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DEVELOPMENT OF A NEW GENERATION OF AUTONOMOUS SURFACE AND UNDERWATER VEHICLES USING THE ADVANCED TECHNOLOGIES AND ACHIEVEMENTS TOWARDS THE APPLICATION OF CONTROL SYSTEMS BY ARTIFICIAL INTELLIGENCE AI

Abstract: The operation of offshore structures at sea requires the implementation of advanced systems of permanent monitoring of the work of such installations. Novel solutions concerning such systems should be associated with the application of unmanned maritime surface and underwater platforms. The unmanned maritime platforms are and will be based on applying the newest achievements of some critical technologies. Between these technologies is an important role played by the AI artificial technology used by the advanced control systems. Implementing advanced systems of permanent monitoring of work of offshore installations using AI-based systems may increase the functionality, performance and safety of such structures and systems. This paper presents a general approach to further developing the AUV Autonomous Underwater Vehicle and USV-WIG Unmanned Surface – Wing in Ground Vehicles equipped with a control system based on AI technology. It is shown within the paper that it is relatively easy to develop an idea for the implementation of the AUV and USV-WIG unmanned maritime vehicles. However, at the same time, it can be challenging to reach a level of real applications. The paper presents a general approach to the AUV and USV-WIG vehicle designs. The complexity of an approach to a vehicle design is shown using the performance-oriented risk-based method. The main design drives are presented, too. A brief description of a control system for the AUV and USV-WIG vehicles based on the mini-brain AI control system is described. Some results of research in this area are presented. The practical remarks and conclusions are given in the paper's final part.

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Keywords: unmanned vehicle, AUV – autonomous underwater vehicle, USV-WIG – unmanned surface vehicle, WiG – wing in ground vehicle moving by the wing in ground effect, AI – artificial intelligence, control system, AI-based mini-brain control system.

1. INTRODUCTION

The last decade has been a permanent work of further developing and implementing crewless maritime vehicles. Between them are the AUV autonomous underwater vehicles and USV unmanned surface vehicles. Some USV vehicles may be of the WIG wing in ground type, which means using the aero-hydrodynamic wing in ground effect. There is a growing interest in working out and implementing the fully developed implementations of unmanned maritime vehicles. The main drivers towards the development of such vehicles are the technologies such as the hull form geometries, innovative construction materials including nano-materials and "intelligent" materials, innovative energy supply sources, propulsion systems combining the efficient and silent engines and propellers, autonomous systems, sensors, effectors and innovative IT technologies including systems of navigation, communication and control. Between these technologies is an important role played by the AI artificial technology used by the advanced control systems. The additional features the AUV vehicles may possess are stealth-based and bio-technology-based solutions.

Implementing AUV and USV-WIG vehicles at sea may concern the conventional patrol and reconnaissance tasks. Such applications require advanced hardware and software solutions to be used onboard to provide high control and autonomy to the AUV and USV-WIG vehicles. The general requirements to obtain such vehicles are associated with autonomy from the energy supply, self-control and self-navigation point of view. It may concern no communication with the centre of mission case as well. Even a basic level of autonomy requires innovative solutions concerning the sensors, effectors and control to be implemented. The biggest challenge associated with these vehicles is to work out and apply an intelligent vehicle itself. In order to obtain such a vehicle, it is essential to acquire precise data from the surrounding environment, process it, and use it to perform the mission's tasks in the actual time domain. There is a proposal to use a mini-brain for the control process to compare the onboard virtual reality from the database with the reality outside the vehicle. It is possible with the help of the sensors, mini-brain control system, and effectors with which a vehicle may be equipped. Such an online comparison may enable us to obtain the expected functionality, performance and safety of a vehicle for the benefit of the mission.

2. INTRODUCTION TO THE IMPLEMENTATION OF UNMANNED VEHICLES IN THE OFFSHORE SECTOR

The operation of offshore structures at sea requires the implementation of novel systems for the permanent monitoring of the work of such installations. The need to implement the new solutions comes from the challenges following ordinary and abnormal operational conditions and hazards such as terrorism and military conflicts. A fast development of new technologies enables the implementation of deck robots and unmanned maritime surface and underwater vehicles and platforms for permanently monitoring offshore structures at sea. The operational and safety systems of offshore structures supported by the deck robots and unmanned maritime vehicles/platforms may increase the functionality, performance and safety of offshore structures and systems. The significant elements of a novel system for the permanent monitoring of work of offshore installations are presented in Figure 1.

