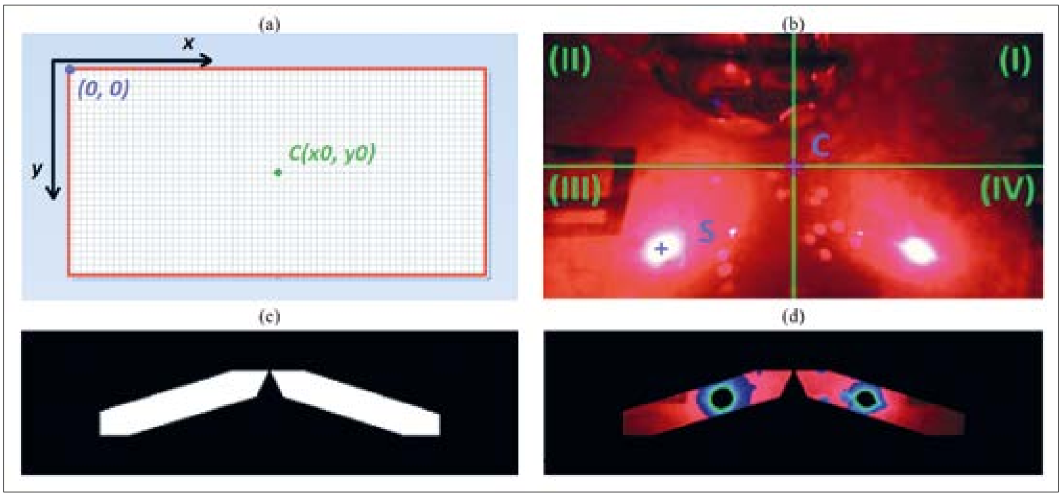

Fig. 4. Image processing phases: (a) image representation, (b) image division into quadrants, (c) mask, (d) image processing result

Fig. 5. Result of operation of the Blob Detection algorithm

When determining the submergence depth, the measurement is carried out by a pressure sensor coupled to an inertial measurement system IMU. The control system responsible for controlling the operational depth takes the Z-coordinate as the reference signal value, but relative to the ECEF system.

ROV CONTROL IN COLLISION SITUATIONS

In literature, several methods have been used for path planning with object detection and obstacle avoidance, and these include graphical methods and artificial intelligence methods, such as evolutionary algorithms for planning an optimal movement trajectory [15]. The planning task in this case is reduced to finding an executable and optimal route that will allow autonomous and safe movement of the vehicle from one place to another in the marine environment. A detailed review of path planning methods is given in [2], [3]. As previously mentioned, effective control instruments for underwater navigation are controllers using PD control principles and fuzzy logic [13]. The use of fuzzy logic allows controlling an underwater vehicle with any propulsion configuration, where the propellers may be distributed both vertically and horizontally. It can be assumed that fuzzy controllers are applicable to systems in which controllers designed using conventional methods do not fulfill the requirements. However, the disadvantage of the fuzzy controllers is the labor-intensive process of defining rules and tuning their parameters. Another solution is automatic tuning of controllers by modifying the knowledge base, which leads to adaptive fuzzy control [21]. In this paper, three proportional-differential controllers with Fuzzy Data Processing (FPD) are used to control the motion of the underwater vehicle attempting to avoid collision with a detected stationary obstacle [21]. When applying fuzzy controllers to this task, a classical linguistic model with Mamdani-type Implication Inference (MII) is used. This type of regulator consists of fuzzification, evaluation rules, and defuzzification operation, which connects a group of fuzzy inputs and outputs. The regulators designed in this way make it possible to control the distance from and the orientation of the detected obstacle, and the submergence depth of the underwater vehicle. The use of controllers significantly relieves the workload of the ROV operator, and allows the vehicle to autonomously maintain a safe distance from the stationary obstacle [14]. In this case, the input signals to the fuzzy distance controller are the distance deviation from the detected obstacle e_d, being the difference between the set value d_{ref} and the estimated distance measurement $\hat{d}$, and the distance deviation change Δe_d. The work of the controllers consists in controlling the vehicle's distance and orientation relative to the detected stationary obstacle which will allow the vehicle to pass it at a certain distance. The controller intended to maintain the appropriate distance from the obstacle is responsible for controlling the forward/reverse torque T_{N1}, while the orientation controller is responsible for the underwater vehicle torque T_{N2}. The torques T_{N1} and T_{N2} are obtained by assigning appropriate rotational speeds to thrusters situated on ROV's starboard side (left) and port side (right) (Fig. 6). To enable smooth ROV control in the collision avoidance process, the distance and orientation controllers have been integrated together [30]. The sum of torques T_{N1} and T_{N2} is corrected by a block to scale the response of the controllers so that the thruster speeds do not exceed the range of the control signals. As a result of operation of this block, the combined torque T_N for the right and left thrusters is generated (Fig. 6).

