POLISH HYPERBARIC RESEARCH 1(74)2021
Journal of Polish Hyperbaric Medicine and Technology Society

STABILITY TESTING METHOD FOR UNDERWATER ROVS

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ABSTRACT

The article presents the results of research carried out in the framework of an engineering thesis prepared at the Department of Underwater Works Technology of the Naval Academy in Gdynia. The objective of the work was to develop a method and a station to test the stability of deep-sea ROVs. The study presents the theoretical basis of the method as well as the results of performed experiments.

Keywords: mechanical engineering, underwater technology, unmanned underwater vehicles.

ARTICLE INFO

PolHypRes 2021 Vol. 74 Issue 1 pp. 23 – 34
ISSN: 1734-7009 **eISSN:** 2084-0535
DOI: 10.2478/phr-2021-0002
Pages: 12, figures: 6, tables: 2
page www of the periodical: www.phr.net.pl

Publisher
Polish Hyperbaric Medicine and Technology Society

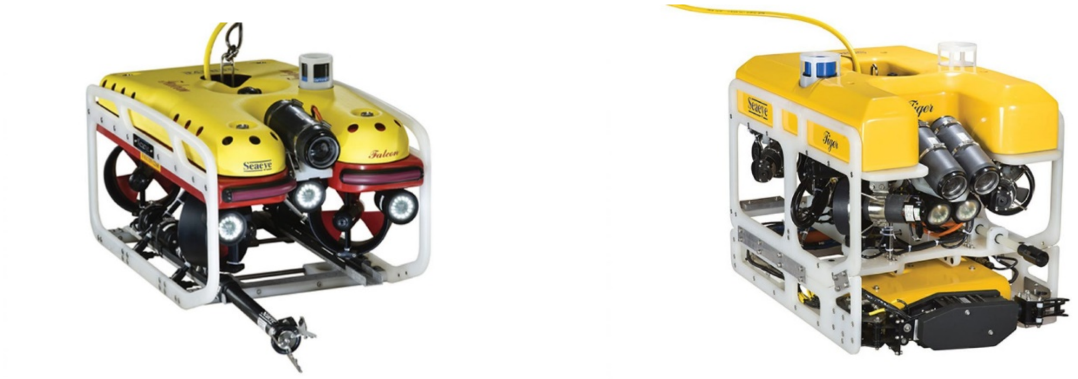
Original article

Submission date: 08.09.2020 r.
Acceptance for print: 14.01.2021 r.

INTRODUCTION

The recent decades are a period of turbulent development of underwater technologies towards the use of unmanned devices, very often considerably automated [1,2,3]. The main focus of these devices is embedded in the reductionist model of deep-sea technology development, i.e. the development trend towards the elimination of the human factor from the underwater workplace [4]. It is the trend that is currently emerging from every area of modern technology. An increasing number of tasks hitherto performed by man are being executed by devices remotely controlled or operating in semi-autonomous or autonomous mode. Taking into account the conditions of work in an underwater environment, the development of such technologies used to perform underwater work is evident and clearly visible in the development of deep-sea technology [4].

At present, we can encounter a number of devices used in underwater applications that have been developed using different design concepts and solutions, where the most avant-garde approach to the construction of these devices is represented by the approach related with imitation of living organisms, i.e. the so-called biomimetic vehicles [5]. However, it is the prototypes of this developmental trend in the deep-sea technology, i.e. unmanned remotely operated vehicles (ROVs) that stand out in terms of the widest range of application and use in underwater environments – Fig. 1. Regardless of the degree of their robotisation, they always provide a platform for mounting various types of specialised equipment and peripheral devices, which results directly from the function that a given solution is to perform and is a derivative of the requirements and needs of its end user.



ROV Falcon

ROV Tiger

ROV Lynx

ROV Cugar Compact

Fig. 1. Typical representatives of deep-sea ROV constructions - vehicles manufactured by Saab Seaeye Ltd. from Great Britain [9].