Combining the unmanned vehicles/platforms with novel sensors and effector systems may help build a new generation of monitoring systems for the safe operation of offshore installations. The paper presents the major issues associated with developing the AUV and USV-WIG vehicles/platforms for monitoring activities at sea. The development method of vehicles/platforms equipped with modern sensors and effectors is presented. The designs of such vehicles/platforms under development are briefly described. It is underlined in the paper that a precise prediction of the performance characteristics of the ve-

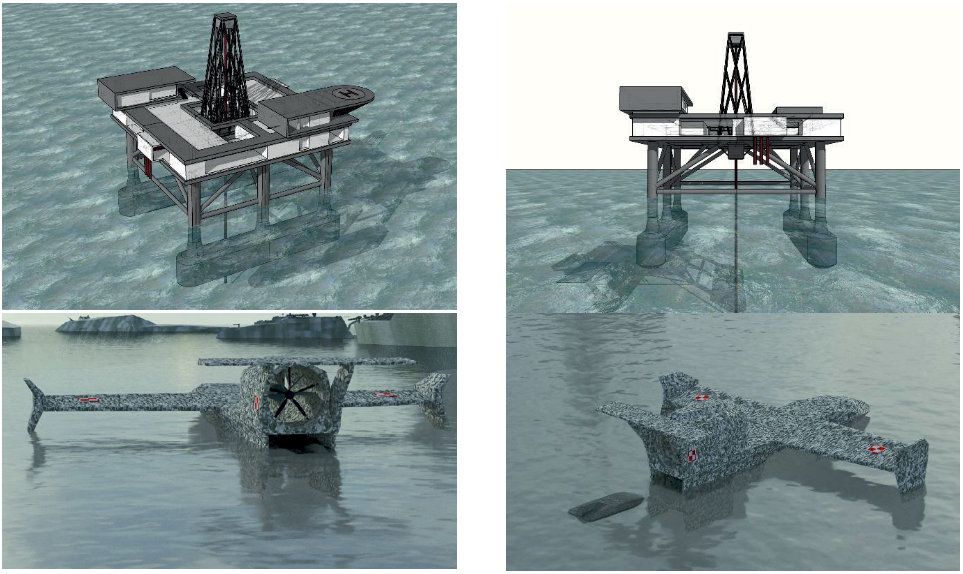

Figure. 1. The significant elements of a novel system for permanent monitoring of work of offshore installations.

hicle/platform is a crucial driver factor of estimation of the power of source of energy, range and autonomy of each unmanned vehicle/platform presented. These characteristics are the basis for the design of the sensors and effectors, which are the main components enabling the monitoring activities. A precise estimation of the energy source power necessary for the work of sensors and effectors enables the preparation of the unmanned vehicle/platform for the 2, 4, 8, 12 and 24-hour monitoring activities – the conclusions following the current research are given. Implementing such solutions concerning unmanned maritime vehicles/platforms may undoubtedly increase the functionality, performance and safety levels of the offshore structures and installations.

3. GENERAL APPROACH TO AUV AND USV-WIG DESIGN

To obtain a successful final solution concerning the AUV and USV-WIG designs, it is essential to conduct a procedure towards obtaining good functionality, performance and safety standards for a vehicle. Success may be guaranteed when such a procedure could contain the following steps[1]:

1. Definition of design: The design problem is defined as the AUV or USV-WIG design and information on the mission;
2. Definition of requirements: They concern the vehicle and mission;
3. Identification of options for solutions: research into previous designs, brainstorming ideas for novel designs and improved approaches;
4. Examination of tradeoffs and development of conceptual design(s): concept is a high-level design study of the significant components within the design to determine basic functionality; design steps may include power components, navigational hardware, propulsion, basic hydrostatics and dynamics, major structural components, etc.; specifications are further developed using the spiral development process;
5. Cost analysis: Cost analysis for the major components should be considered to determine the budget requirements; the project plan and timeline should be assessed;
6. Selection of concept option and design: The selected concept option should be matured through a final fabrication design; the design process is an iterative one, requiring give and take between the various disciplines; the design spiral process is followed, allowing the team to evaluate decisions made along the way concerning their effect on other design aspects. It follows from the experience that it is necessary to define the critical design and operational drivers, which are very important to obtain a first vision of an AUV or USV-WIG vehicle;

[1] AUVSI/ONR Engineering Primer Document for the Autonomous Underwater Vehicle (AUV) Team Competition. Association for Unmanned Vehicle Systems International (AUVSI), US Navy Office of Naval Research (ONR), Version 01 – July 200.7

4. APPROACH TO AUV DESIGN BASED ON PERFORMANCE-ORIENTED RISK

The significant features of AUV and USV-WIG vehicles are functionality, performance and safety. The functionality is connected with the application area the vehicle is designed for. The functionality requires the mission and tasks in operation to be defined. The current research and design tasks require considering the vehicles' sea surface and underwater activities. Between them are the patrol and reconnaissance tasks. The best method to define the missions and tasks to be performed in operation is the event trees (FTA – Fault Tree Analysis, ETA – Event Tree Analysis called the tree of consequences). The operational officers should work out the event trees for each mission and each task performed during the mission. The event trees are the base for predicting each event's AUV and USV-WIG vehicles' performance separately.