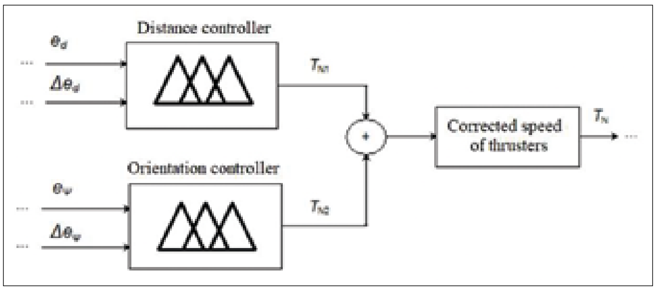

Fig. 6. Scheme of the integrated distance and orientation controller

COLLISION AVOIDANCE ALGORITHM

The collision avoidance algorithm is based on the work [14], but several modifications have been made due to the use of LVS and IMU systems and the method of controlling the ROV thrusters used in the study. In this case, the OpenROV has only three thrusters: one up/down vertical motion thruster located in the central part of the vehicle, and two left LM and right RM horizontal motion thrusters located in its rear part (Fig. 7) [30]. In comparison, in [14] analyzed the control of six thrusters.

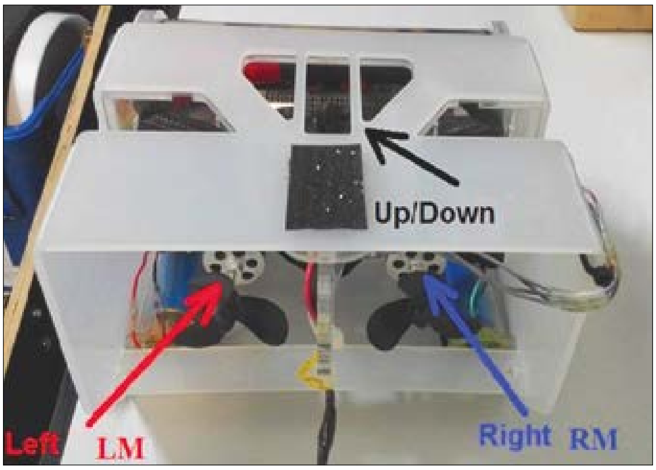

Fig. 7. Distribution of propellers in the experimental vehicle OpenROV

When designing the fuzzy controllers, it should be noted that the torque control of forward/reverse propulsion and rotation of OpenROV concerns its motion in the horizontal plane. Naturally, the submergence depth control, referring to its motion in vertical direction, is also an important issue for the underwater vehicle performing its task. This issue, however, goes beyond the scope of the present work, which only concerns collision avoidance. It is assumed that the vehicle has achieved the operational submergence depth, and this depth is constant during the collision avoidance maneuvers.