An underwater assembly platform is in this case nothing more than a remotely operated deep-sea vessel, and in order to function properly in the environment for which it has been constructed, it requires appropriate maritime capabilities. One one of the basic capabilities it must possess is the capacity to withstand the action of moments which force it to heel and return to its initial position when they cease, i.e. stability. In simplest terms, it is the ability to maintain the vertical axis of a device aligned in a vertical direction. This capability must be maintained regardless of the position of the vessel in the water: on the surface or in water depth. In the case of ROVs this capability is most often achieved by the appropriate arrangement of weights and buoyancy elements within the structural contour of the device. The behaviour of the vehicle when subjected to a heeling moment depends on the mode of action of the moment - in the case of a static moment we speak of static stability and in the case of a dynamic moment we speak of dynamic stability. Static stability occurs when the heeling moment increases very slowly from zero to a maximum value.

Dynamic stability, on the other hand, is when the heeling moment changes rapidly. Usually, however, when we use the term “stability”, we refer only to static stability because static stability is the most important measure of the heeling behaviour of a ship. For a manned surface vessel, this capability is all the more important as it has a direct effect on the ship’s defence against damage. In this case, the general rule in an emergency is to keep the vessel on a level keel and subsequently to struggle to keep it unsinkable. The simple assumption is that the struggle for unsinkability of a vessel keeping its vertical axis in line with the vertical direction is simply easier and, last but not least, safer for the crew. However, for unmanned deep-sea vessels, in particular remotely operated ones, the lack of this capability has disastrous consequences for the effectiveness of controlling such a vessel - the ROV simply becomes unpredictable.

Changes in control settings on horizontal thrusters that force changes in the direction of the swim will be inadequate to the helmsman’s expectations. Frequently, ROV manufacturers do not make the stability documentation available, focusing mainly on the data concerning the proper weighting of the vehicle, i.e. buoyancy. For these reasons, in the framework of the engineering diploma thesis carried out at the first degree course in the field of mechatronics, with a specialisation in underwater works at the Department of Underwater Works Technology of the Naval Academy in Gdynia, the following thesis topic was generated: “*Stability testing method for deep-sea ROVs*” [6]. The thesis was executed by midshipman Patryk Zając from 175U training group, and it was supervised by Adam Olejnik, Ph.D., whereas the consultant Marek Dawidziuk M.Sc. The aim of the thesis was to develop a measuring station to test the stability of deep-sea ROVs and its verification using a selected vehicle construction. The thesis was defended in January 2021.

STABILITY OF A DEEP-SEA VEHICLE

A vessel submerged in water will always seek to assume a position in which all forces and moments acting upon it cancel each other out, which means that it is in equilibrium when its weight ($\vec{P}$) and buoyancy ($\vec{D}$) are equal but of opposite directions (Fig. 2A). When a vessel is tilted from the vertical axis, neither its displacement nor its weight changes, and neither does the position of the centre of gravity. However, the position of the centre of buoyancy (W_1) is altered due to the change in shape of the submerged part – Fig. 2B. For different heeling angles, this centre will be located at different points, moving along the curve. For small angles of heel, its position will oscillate at a point which is the centre of this curve and is called the metacentre (M).

When the vessel is tilted, the directions of the buoyancy force and the gravity force still act in a direction perpendicular to the plane of the water, so a change in the position of the centre of buoyancy and the direction of the forces generates the moment of the pair of forces $\vec{P}$ and $\vec{D}$. If the metacentre is above the position of the centre of gravity then this moment of force pair is the righting moment and the balance of the craft is constant. During immersion, the centre of buoyancy and the metacentre move until they assume a common position for full immersion. The mutual position of the centre of buoyancy and the centre of gravity also changes – the centre of gravity is located below the centre of buoyancy (Fig. 2C), which is a direct result of the radically changed shape of the underwater part after immersion.