According to the event trees, the vehicle's performance can be predicted for each task of the event tree. The performance assessment is connected with estimating each event's AUV and USV-WIG vehicle parameters, characteristics and features. Such an approach enables checking if the vehicle can perform the tasks defined for each mission. It is a suitable method and tool for the training purposes of the operators and for controlling the tasks during the data mission. Considering the event tree and assessment of performance, it is possible to perform the qualitative and quantitative risk assessment (QQRA) of the AUV and USV-WIG mission, taking into account the risk of each event.

All the above steps create the performance-oriented, risk-based method of the AUV and USV-WIG design. This method can be used at the design stage and during the operation as it is based on the exact definition of the event tree, assessment of the vehicle's performance and risk assessment. The general structure of the method is presented in Figure 2.

The following steps are conducted to achieve a basic set of parameters, characteristics and features of a vehicle design when the performance-oriented risk-based method is applied[2]:

1. Define the design functionality: Define the missions, the tasks within each mission, and the entire event tree for each mission and each task within the data mission.
2. Assessment of performance: estimation of parameters, characteristics and features for each event within the defined event tree (mission).
3. Qualitative and quantitative risk assessment based on the definition of event tree (mission) and assessment of AUV performance.

[2] Gerigk M. Kompleksowa metoda oceny bezpieczeństwa statku w stanie uszkodzonym z uwzględnieniem analizy ryzyka (rozprawa habilitacyjna) - in Polish. A complex method for safety assessment of ships in damaged conditions using the risk assessment – in English. Wydawnictwo Politechniki Gdańskiej, Monografia 101, Gdańsk 2010.