The first phase of operation of the collision avoidance algorithm (Fig. 10) consists in calculating the estimated distance $\hat{d}$ and the estimated orientation $\hat{\psi}$ [16] [30] of the ROV relative to the stationary obstacle based on equations (10), and checking that the safe distance condition is satisfied. This condition check says whether the distance between the ROV and the stationary obstacle is equal to the reference distance $d_{ref}(\hat{d} = d_{ref})$. If this condition is fulfilled, the collision avoidance controls and the fuzzy distance and orientation controls are activated, assuming that the vehicle maintains its submergence depth. The set orientation is a fixed value equal to $\psi_{ref} = 90°$. The output signal is the torque T_{N1}. The experimentally selected distance controller membership functions for both the input and output of the controller are shown in Figure 8. Here, e_d, Δe_d are referred to as the distance deviation and distance deviation change, respectively. The inference rule matrix, selected based on the work [14], is shown in Table 1. It should be noted here that to produce a water thrust force directed parallel to the symmetry plane of the ROV, the controller must control the thrusters in such a way as to achieve the same rotational speed on both thrusters.

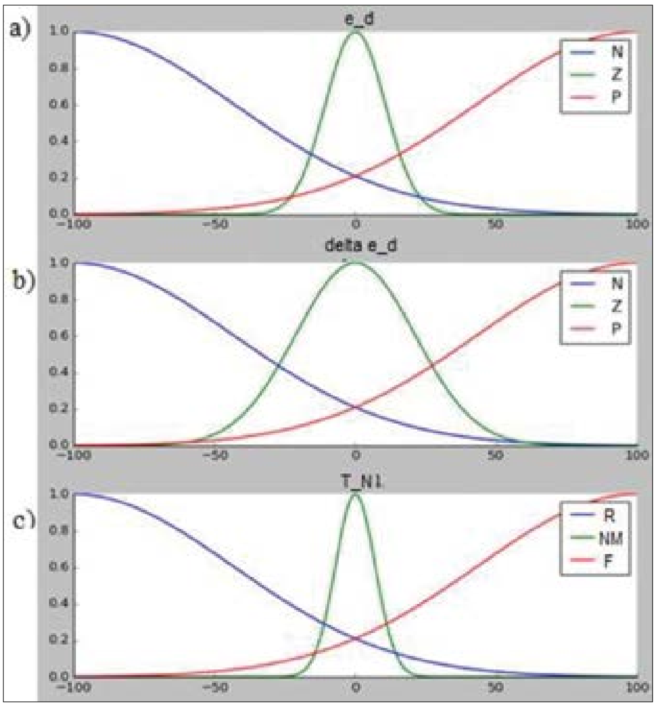

Fig. 8. Distance controller membership functions: (a) input - distance deviation e_d, (b) input - distance deviation change Δe_d, (c) output - torque TN1

Tab. 1. The base of inference rules for distance controller

Δe_d \ e_d	N	Z	P	
N	R	R	NM	Torque T_{N1}:
	R	R	NM	
Z	R	NM	F	right thruster RM (blue)
	R	NM	F	
P	NM	F	F	left thruster LM (red)
	NM	F	F	

Based on Table 1, the exemplary fuzzy control rules (if, then) of the ROV distance controller relative to the detected stationary obstacle are as follows:

- **if** the obstacle is far away (distance control deviation e_d is P - positive), and the vehicle is not moving (the distance deviation change Δe_d is Z - zero), **then** go forward (thrusters RM and LM have the value F - forward),
- **if** the obstacle is in range (distance control deviation e_d is Z - zero), and the vehicle is not moving (the distance deviation change Δe_d is Z - zero), **then** stop (thrusters RM and LF have the value NM - no motion),
- **if** the obstacle is close (the distance control deviation e_d is N - negative), and the vehicle is moving forward (distance deviation change Δe_d is N - negative), **then** go backward (thrusters RM and LF have the value R - reverse).

Controlling the orientation of the underwater vehicle requires ensuring that the horizontal thrusters are at correct speed. During the operation of the controller, the RM and LM thrusters have to generate opposite torques to activate the corresponding rotational motion of the underwater vehicle.