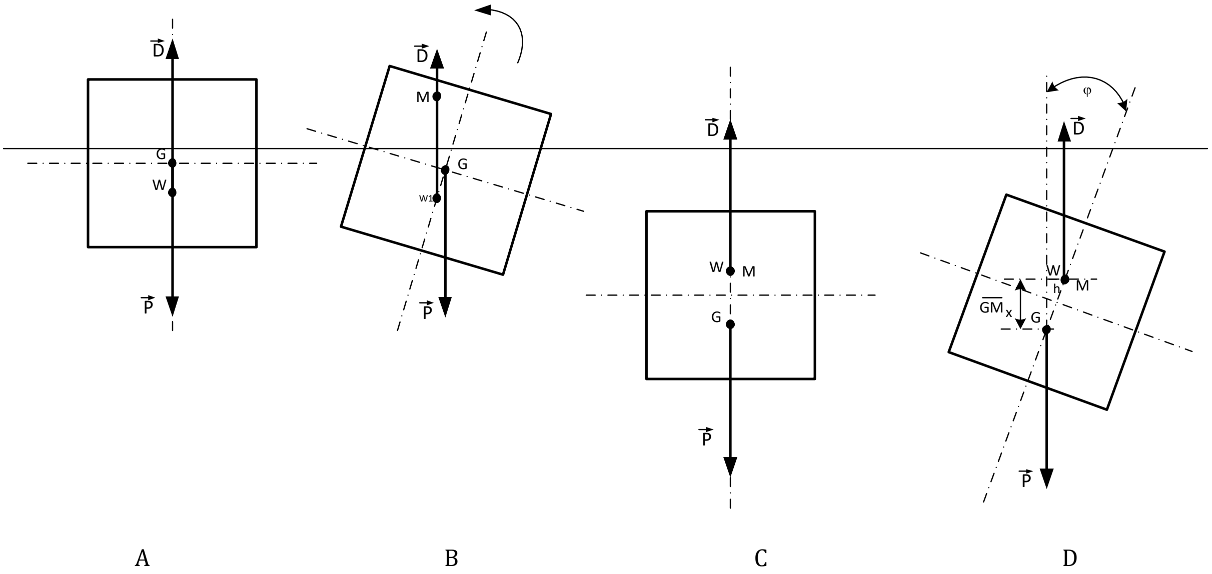


Fig. 2. Transverse stability of the vessel.

The action of the pair of forces $\vec{P}$ and $\vec{D}$, as previously mentioned, generates a righting moment whose value is determined by the product of the numerical value of one of the forces and the length of the righting arm. This can be expressed as follows:

$$M_p = \vec{P} \cdot h \tag{1}$$

Where h is the numerical value (length) of the righting arm, which can be calculated from the relationship:

$$h = \overline{GM} \cdot sin\varphi \tag{2}$$

Then equation (1) can be expressed as:

$$M_p = \vec{P} \cdot h = \vec{P} \cdot \overline{GM} \cdot sin\varphi \tag{3}$$

It follows that for small roll angles the value of the righting moment is primarily dependent on the force ($\vec{P}$) and the distance between the position of the centre of gravity and the metacentre, i.e. the metacentric height ($\overline{GM}$):

$$M_p = f(\vec{P}, \overline{GM}) \text{ for small } \sphericalangle \varphi \tag{4}$$

The issues described above constitute the basic theory of transverse stability of vessels widely described in the literature, for instance in [2,4,5,10]. This theory is also the basis of the method of testing the stability of an underwater ROV developed within the framework of the diploma thesis. It follows directly from relation (4) that determination of the righting moment value requires knowledge of the vehicle weight ($\vec{P}$) and the value of the righting arm length, for small roll angles depending primarily on the value of metacentric height ($\overline{GM}$). This means that the main research problem is to determine the position of the centre of gravity and the centre of buoyancy. Since the metacentric height is defined by the distance between the position of the centre of gravity and the metacentre, which for an underwater vessel in its submerged position is in the same place as the centre of buoyancy.