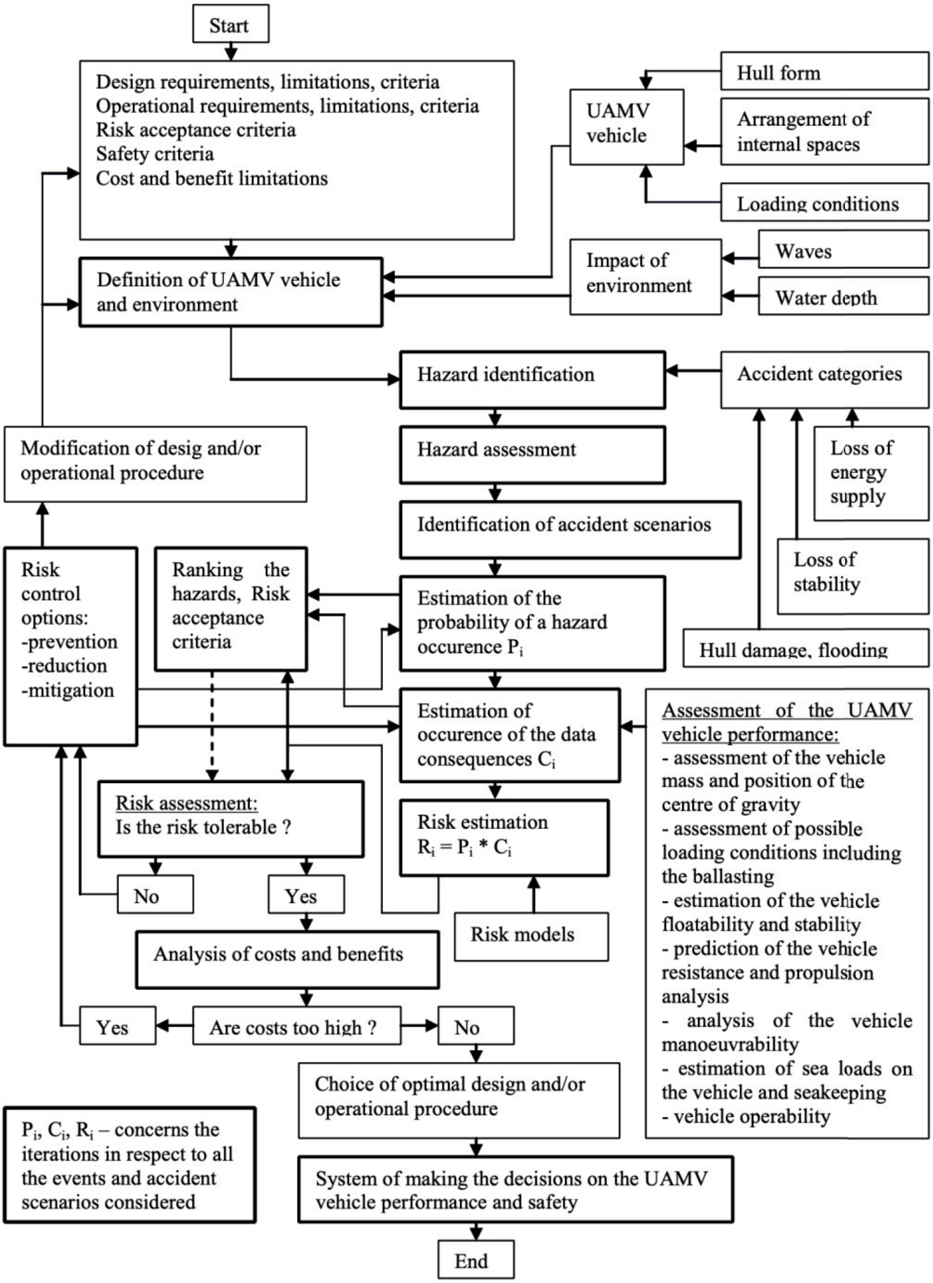

Figure 2. A Structure of the method for assessment of the AUV or USV-WIG vehicle performance and risk assessment (Gerigk M.K., 2014–2018).

The research and design methodology is based on the application of critical advanced technologies, which should provide an innovative solution to the final design of the vehicle design.

KEY DESIGN AND OPERATIONAL DRIVERS OF AUV AND USV-WIG VEHICLES

A basic set of design and operational parameters, characteristics and features necessary to control a vehicle may be estimated during the assessment of performance using the algorithms presented in Table 1 and Tabe 2.

Table. 1. Basic set of design and operational parameters, characteristics and features necessary to find the dynamics towards controlling the vehicle[3].

Design stage	Description of the design stage	AUV or USV-WIG performance
Stage 1	The main aim, design objectives	good floatability, stability, resistance and propulsion, manoeuvrability, seakeeping
Stage 2	Definition of vehicle Environment definition	hull form, length, breadth, height, buoyancy, displacement sea state, depth
Stage 3	Arrangement of internal spaces	Subdivision, number of bulkheads, capacity of compartments
Stage 4	Selection of structure materials	material, features of material, structure mass and weight, centre of gravity, skin thickness, internal structure thickness
Stage 5	Selection of equipment and onboard systems	distribution of mass and weights, the centre of gravity of each mass and weight, position and mass of each mass and weight
Stage 6	Estimation of mass and weight of light vehicle	mass and weight of light vehicle, the position of the centre of gravity of light vehicle
Stage 7	Estimation of mass and weight of a vehicle for all the operational loading conditions, including the internal loads	mass and weight of the vehicle for each loading condition, the position of the centre of gravity of the vehicle for each loading condition
Stage 8	Performance of vehicle – statics	phenomena, draft, immersion, trim, angle of heel, buoyancy, displacement, righting arms, criteria, floatability, stability, survivability

[3] Research project No. PBS3/A6/27/2015 entitled “Model obiektu wodnego typu stealth o innowacyjnych rozwiązaniach w zakresie kształtu, konstrukcji i materiałów decydujących o jego trudno-wykrywalności” – in Polish. “A model of the waterborne stealth-type object of innovative solutions concerning the hull form, structure and materials having an impact on the object stealth characteristics” – in English. A project conducted at the Gdańsk University of Technology between 2015 and 2018 and founded by the National Centre for Research and Development NCBiR within the PBS III initiative.

Stage 9	Performance of vehicle – dynamics	– phenomena, speed, number of propellers, resistance curve, demanded and operational power curves, propeller thrust curves, resistance-based hydrodynamic forces, propeller-based hydrodynamic forces, criteria, resistance and propulsion – phenomena, diameter of circulation curve, zig-zag type dynamics, course keeping, turning, criteria, manoeuvrability – phenomena, degrees of freedom, equations of motion, amplitudes of linear and angular characteristics of motion, velocities and accelerations, criteria, seakeeping

Table. 2. Basic design, operational parameters, characteristics, and features are necessary to predict the vehicle's demanded energy source power.