The input signals to the controller are the orientation deviation from the detected stationary object e_ψ , being the difference between the setpoint ψ_{ref} and the estimated measurement $\hat{\psi}$, and the orientation deviation change Δe_ψ. The output signal is the torque T_{N2}. The membership functions of the orientation controller are shown in Figure 9. In this case, to produce the appropriate torque, the controller provides signals of opposite values to the horizontal thrusters. The inference rule matrix for this controller, developed based on the work [14], is shown in Table 2.

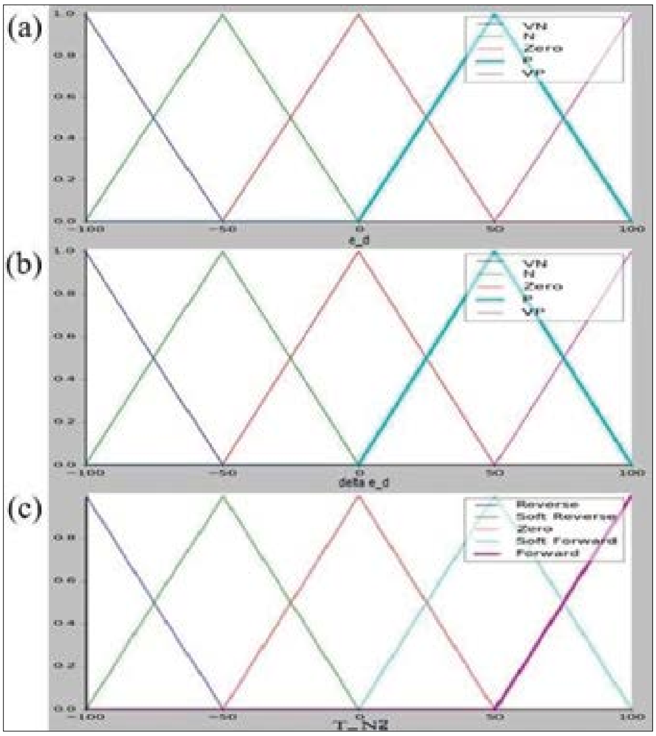

Fig. 9. Orientation controller membership functions: (a) input - orientation deviation e_ψ, (b) input - orientation deviation change Δe_ψ, (c) output - torque T_{N2}

Tab. 2. The base of inference rules for orientation controller

$e\psi$ / $\Delta e\psi$	VN	N	Z	P	VP	
VN	R	R	SR	SR	NM	Torque T_{N2}:
	F	F	SF	SF	NM	
N	R	SR	SF	NM	SR	
	F	SF	SF	NM	SR	
Z	SR	SR	NM	SF	SR	right thruster RM (blue)
	SF	SF	NM	SR	SR	
P	SR	NM	SF	SF	F	
	SF	NM	SR	SR	R	left thruster LM (red)
VP	NM	SF	SF	F	F	
	NM	SR	SR	R	R	

Based on Table 2, the exemplary fuzzy control rules (if, then) of the orientation controller of the ROV relative to the detected stationary obstacle are as follows:

- **if** the orientation of the vehicle relative to the obstacle is less than 90° (the orientation control deviation e_ψ is P - positive or VP - very positive), and the vehicle does not rotate about its axis (the orientation deviation change Δe_ψ is Z - zero), **then** execute the left turn (the RM thruster has the value SF - soft forward - go slowly forward, and the LF thruster has the value SR - soft reverse - go slowly backward),
- **if** the orientation of the vehicle relative to the obstacle is equal to 90° (the vehicle is situated perpendicular to the obstacle - orientation deviation e_ψ is Z – zero), and the vehicle does not rotate about its axis (the orientation deviation change Δe_ψ is Z - zero), **then** stand to stop (thrusters RM and LF have the values NM - non-move),
- **if** the orientation of the vehicle relative to the obstacle is greater than 90° (the orientation control deviation e_ψ is VN - very negative), and the vehicle rotates about its axis (the orientation deviation change Δe_ψ is N - negative), **then** execute the right turn (the RM thruster has the value R - reverse, and the LF thruster has the opposite value F - forward).

