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CHALLENGES ASSOCIATED WITH DEVELOPMENT OF AUV – UNMANNED AUTONOMOUS UNDERWATER VEHICLES TO BE OPERATED USING THE AI-BASED CONTROL SYSTEMS

Abstract: This paper presents a general scientific approach to further development of the AUV autonomous Underwater Vehicles equipped with a novel control system based on the artificial intelligence (AI) methodology. It is shown with the paper that it is relatively easy to develop an idea of autonomous underwater vehicles but it seems to be a difficult task to reach a level of the AUV application indeed. First of all the paper presents a general approach to the AUV vehicle design. Then a more complex approach to the AUV vehicle design which is based on the performance-oriented risk-based method is described. All such the drives are presented within the paper. The key solutions regarding the concept of mini-brain control system for the AUV-AI-based vehicle is described. The preliminary results of research in this are shown. In the final part of paper the scientific and practical conclusions are given

Keywords: unmanned vehicle, AUV – autonomous underwater vehicle, control system, AI – artificial intelligence, AUV-AI-based mini-brain control system

INTRODUCTION

The last decade has been devoted to further development of the UUVs, or unmanned underwater vehicles, which may be of two types: the USVs – unmanned surface vehicles and UUVs – unmanned underwater vehicles. There is a growing interest in creating and implementation of fully advanced AUVs, or autonomous underwater vehicles. The main drivers for the development of such vehicles are technologies of autonomous systems, sensors and effectors, innovative materials including the nano-materials and "intelligent" materials, innovative energy supply sources, innovative propulsion systems combining the efficient and silent engines and propellers, innovative IT technologies, including the double mode air-underwater control, and, finally, navigation and communication systems. Additional features the AUV vehicles may possess are the stealth-based and bio-technology-based solutions.

Commercial applications of AUVs cover conventional patrol and reconnaissance tasks. The navy-devoted AUV may enable reconnaissance and combat missions. Regardless of the application, it is necessary to implement advanced on-board hardware and software solutions to provide a high level of autonomy to the vehicles. The general requirements to obtain an autonomous AUV are concentrated on its autonomy from the energy supply, but also on self-control and self-navigation. It may be associated with not using communication with the center of mission; such a level of autonomy requires innovative solutions concerning the vehicle's sensors, effectors and control. The biggest challenge associated with the AUV development is to work out and implement an intelligent vehicle. A major difficulty to obtain such a vehicle is to acquire precise data from the surrounding environment, to process this data and to use it to perform all the tasks and mission in real time. The AU-AI-based vehicle should be equipped with a sort of a mini-brain to compare the on-board simulated virtual reality with the reality outside the vehicle due to activity of sensors, mini-brain control system and effectors. Such an on-line comparison may enable the achievement of expected functionality, performance and safety of the AU-AI-based vehicle for the benefit of a given mission.

1. GENERAL APPROACH TO AUV DESIGN

The following steps are usually conducted to achieve a basic set of characteristics of a successful AUV design[1]:

1. Define the design problem: design problem is defined as the AUV design and information on mission.
2. Determine the requirements: requirements concern the mission and vehicle.
3. Identify options for solutions: research into previous solutions to similar problems, brainstorming ideas for novel or improved approaches.
4. Examine tradeoffs & develop conceptual design(s): concept is a high-level design study of the major components within the design to determine

[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 2007

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. Perform 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. Select concept option & 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 with respect to their effect on other design aspects.

2. APPROACH TO AUV DESIGN BASED ON PERFORMANCE-ORIENTED

RISK-BASED METHOD

The major features of AU-AI-based vehicles should be their functionality, performance and safety. The vehicle's functionality is closely connected with the application area the vehicle is designed for. The definition of functionality requires the missions and tasks in operation to be defined. The current paper concentrates on AU vehicles for the underwater activity (patrol, reconnaissance, combat tasks and missions). The best techniques to define the missions and tasks to be performed in operation are the entire event trees (FTA – Fault Tree Analysis, ETA – Event Tree Analysis, called the consequences). The event trees should be implemented by the operational officers for each mission and each task within the data mission. These event trees are the basis for prediction of the vehicle performance for each event separately.

According to the event trees defined above, the vehicle's performance can be predicted for each task of the entire event tree. The assessment of performance is connected with estimation of the AUV parameters, characteristics and features for each data event. Such an approach enables to check if the vehicle is able to perform any task defined for each mission. It seems to be a good method and tool for training purposes of AUV operators and for controlling the tasks during the data mission. Taking into account the event tree and assessment of performance defined above, it is possible to perform the qualitative and quantitative risk assessment (QQRA) of the AUV mission taking into account the risk of each event.