Design stage	Description of the design stage	Performance of vehicle: – Features (F) – characteristics (CH) – Parameters (P)
Stage 10	Estimation of demanded power necessary to run the sensor systems	F: Sensor systems control power CH: demanded power by the pressure measuring system, hydroacoustic system (sonar, echo sound, hydrophone), thermovision system, and electromagnetic system. P: Data signals in the time domain, current intensity, the voltage of the current
Stage 11	Estimation of demanded power necessary to run the IT deck-steering, navigation and communication systems	F: deck-steering, navigation, communication systems control power CH: demanded power by each system depending on the time of work P: Data signals in the time domain, current intensity, voltage of the current
Stage 12	Estimation of demanded power necessary to run the effector systems	F: Effector (manipulator, dedicated) systems control power CH: demanded power by each system depending on the time of work P: Data signals in the time domain, current intensity, voltage of the current
S13	Estimation of demanded power necessary to run the mini-brain control system	F: Mini-brain control system power CH: demanded power by the mini-brain control system depending on the time of work (online system) P: Data signals in the time domain, current intensity, the voltage of the current

	S14	Estimation of demanded power of batteries necessary to run the propulsion and remaining onboard systems	F: demanded power used by propulsion system, demanded power used by the remaining systems CH: demanded power characteristics depending on the time of work (online system) P: Data signals in the time domain, current intensity, voltage of the current

Based on the algorithms mentioned above, it is possible to predict the necessary level of autonomy to be achieved by the given vehicle due to the performance data. The level of autonomy from null up to two may concern a vehicle, a kind of automated robot performing the programmed tasks. The levels from three up to five regard the vehicles with more advanced solutions concerning the sensors, control systems and effectors. The most advanced solution, level five of autonomy, comes when the vehicle has an onboard mini-brain that can compare the current situation outside the vehicle (reality) using the sensors with the virtual reality stored and simulated within the vehicle's mini-brain.

A brief explanation of the significant problem of predicting the power of energy sources may be explained as follows. The battery-powered underwater vehicles are power-limited, meaning that the available onboard power has a limited value over a finite time. The amount of power required for a vehicle can be estimated by the range and speed defined by the mission for which the vehicle is designed.

Power is defined as force times velocity.

$$\mathrm{P(t) = F(t) \cdot v(t)} \tag{1}$$

P is the power, F is the force, v is the vehicle's velocity, and t is the time domain. Therefore, as an initial estimate, the required propulsive power can be evaluated from the drag of the vehicle (D) and the speed at which the vehicle is travelling. From the hydrodynamics of the vehicle, the drag is proportional to the velocity of the vehicle squared.

Therefore, the required power is:

$$\mathrm{P(t) = D(t) \cdot v(t) = c_D \cdot 0,5 \cdot \varrho \cdot A \cdot v(t)^2 \cdot v(t)} \tag{2}$$

$_{\mathrm{CD}}$ is the vehicle's drag coefficient previously defined in the hydrodynamics section. Also, the amount of energy used is defined as the force acting on the vehicle times the distance, or range, over which the vehicle has travelled. Therefore, the amount of energy that must be stored in the vehicle can be estimated as follows:

$$\mathrm{E(t) = F(t) \cdot d(t) = D(t) \cdot d(t) = c_D \cdot 0,5 \cdot \varrho \cdot A * v^2 \cdot R(ange)} \tag{3}$$

Where E is the energy available. The generic term d (distance) can be equated to R(range), which is the range of the vehicle.

To estimate the range achievable by a vehicle with a given battery pack, the above relationship is rearranged to resolve range, *R*.

$$\mathrm{R} = \mathrm{Range} = \mathrm{E}/\left(\mathrm{c_D} \cdot 0,5 \cdot \varrho \cdot \mathrm{A} \cdot \mathrm{v}^2\right) \tag{4}$$

Other sensors onboard also use power from the battery pack. To include the effect of the power used by the onboard equipment on the range achievable by the AUV, the range equation can be augmented to include the "hotel power," or the power needed to maintain the onboard functions of the vehicle. Referring to the definition of power above, an equivalent force acting on the system can be estimated from the required hotel power:

$$\mathrm{P_{AP}} = \mathrm{F_{AP}} \cdot \mathrm{v} \ \text{ or } \ \mathrm{F_{AP}} = \mathrm{P_{AP}}/\mathrm{v} \tag{5}$$

Then, using the energy equation, the total energy required to travel a distance *R, Range is:*

$$\mathrm{E} = (\mathrm{R} + \mathrm{F_{AP}}) \cdot \mathrm{Range} \tag{6}$$

Rearranging to evaluate the range achievable:

$$\mathrm{Range} = \mathrm{E}/(\mathrm{R} + \mathrm{F_{AP}}) = \mathrm{E}/\left(\mathrm{c_D} \cdot 0,5 \cdot \varrho \cdot \mathrm{A} \cdot \mathrm{v}^2 + \mathrm{P_{AP}}/\mathrm{v}\right) \tag{7}$$

Therefore, when selecting the batteries for an AUV or USV-WIG, the mission must be established and defined to select and size the required power pack.