As a result of the operation of the distance and orientation controllers, the values of the torque control signals for thrusters T_{N1} and T_{N2} are obtained. Then the sum of the T_{N1} and T_{N2} torques is corrected by the block rescaling the response of the controllers (Fig. 6) to the speed of individual thrusters. As a result of the operation of this block, PWM signals are generated for the right RM and left LM thrusters.

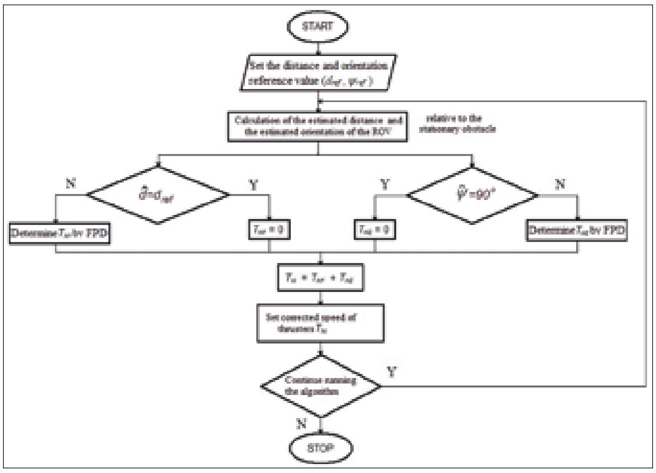

Fig. 10. The simplified scheme of the algorithm for avoiding collision with a detected stationary obstacle

RESEARCH AND TESTS

To evaluate the performance of the designed fuzzy controller-based algorithm for avoiding collision with detected stationary obstacles, simulation and experimental tests were done with ROV control, the latter being conducted in real conditions in the test pool owned by the Gdansk University of Technology.

SIMULATION STUDIES

Simulation studies were conducted based on the *SciKit-Fuzzy* library [22] in the *Python* programming language. After introducing the specified reference values of the distance d_{ref} and orientation ψ_{ref} into the algorithm and applying the membership functions (Fig. 8, Fig. 9) in the fuzzy controllers, the control planes for individual thrusters were determined.

Examples of control planes obtained from the fuzzy distance and orientation controllers for the right horizontal thruster RM are shown in Fig. 11. Based on the control planes, the torques T_{N1} and T_{N2} relating to the fixed individual speed values of the RM and LM thrusters, respectively, were determined for specified values of distance deviation ed and orientation deviation e_ψ from the detected obstacle, as well as for distance deviation change Δe_d and orientation deviation change Δe_ψ.

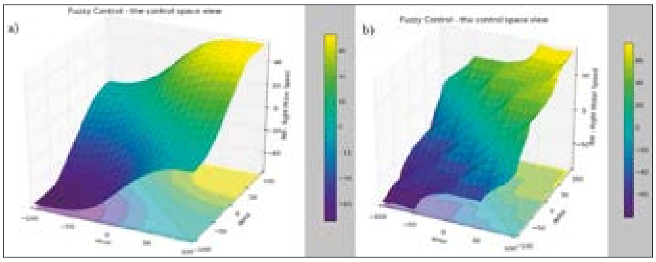

Fig. 11. Control planes obtained from fuzzy controllers for the right horizontal thruster RM: a) distance, b) orientation.

Experimental studies were performed in the test pool owned by the Gdansk University of Technology, using a mini ROV-OpenROV type unit controlled by a PC-class computer via a connecting cable which allowed both control and power supply of the unit.

Examples of time waveforms of simulation tests of the operation of distance and orientation controllers for the assumed permissible maximum distance from the obstacle equal to d_{ref} = 0.5 m and fixed orientation not exceeding the maximum value ψ_{ref} = 90° are shown in Fig. 12. In this case, the simulated obstacle was the plane of the test pool side wall.