All the above steps create the performance-oriented risk-based method of the AUV design. This method can be used at the AUV design stage and during the AUV operation, as it is based on the same definition of event tree, assessment of vehicle's performance and risk assessment. The following steps are conducted to achieve a basic set of parameters, characteristics and features of a successful AUV vehicle design when the performance-oriented risk-based method is applied[2]:

1. Define the AUV design functionality: define the missions, define the tasks within each mission, define the entire event tree for each mission and each task within the data mission.
2. Assessment of the AUV 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.

The research and design methodology is based on application of key advanced technologies which should provide the innovative solution to the final design of the AU-AI-based vehicle. Between those technologies, the major role is played by the following technologies:

– autonomous systems – has an impact on the AUV-AI-based vehicle design,
– sensors and effectors – has an impact,
– materials including the advanced composite materials – has an impact,
– innovative energy supply sources – has an impact,
– innovative propulsion systems – has an impact,
– IT technologies including the communication, navigation and controlling,
– stealth technologies – has an impact,
– space and satellite technologies – has an impact.

The above simply means and all the above technologies should be incorporated within the proposed AUV-AI-based design.

3. KEY DESIGN AND OPERATIONAL DRIVERS OF AU-AI-BASED VEHICLES

A basic set of design and operational parameters, characteristics and features which is necessary to control the AU-AI-based vehicle may be estimated during the assessment of performance using the algorithm presented in Table 1.

One between the major research objectives is to work out an AU-AI-based stealth vehicle which may possess a few features enabling to obtain a stealth-type performance of the vehicle. Between these features are:

– limited boundary layer and wake,
– limited emission of noise and vibration,
– other.

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[2] M. Gerigk, 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.

Table. 1. An example of a basic set of design and operational parameters, characteristics and features necessary to control the AUV-AI-based vehicle[3].

Design stage	Description of design stage	AUV vehicle performance – features (F) – characteristics (CH) – parameters (P)
S1	Main aim, design objectives	F: good floatability, stability, resistance and propulsion, manoeuvrability, seakeeping CH: associated with the above features P: associated with the above features and characteristics
S2	AUV definition Environment definition	F: hull form Ch: buoyancy, displacement P: length, breadth, height P: sea state, depth
S3	AUV arrangement of internal spaces	F: subdivision Ch: capacity of compartments P: number of bulkheads
S4	Selection of structure materials	F: material, features of material Ch: AUV structure mass and weight, centre of gravity P: skin thickness, internal structure thickness
S5	Selection of equipment and on-board systems	F: distribution of mass and weights Ch: centre of gravity of each mass and weight P: position and mass of each mass and weight
S6	Estimation of mass and weight of AUV light vehicle	Ch: mass and weight of AUV light vehicle P: position of centre of gravity of AUV light vehicle
S7	Estimation of mass and weight of AUV vehicle for all the operational loading conditions including the internal loads	Ch: mass and weight of AUV vehicle for each loading condition P: position of centre of gravity of AUV vehicle for each loading condition
S8	AUV performance – statics	F: phenomena, floatability, stability, survivability Ch: buoyancy, displacement, righting arms, criteria P: draft, immersion, trim, angle of heel

[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 waterborne stealth-type object of innovative solutions concerning the hull form, structure and materials having an impact on the object stealth characteristics" - in English. 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.

Design stage	Description of design stage	AUV vehicle performance – features (F) – characteristics (CH) – parameters (P)
S9	AUV performance – dynamics	F: phenomena, resistance and propulsion Ch: resistance curve, demanded and operational power curves, propeller thrust curves, resistance-based hydrodynamic forces, propeller-based hydrodynamic forces, criteria P: AUV speed, number of propellers F: phenomena, manoeuvrability Ch: course keeping, turning, criteria P: diameter of circulation curve, zig-zag type dynamics F: phenomena, seakeeping Ch: degrees of freedom, equations of motion, amplitudes of linear and angular characteristics of motion, velocities and accelerations, criteria

The stealth technology is defined as: minimizing the probability of detection of the S-AUV using the well known and „unknown" means (technologies, devices, etc.). The "stealth" function is anticipated as follows:

$E = E\ [p_1, p_2,..., p_n, f_1(x_1, x_2,..., x_{m1}), f_2\ (x_1, x_2,..., x_{m2}), ..., f_k\ (x_1, x_2,..., x_{mt})]$(1)

where: k – No. of a stealth technology applied; $m_1, m_2, m_3, m_4, m_5, m_6, m_t$ – No. of independent (dependent) characteristics for the data stealth technology; p – parameters; x - variables; f – a stealth characteristics (function, polynomial, etc). The physical fields for the research have been anticipated as follows: F1 – main particulars, hull form (geometry), F2 – skin covers (nano-surface) – materials; F3 – noise and vibrations; F4 – electromagnetic, magnetic; F5 – thermal (heating); F6 – boundary layer and wake; F - visibility. The first step during the research was to check how much a hull skin cover may affect the AU-AI-based vehicle flow including the boundary layer and wake. During the computer simulation of the flow the mesh consisting of 3 275 000 elements was used. The numerical domain had the size[4]: 5 meters x 1.5 meters x 1.2 meters. The water flow velocity was anticipated to be from 0.5 up to 2.5 meters per second with the step 0.5 meters per second. During the simulation the hull skin cover was generated by the skin roughness as follows:

– Ra 80 – as a normal steel plate surface,
– Ra 1.25 – as a slightly polished steel plate surface,
– Ra 0.01 – as a polished steel plate surface,
– Ra 0.0025 – extremely polished steel plate surface (so-called nano-surface).

[4] D. Kardaś, P. Tiutiurski, M. Gerigk, Internal report of the Gdańsk University of Technology: "Modelowanie opływu obiektu OWS. Model warstwy przyściennej". Opracowanie nr 1/IMP, Projekt PBS3/A6/27/2017, Politechnika Gdańska, Gdańsk 2016.

The flow was estimated for the distance 0.5 meters, 1.0 meters, 1.5 meters and 2.0 meters behind the AU-stealth vehicle. The second step during the research was to check the influence of the parameters (modelled roughness, nano-surface) of the hull skin cover on the flow including mainly the boundary layer. During the computer simulation three types of nano-surface has been modelled. Some results of the computer simulation of the flow estimation in the boundary layer (for the data skin roughness, for the nano-surface modelled)[5]. The third step was to check the influence of the hull skin cover on the sonar system signal. During the towing tank investigations three types of AUV-Stealth hull skin covers were tested[6].

The above mentioned information shows the level of research associated with prediction of some performance features, characteristics and parameters, which have an impact on the AU-AI-based vehicle performance in operation. It is necessary to underline that prediction of the set of design and operational parameters, characteristics and features, which is necessary to control the AUV-AI-based vehicle presented in Table 1, should be followed by an algorithm for prediction of the so-called AUV control power, presented in Table 2.

Based on the above mentioned algorithms, it is possible to predict the necessary level of autonomy to be achieved due to the AUV performance data. The level of autonomy from null up to two may concern a vehicle which is a kind of an automated robot performing programmed tasks. Levels from three up to five refer to the AUV vehicles which posses more advanced solutions concerning the sensor, control and effector systems. The most advanced solution, the level five of autonomy, is a case when the vehicle has an on-board mini-brain which enables to compare the current situation outside the vehicle (reality) using the sensors with the virtual reality stored and simulated within the vehicle's mini-brain.

Nonetheless, construction of an AU-AI-based vehicle does not mean merely equipping it with a steering system consisting of the sophisticated hardware and AI-based software. On the contrary, it requires the achievement of an innovative hull form which should be capable of diving. If the AUV performance is very good, the sensors, control and effectors driven by the AUV mini-brain guarantee the highest level of functionality, performance and safety. It is highly probable in such a setting that all the tasks within the mission will 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 on-board

[5] E. Ciba, P. Dymarsk, M.K. Gerig, Internal report of the Gdańsk University of Technology: "Modelowanie opływu obiektu OWS. Model pokrycia nano. Model warstwy przyściennej". Opracowanie nr 1/PG/WM, Projekt PBS3/A6/27/2017, Politechnika Gdańska, Gdańsk 2018.

[6] F. Barański, M.K. Gerigk, Internal report of the Gdańsk University of Technology: "Badania hydroakustyczne modelu obiektu AUV-Stealth". Opracowanie nr 1/PG/KFB, Projekt PBS3/A6/27/2017, Politechnika Gdańska, Gdańsk 2018.

Table. 2. An example of a basic set of design and operational parameters, characteristics and features necessary to predict the AUV-AI-based vehicle control power.