For the determination of the coordinates of the centre of gravity, the method of static moments and the measurement of the roll angles resulting from the introduction of additional mass at a particular place within the vehicle structure can be applied. On the other hand, the coordinates of the centre of buoyancy can be determined by measuring the angles of roll resulting from the displacement of the mass.

ROV STABILITY TESTING METHOD

In the proposed stability test method, stability is determined mainly by determining the value of the metacentric height of the vehicle structure. It results directly from from relation (4), where the parameter related to vehicle mass $(\vec{P})$ is usually known and specified by the manufacturer. However, the value of the vehicle metacentric height $(\overline{GM})$ remains an unknown quantity. From the trigonometric relationships, it is possible to derive the relation for the calculation of this quantity (with respect to Z-axis – Fig. 3):

$$\overline{GM} = \frac{Z_G - Z_w}{sin\alpha} \tag{5}$$

where:

¯GM - metacentric height,
Z_G - coordinate Z of the vehicle's gravity centre,
Z_W - coordinate Z of the vehicle's buoyancy centre,
A - transverse roll angle.

It follows directly from relation (5) that in order to determine the value of the metacentric height it is necessary to determine the position of coordinates X of the centre of buoyancy and the centre of gravity. In the present material, the solution of this problem was proposed by means of an experiment.

First, an experiment needs to be performed to determine the coordinates of the position of the centre of gravity. The experiment consists in placing the vehicle in the air on a sling allowing it to tilt with respect to its horizontal axis for the reference system. After measuring the angles of roll with respect to the axes, the experiment is repeated with an appropriately defined ballast placed at precisely defined points on the structure. Then, the coordinates of the centre of gravity are determined on the basis of the known mass of the vehicle, the mass of the ballast and the coordinates of the ballast added, using the following formula:

$$X_{G0} = tg\alpha_0(H - Z_{G0})$$

$$Y_{G0} = tg\beta_0(H - Z_{G0}) \qquad (6)$$

$$Z_{G0} = H + \frac{O[X_0 + tg\alpha_1(Z_0 - H)]}{M_0(tg\alpha_0 - tg\alpha_1)}$$

where:

X_G0;Y_G0;Z_G0 - coordinates of the centre of gravity in its original position,
M_0 - mass of the vehicle without additional ballast,
O - mass of the additional ballast,
H - vehicle height,
X_0 - coordinate X of the ballast,
α_0 - roll angle without additional ballast,
α_1 - roll angle with additional ballast,
β_0 - longitudinal roll angle without additional ballast.

The second step in the proposed method, is to experimentally determine the coordinate of the centre of buoyancy X. For this purpose, the vehicle is placed in a test pool. The data sought are calculated from the measurement of the angle of roll caused by the change in position of the mass of the vehicle's structural element; in the case under discussion, the changes in the position of the mass resulting from the vehicle's manipulator deflection were used. The coordinates of the centre of buoyancy were calculated from the relation:

$$X_{WP} = \frac{B_{rov}(tg\alpha * X_{G2} - tg\alpha' X_{G0}) + B_u(tg\alpha' * X_{BU1} - tg\alpha * X_{BU}}{B_P(tg\alpha - tg\alpha')} \qquad (7)\_)$$

where:

X_WP - coordinate X of the centre of buoyancy,
B_rov - total buoyancy of the vehicle and manipulator,
α - initial angle of roll of the vehicle in water,
α^' - angle of vehicle roll due to manipulator repositioning,
X_G2 - coordinate of the centre of gravity of the vehicle after the additional mass has been added,
X_G0 - coordinate of the centre of gravity of the vehicle in its original position,
B_U - vehicle manipulator buoyancy,
X_BU1 - coordinate of the centre of gravity of the manipulator in the original position,
X_BU2 - coordinate of the centre of gravity of the manipulator after repositioning of the manipulator,
B_P - vehicle buoyancy without manipulator.