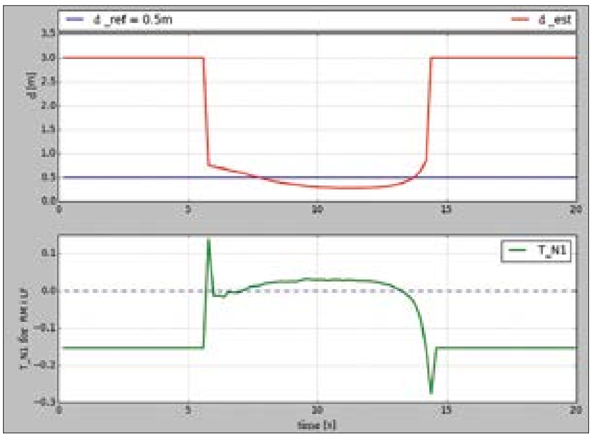

Fig. 12. Time waveforms of distance d and torque TN1 during obstacle avoidance by the ROV

Based on the presented waveforms (Figure 12), it should be concluded that the LVS system correctly detected the obstacle at a distance of less than 1 m. After locating the obstacle, the fuzzy distance controller calculated the value of torque T_{N1}. In this case, a positive value meant that the reverse gear of both the right RM and left LM thrusters was activated, which, as a consequence, reversed the movement of the vehicle. The permissible maximum distance of vehicle's approach to the obstacle was assumed d_{ref} = 0.5 m.

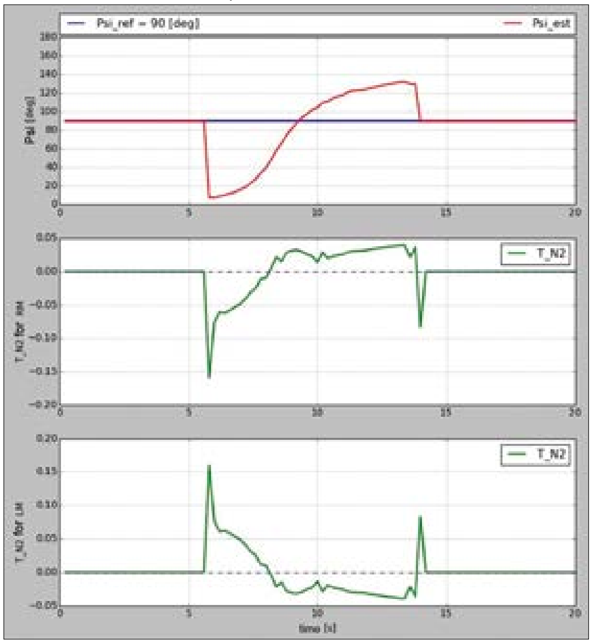

Fig. 13. Time waveforms of orientation ψ and torques T_{N2} affecting the right and left thrusters during obstacle avoidance by the ROV

In turn, the waveforms in Fig. 13 show that after detecting and locating the obstacle, and determining its orientation, along with verifying that this orientation does not exceed the maximum value ψ_{ref} = 90°, the fuzzy orientation controller generated the values of T_{N2} torques on both the right RM and left LM thrusters, thus allowing the vehicle to rotate. However, during this maneuver, the permissible maximum distance of vehicle's approach to the obstacle, d_{ref} = 0.5 m, must not be exceeded. This way, the simulation tests of the vehicle orientation control confirmed the correctness of controller's operation. By applying opposite control signals to the thrusters, the ROV could rotate about its axis.

EXPERIMENTAL RESEARCH

Based on the simulation studies and the verification of the control algorithms for a real vehicle mini ROV in real environment, appropriate scaling factors of fuzzy controllers were selected for the range of deviation k_e, the range of deviation change $k_{\Delta e}$, and the range of control signals k_τ of the designed controllers. These coefficients are shown in Table 3. Then, real tests of the collision avoidance process control algorithm were carried out with the underwater vehicle [30]. Calculations and data recording were performed on a PC, which allowed the LVS system to process images in real-time. The optimal frequency for performing measurements and their estimation was determined experimentally at f = 5Hz.