It has to be underlined that obtaining an AI-based vehicle does not mean equipping the vehicle with a steering system consisting of sophisticated hardware and AI-based software. Obtaining the AI-based vehicle requires achieving an innovative hull form, which should be keen on diving, for example. It means that if the vehicle performance is good, the sensors, control system and effectors driven by the AI mini brain guarantee the highest level of functionality, performance and safety. There is a high probability level that all the tasks with the mission may be performed, satisfying the mission requirements. The innovative hull form, arrangement of internal spaces, materials used for the vehicle's structure, distribution of equipment and onboard systems may bring the optimal position of the vehicle's weight gravity force and the global hydrodynamic force in each period. Then, the internal and external loads on the vehicle's structure impact the energy used during the operation. The significant impact of this is the vehicle's resistance force. Of course, this force depends on the vehicle's speed and decides the range of the AI-based vehicle. The vehicle's hull form and propulsion system significantly impact the vehicle's speed and range. This is why applying the most innovative solutions from the design and performance point of view is necessary. The entire capacity of the energy supply source should be increased due to the energy necessary to supply the work of the sensors, mini-brain control system and effectors. The mini-brain control system should be treated as a governor coordinating the energy and information distribution for all the onboard systems and the AI-based vehicle.

Considering the navy applications, it is necessary to deliver the limited boundary layer and wake, limited emission of noise and vibration and other factors. They may prevent the AI-based vehicle from being easily detected and better prepared to perform the mission. Then, better performance means detecting the obstacles and the enemies better rather than being detected at each stage of the mission.

6. A CONCEPT OF A MINI-BRAIN CONTROL SYSTEM

PRELIMINARY RESULTS OF AI-BASED VEHICLE DESIGN

When working on autonomous AI-based vehicles, it is necessary to replace two or three-dimensional work concepts towards concepts based on the information space of work. Within the workspace, humans will be supported and sometimes replaced by AI. The information will be exchanged online between all the linked systems having access[4]. With the information space of work, data exchange in the actual time domain should be permanent. The complex air-based systems require data transfer speed of 500 or more Mb/s. The unmanned autonomous underwater or surface systems should be a system of systems. It is necessary to apply such an approach if the future AUV and USV-WIG vehicles should be functional, performing well and safe in the workspace.

The sensor and AI-based mini-brain control systems decide about the AI-based vehicle senses. The AI-based mini-brain control system processes the visual, pressure, electromagnetic and hydroacoustic signals. This system works as an Inference Engine combining the Forward and Backward Chaining algorithms[5]. Such an approach enables us to compare the AI-based Mask (virtual reality) with the reality described by the sensor systems.

The preliminary results of the research have shown that it is possible to let the AI-based vehicle be a kind of intelligent vehicle if the functional, performance, operational (mission, tasks) and safety standards, limitations and criteria are under control by the AI-based mini-brain control system.

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4 Sejnowski T.J. Deep learning, Głęboka Rewolucja, Kiedy sztuczna inteligencja spotka się z ludzką. Wydawnictwo Poltext (Tłumaczenie). © 2018 Massachusetts Institute of Technology. ISBN 978-83-7561-962-1.

5 Chabris Ch.F. A primer of artificial intelligence. © Multiscience Press Inc. 1987, 1988. ISBN 1-85091-698-5.

The AI-based mini-brain control system should be then equipped with a set of sensors enabling the analysis of the following physical fields:

- acquisition, analysis and use of electromagnetic signals
- acquisition, analysis and using the noise and vibration-based signals
- acquisition, analysis and using the hydroacoustic signals
- acquisition, analysis and using the thermal signals
- acquisition, analysis and using the pressure signals
- acquisition, analysis and use of visual-based signals
- emitting the false signals

The double-mode control, navigation, and communication heads are necessary to apply. A visualisation of the model for using the AI-based control system is presented in Figure 3.