EXPERIMENTAL DETERMINATION OF METACENTRIC HEIGHT

The experiments were carried out in the laboratory of the Department of Underwater Works Technology of the Naval Academy in Gdynia. A Seabotix LBV 200 ROV with a manipulator was used for the tests with the following dimensions: height: 39.4 [cm], width: 25 [cm] and length: 55.0 [cm] with the total mass of 17.52 [kg]. During the determination of coordinates of the centre of gravity, certified laboratory weights of 2 [kg] each were placed in precisely defined places (Fig. 3) (Table 1).

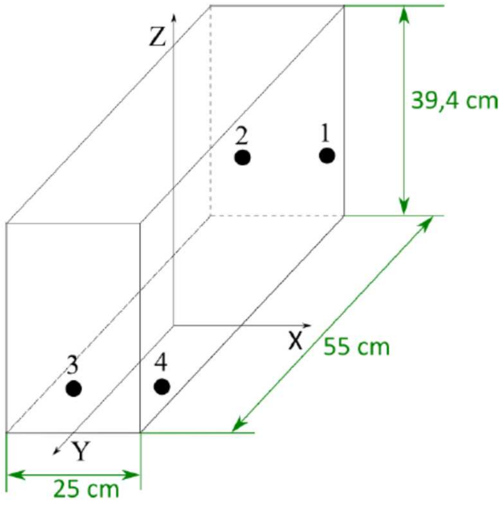


Fig. 3 Distribution points of additional mass during determination of the centre of gravity coordinates.

Tab. 1

Coordinates of the points of application of the additional mass.

No.	Weight	Coordinates of the location of additional mass		
		X	Y	Z
			[cm]	
1	Left stern (1)	8,4	-21,4	13,4
2	Right stern (2)	-5,4	-21,4	13,4
3	Right bow (3)	-8,6	15,1	1,6
4	Left bow (4)	5,1	15,1	1,6

As a result of the measurements, linear values mapping the cant angles were obtained, which were converted to cant angles taking into account the vehicle dimensions and trigonometric relationships. Then, the results were used to calculate the coordinates of the centre of gravity: $X_{G0} = -0{,}36\ [cm], Y_{G0} = 3{,}38\ [cm], Z_{G0} = 19{,}4\ [cm]$.

Determination of the position of the centre of buoyancy was commenced from the moment of immersion of the vehicle in the test pool (Fig. 4). The experiment consisted in measuring intermediate roll angles when changing the position of the vehicle manipulator (Table 2). For example, it was observed that a change in position of the 0.6 [kg] manipulator resulted in a roll exceeding 4^0.

Fig. 4 Seabotix LBV 200 ROV during the experiment in the test pool.

Tab. 2

Coordinates of the manipulator during the experiment.

Original location			After location change		
X	Y	Z	X	Y	Z
	[cm]			[cm]	
-9,2	2,8	3,7	9,2	2,8	3,7

As a result of the calculations, the coordinates of the centre of buoyancy were obtained: $X_{WP} = -0{,}033\ [cm], Y_{WP} = 0{,}08\ [cm], Z_{WP} = 24{,}84\ [cm]$. Based on the measurements, the coordinates of the centre of gravity and the coordinates of the buoyancy centre of the tested structure were determined (Fig. 5).

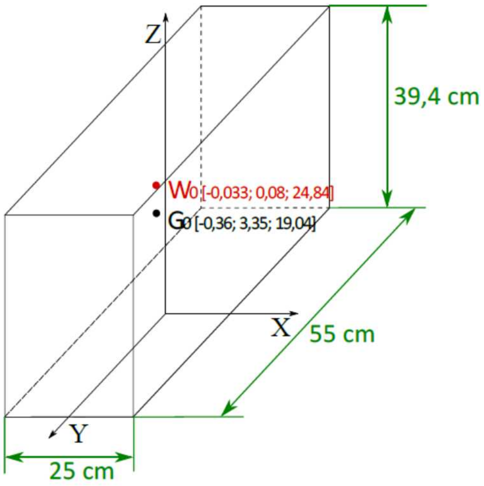


Fig. 5 Coordinates of the centre of gravity (G) and the centre of buoyancy (W) of the tested structure determined during the experiments.