Tab. 3. Scaling factors for the range of deviation, variation of deviation and control the signal range of the designed controllers

Controllers	Scaling factors		
	for the range of deviation k_e	for the range of deviation change $k_{\Delta e}$	for the range of control signals k_τ (for T_z, T_{N1}, T_{N2})
submergence depth	5 m	1.25 m	-1.00 to 1.00
distance	2.4 m	0.6 m	-0.50 to 0.50
orientation	180°rad	30°rad	-0.50 to 0.50

Before starting the main tests with the collision avoidance algorithm, a number of preliminary tests were performed with the controller for keeping the vehicle at a safe distance from an obstacle. In these tests, at time $t = 0$ s, the distance separating the ROV from a stationary obstacle was $d_0 = 3.0$ m, while the permissible maximum distance of vehicle's approach to the obstacle was set as $d_{ref} = 0.5$ m. The results of automatic distance control are shown in Figure 14.

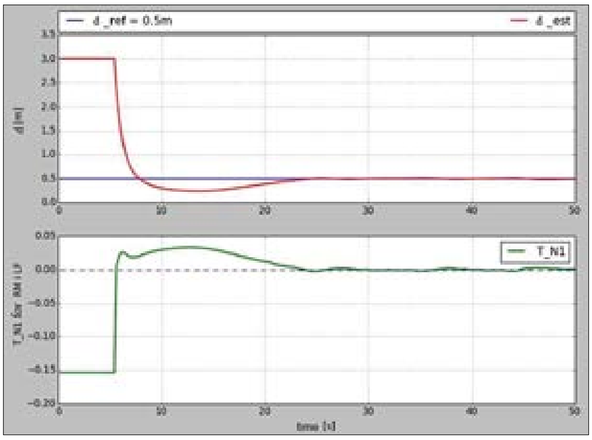

Fig. 14. Control time waveforms of the OpenROV vehicle collision avoidance process - keeping the distance $d_{ref} = 0.5$ m from the stationary obstacle

When analyzing the control time waveforms of the collision avoidance process with the ROV remaining at a certain distance from the stationary obstacle, it can be seen that the ROV braking process occurred after the obstacle was detected. The braking process was executed by applying positive T_{N1} control signals to both thrusters, which confirmed the correct behavior of the vehicle in a collision situation.

The synthesis of fuzzy algorithms for controlling the distance from and orientation of the detected stationary obstacle was verified under conditions where at time $t = 0$ s, the real distance separating the ROV from the stationary obstacle was unknown but the permissible maximum distance setpoint was assumed at $d_{ref} = 0.5$ m. The orientation setpoint was a fixed value equal to $\psi_{ref} = 90°$. The results of automatic control of the OpenROV collision avoidance process are shown in Fig. 15. The control time waveforms reveal characteristic changes in time of the signals T_{N1} and T_{N2} for the thrusters RM and LM (Fig. 15 b), respectively, as well as of the corrected T_N signal for the RM and LM thrusters (Fig. 15 c). Fig 16 shows the visualization of the phases of implementation of the port side maneuver in the test pool, where the side wall was an obstacle for the vehicle to avoid collision with.