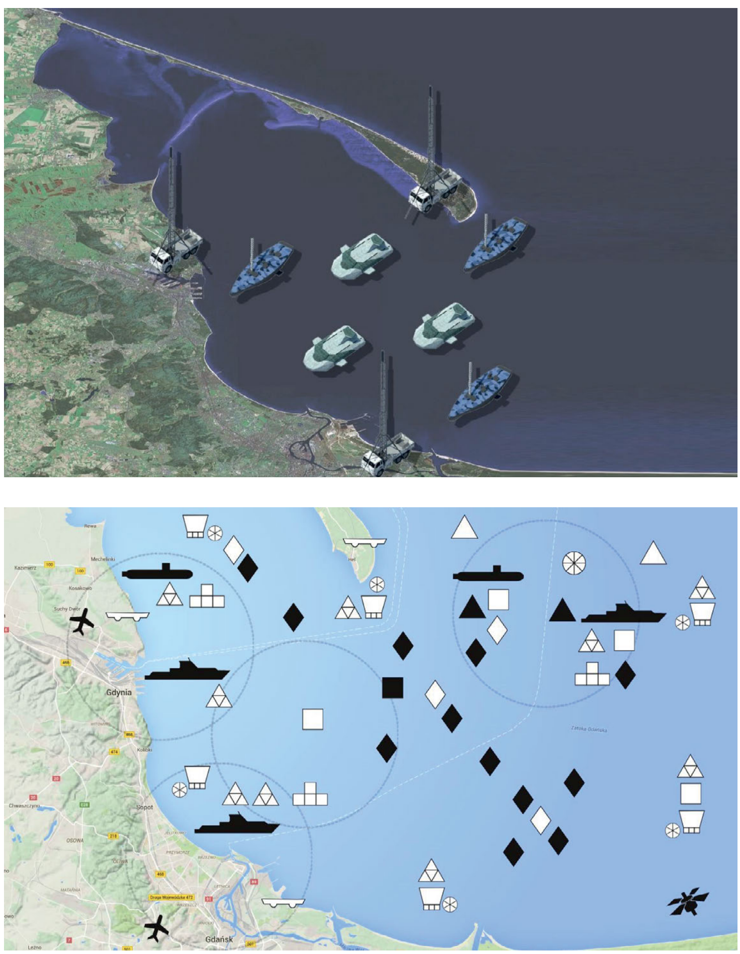

Figure 3. A visualisation of the model for using the AI-based control system (Gerigk M.K., 2017–2022).

The methodology of work of the AI-based mini-brain control system is according to the following steps:

– setting the requirements,

– defining the AI-based vehicle operational conditions (defined mission and tasks, mission route, critical points of mission route, energy supply source state, autonomy state: time and range, control points, coded communication),

– Identifying the operational hazards and event scenarios during the mission,

– assessing the AI-based vehicle performance during the mission,

– estimating, assessing and managing the mission risk,

– making the decisions on safety,

– selecting the best operational solutions that meet the mission requirements,

– optimising the mission.

Obtaining an intelligent AI-based vehicle does not mean equipping the vehicle with advanced hardware and an AI-based software control system. It has been decided that the intelligent AI-based vehicle requires innovative hardware (novel hull form, innovative solutions concerning the sensors, etc.) and software which helps to satisfy the functional, performance and safety requirements during a mission in an “intelligent way”. From the practical point of view, the AI-based vehicle can better detect the underwater reality, including the obstacles, and better perform the dedicated tasks and the entire mission.

The critical solution concerning the control system. The sensor systems and AI-based control systems combined decide about the AI-based vehicle senses. The AI-based mini-brain control system processes the visual, pressure, thermal, electromagnetic and hydroacoustic signals. This system works as an Inference Engine combining the Forward and Backward Chaining algorithms.

Such an approach enables us to compare the AI-based Mask (virtual reality) with the reality described by sensor system components. The major components of the AI-based and AI-based Mask systems for the AUV vehicle are presented in Figure 4. Similar solutions are prepared to be implemented in the case of the USV-WIG vehicle presented in Figure 5.

7. CONCLUSIONS

The last decade has been devoted to further developing the UUV uncrewed and AUV-type autonomous underwater vehicles. There is a growing interest in obtaining the successful implementations of fully AUV autonomous underwater vehicles[6].

[6] Gerigk M.K. Modeling of combined phenomena affecting an AUV stealth vehicle. TRANSNAV the International Journal on Marine Navigation and Safety of Sea Transportation, Volume 10, Number 4, December 2016 (druk: 2017), DOI: 10.12716/1001.10.04.18.