Next, based on the determined coordinates of the centre of gravity and the vehicle's centre of buoyancy, the value of the metacentric height for the tested structure was calculated ($\overline{GM} = 5{,}8\ [cm]$). The determined value of metacentric height and the known vehicle mass enabled calculation of the theoretical value of the righting moment generated for small roll angles $\sphericalangle \propto \in (0 \div 30)^0$ (Fig. 6).

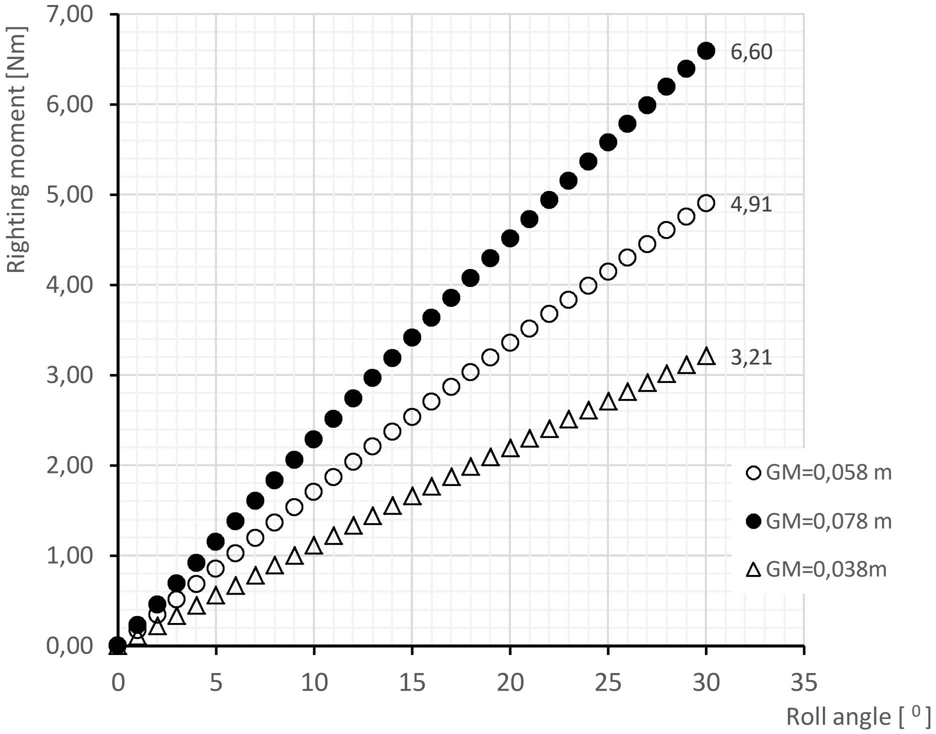


Fig. 6 Theoretical values of the righting moment for a vehicle with metacentric height equal to 3.8 [cm] and 5.8 [cm] and 7.8 [cm] for roll angles between 0^0 and 30^0.

The figure above presents the values of righting moments calculated for the roll angles from 0^0 to 30^0 degrees and for the metacentric height of 5.8 [cm] determined during the experiment, as well as theoretical values of righting moments for hypothetical values of metacentric height within ±2 [cm] from the experimental value. The influence of the metacentric height value on the vehicle stability is evident. In the case of changes within ±30% of the experimentally determined value, the moment value changes by approx. ±35%. This shows how important, from the vehicle operator's point of view, the correct distribution of additional masses and buoyancy elements from the vehicle operator’s point of view, which will be important for the vehicle manoeuvrability while swimming.