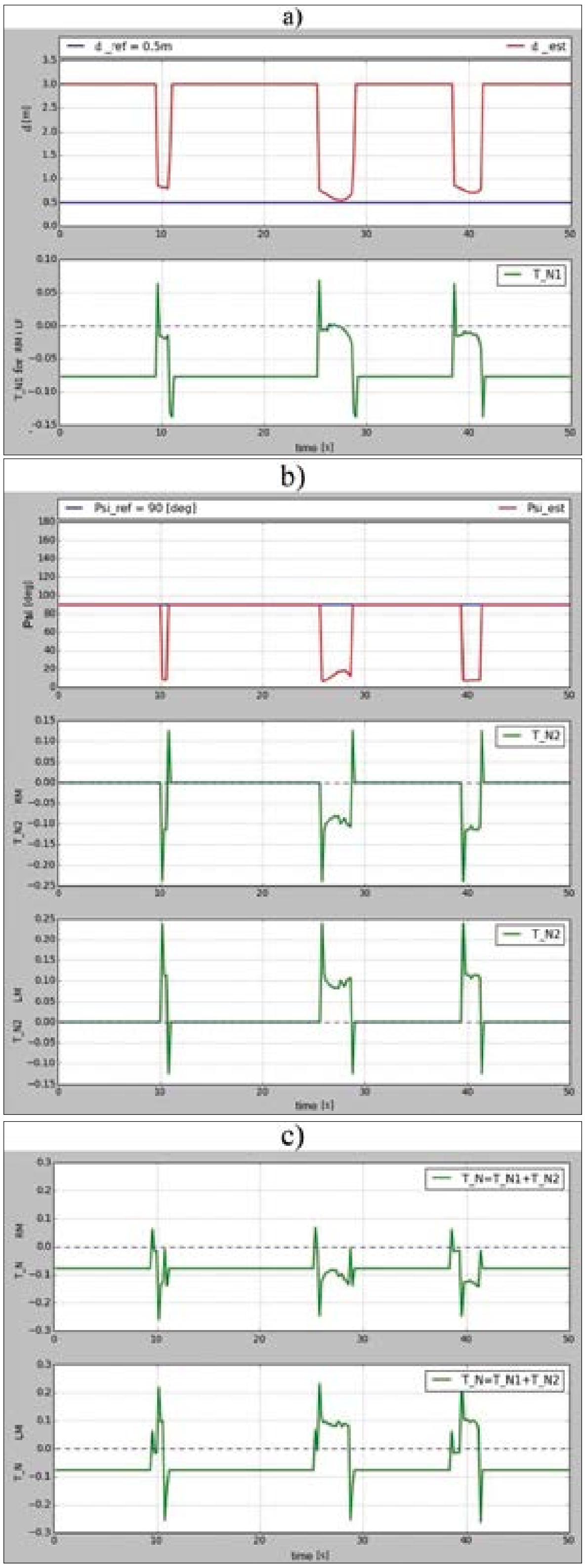

Fig. 15. Control time waveforms of the OpenROV collision avoidance process for the set reference distance $d_{ref} = 0.5$ m and fixed orientation $\psi_{ref} = 90°$

Fig. 16. Visualization of the phases of implementation of the port side maneuver in the test pool, where the side wall is an obstacle: times from t_1=9s to t_4=12s for d_{ref} = 0.5m

The control time waveforms of the OpenROV collision avoidance process confirmed the correct behavior of the vehicle in a collision situation. The OpenROV began reducing speed by applying positive control signals (t_1 = 9 s) to both horizontal thrusters so as to maintain the distance d_{ref} = 0.5 m from the obstacle. Then, the controller generated counter torques to both the right thruster RM and the left thruster LM, making the vehicle turn and move away from the obstacle (t_4 = 12 s.).

CONCLUSIONS

This paper presents the design, implementation, and verification of a fuzzy algorithm for controlling the collision avoidance process of an underwater vehicle. The ROV collision avoidance algorithm is composed of the algorithm calculating the distance between the underwater vehicle and a stationary object detected by the LVS system, and the algorithm controlling the distance and orientation of the vehicle with respect to the detected stationary object. The integration and software implementation of the two above algorithms were done using the Python programming language and the SciKit-Fuzzy library, which allowed the design of algorithms based on fuzzy logic. The results of the tests conducted in real environment in the test pool have confirmed that it is possible to control the process of avoiding collisions of the OpenROV underwater vehicle with stationary objects using FPD controllers. The presented method allows to control the motion of the underwater vehicle when avoiding collision with an obstacle at a specified passing distance. The use of an autonomous control system for controlling ROV motion in collision situations with detected stationary obstacles will significantly reduce the workload of the ROV operator.

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