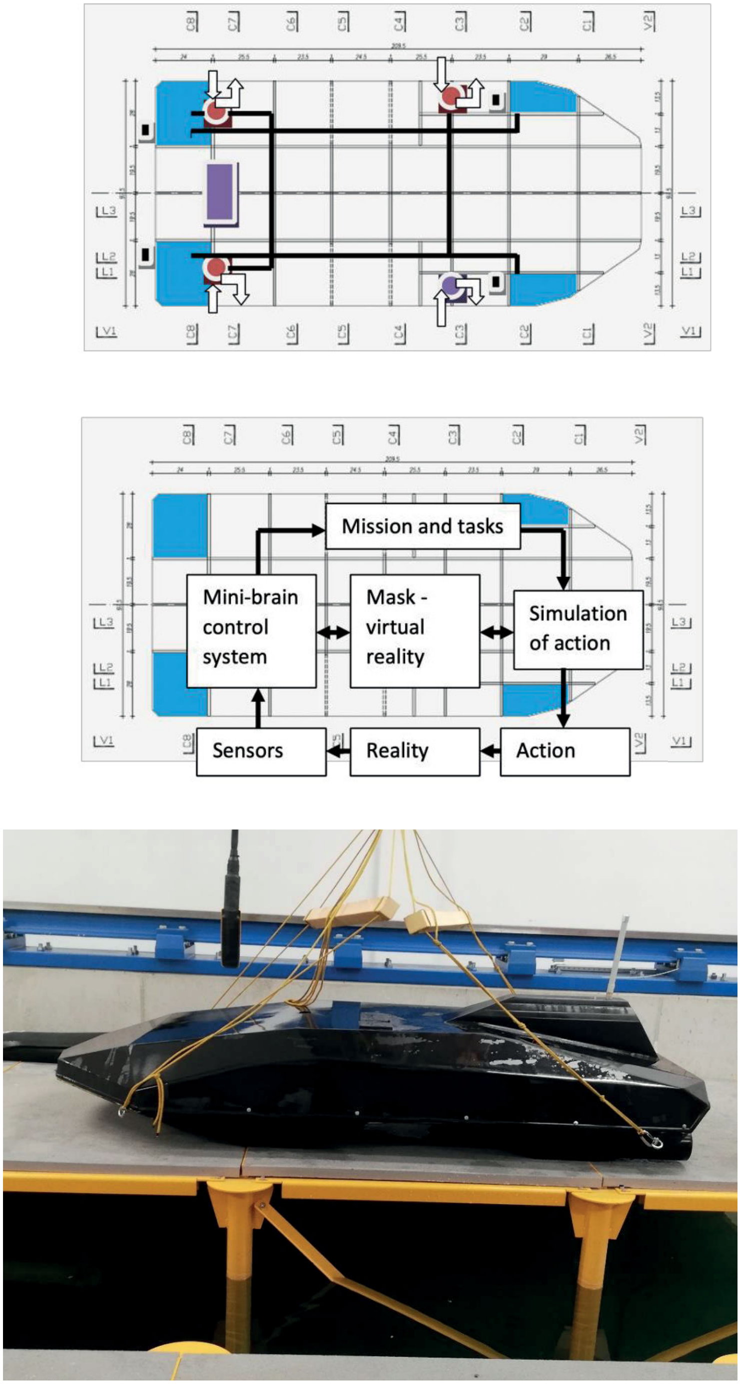

Figure. 4. Some elements of the AUV-AI-based control system, including the ballast system and elements of the AUV-AI-based Mask systems, also some elements of the novel USV-WIG platform system, including the AI-based control system.

The main drivers for further development of AUV vehicles are the following technologies: autonomous systems, sensors and effectors, materials, energy supply sources, propulsion systems, IT technologies and stealth technologies. There is a growing necessity for fast development of IT technologies, including the combined control, navigation, communication, sensor and effector systems for underwater applications. The developments may bring a vision of a fully autonomous AUV vehicle into practice. Let the AUV-AI-based vehicle be intelligent if the functional, performance, operational (mission, tasks) and safety standards, limitations and criteria are controlled by the AI-based mini-brain control system[7].

The AUV-AI-based vehicle concept has been worked out where the combined sensor and AI-based control systems enable the comparison of reality and onboard virtual reality in operation. According to this concept, the basic functional, performance, operational and safety features, characteristics and parameters of the AUV-AI-based vehicle have been investigated.

Obtaining an intelligent AUV-AI-based vehicle does not mean equipping her with the following:

Steering system consisting of advanced hardware and -AI-based software. The intelligent AUV-AI vehicle requires innovative hardware and software (hull form, etc.), which causes all together that the AUV-AI vehicle to be keen on behaving (diving, etc.) in an "intelligent way"[8].

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