CONCLUSIONS

The article outlines an experimental method for testing ROV stability using the method of static moments. In the proposed method, the vehicle stability testing consists mainly in determining, by means of indirect measurements, the value of metacentric height of the vehicle, which value is not usually disclosed by the manufacturer. During the experiments, a Seabotix LBV 200 ROV was used, pre-equipped with a manipulator.

As part of the research, a bench has been developed that can be used to test the stability of any structure, although the authors are aware of the fact that it may require minor modifications due to different dimensions of the structures to be tested. As can be seen from the results obtained, the mutual position of the centre of buoyancy and the centre of gravity is important for the stability of the vehicle. As Fig. 6 demonstrates, the increase in the value of metacentric height by as little as 2 [cm] results in the increase in righting moment by 1.69 [Nm], which means that the increase in the value of metacentric height directly translates into the improvement of structural stability.

During the experiments, the influence of the tether cable, by which control signals are transmitted to the vehicle while floating in water, was omitted. During normal operation, however, its influence cannot be disregarded. Generally speaking, the tether cable, irrespective of the vehicle design, should have as neutral an effect as possible on the behaviour of the vehicle. An example of a negative influence of a cable on vehicle movement is the lack of a stable trajectory during horizontal swimming. This is the case if the vehicle is fitted with a negative buoyancy cable, which tends to sink to the bottom. Problems of this kind are solved by the operator by using buoyancy floats for the tether cable or other engineering solutions. Thus, they can be disregarded in the course of the vehicle stability test.

The experiments carried out in the course of the work confirmed that it is possible to develop a method for determining the value of metacentric height of a vehicle and then, on the basis of data revealed by the manufacturer, to examine the stability of its structure.

REFERENCES

1. Olejnik A.: Trends in the development of unmanned marine technology; Polish Hyperbaric Research PolHypRes 2016 Vol. 55 Issue 2 pp. 7 – 28; DOI: 10.1515/phr-2016-0008; ISSN 1734-7009; e-ISSN 2084-0535;
2. Olejnik A., Siermontowski P.: Will an underwater robot ever replace the diver?; Polish Hyperbaric Research PolHypRes 2016 Vol. 54, Issue 1 pp. 7 – 18; DOI: 10.1515/phr-2016-0001; ISSN 1734-7009; e-ISSN 2084-0535;
3. Dawidziuk M., Olejnik A.: General construction and classification of underwater vehicle manipulators; Polish Hyperbaric Research PolHypRes 2018 Vol. 63 Issue 2 pp. 21 – 32; DOI: 10.24478/phr-2018-0009; ISSN 1734-7009; e-ISSN 2084-0535;
4. Olejnik A.: Generalized amnistic model for the development of underwater; Polish Hyperbaric Research PolHypRes 2019 Vol. 68 Issue 3 pp. 59 – 70; DOI: 10.2478/phr-2019-0015; ISSN 1734-7009; e-ISSN 2084-0535;
5. Anderson I.A.; Vincent J.F.V.; Montgomery J.C.: Ocean Innovation Biomimetics Beneth the Waves; Taylor&Francis Group LLC CRC Press, ISBN 978-1-4398-3762-7;
6. Zając P.: Method of stability testing for underwater ROVs; engineering diploma thesis supervised by Olejnik A., Wydział Mechaniczno-Elektryczny AMW w Gdyni 2021, str. 51
7. Crist D.R.; Wernli Sr R.L.: The ROV Manual, Elsevier 2014; ISBN 978-0-08-098288-5;
8. Miller D., Jordan J.: Modern submarines; Espadon 1993; ISBN 83-85489-04-5;
9. Moore St., Bohm H., Jensen V.: Underwater Robotics; MATE 2010; ISBN 978-0-9841737-0-9;
10. Rowiński L.: Underwater technology: Underwater vehicles construction and equipment; WIB 2008; ISBN 978-83-928007-0-5.

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