Design stage	Description of design stage	AUV vehicle performance – features (F) – characteristics (CH) – parameters (P)
S10	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, hydro phone), thermovision system, electromagnetic system P: data signals in time domain, current intensity, voltage of the current
S11	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 time domain, current intensity, voltage of the current
S12	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 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 (on-line system) P: data signals in time domain, current intensity, voltage of the current
S14	Estimation of demanded power of batteries necessary to run the propulsion and remaining on-board 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 (on-line system) P: data signals in time domain, current intensity, voltage of the current

systems all contribute to the optimal position of the vehicle's centre of gravity and impact the operation of the global hydrodynamic force in each period of time. Also the internal and external loads on the AUV's structure have an impact on the amount of energy used during operation, with major influence of the vehicles' resistance force. This force depends on the vehicle's speed and is decisive for the maximum range of the AU-AI-based vehicle. The vehicle's hull form and propulsion system have a big impact both on the vehicle's speed and range, hence it is necessary to apply the most innovative solutions from the design and performance point of view. The entire capacity of the energy supply source should be increased due to energy necessary to supply the work of the sensors, mini-brain control and effectors systems. The mini-brain control system coordinates the distribution of energy and information for all on-board systems and AU-AI--based vehicle itself. Taking into account navy applications, it is necessary to deliver a limited boundary layer and wake, limited emission of noise and vibration, as well as other factors. They may enable the AU-AI-based vehicle to remain difficult to be detected, but at the same time to better detect obstacle and enemies, and thus better prepared to perform the mission.

4. KEY SOLUTIONS. A CONCEPT OF MINI-BRAIN CONTROL SYSTEM. PRELIMINARY RESULTS OF OWN AU-AI-BASED VEHICLE DESIGN

Conceptualizing and elaborating autonomous AU-AI-based vehicles requires replacement of two or three dimensional work concepts with concepts based on the space of operation. Within the space of operation, humans will be supported and sometimes replaced by Artificial Intelligence (AI). Information will be exchanged on-line between all the linked systems that have been granted access[7] and the exchange of data in real time domain should be permanent. The complex air-based systems require speed of data transfer at the level of 500 Mb/s, which means that the unmanned autonomous underwater systems like the AU-AI-based vehicles should rather be a system of systems. It is necessary to apply such an approach if the future AU-AI-based vehicles are to be functional, exhibit good performance and remain safe in the space of operation.

The sensor system and AI-based mini-brain control system decide about the AU-AI-based vehicle senses. Visual, pressure, electromagnetic and hydroacoustic signals are processed by the AI-based mini-brain control system. This system works as an Inference Engine combining the Forward and Backward Chaining algorithms[8]. Such an approach makes possible comparison of the AUV-AI-based mask (virtual reality) with reality as described by the sensor systems. Preliminary results of research have shown that it is possible to let the AUV-AI-based vehicle to be an intelligent vehicle if the functional, performance, operational (mission, tasks) and safety standards, limitations and criteria are controlled the AI-based mini-brain control system. The methodology of work of the AI-based mini-brain control system is built according to the following main steps:

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[7] T.J. Sejnowski, 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.

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

– setting the requirements,
– defining the AU-AI-based vehicle operational conditions (defined mission and tasks, mission route, key 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 AUV-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,
– optimizing the mission.

Constructing an intelligent AI-based AUV does not mean to equip the vehicle with a control system consisting of advanced hardware and AI-based software. Intelligent AU-AI-based vehicle requires the use of innovative hardware (novel hull form, innovative solutions concerning the sensors, etc.) and software which help to satisfy the functional, performance and safety requirements during a mission in an "intelligent way". From the practical point of view, it means that the AUV-AI-based vehicle is able to better detect underwater reality, including obstacles, in order to better perform the dedicated tasks and to complete the entire mission successfully.

The key solution concerning the control system. Sensor systems and AI-based control system combined together decide about the AU-AI-based vehicle senses. The visual, pressure, thermal, electromagnetic and hydroacoustic signals are processed by the AI-based mini-brain control system. This system works as a kind of Inference Engine combining the algorithms:
– Forward and
– Backward Chaining.

Such an approach enables to compare the AUV-AI-based Mask (virtual reality) with the reality being described by the components of sensor systems. The major components of the AUV-AI-based and AUV-AI-based Mask systems are presented in Figure 1. The first step of investigations on the development of the AU-AI-based vehicle equipped with some elements of the AI-based mini-brain control system has been done. There is a growing hope that the dedicated AU-AI-based vehicle would successfully reach the second step of the R&D investigations where the manoeuvres presented in Figure 2 will be performed in the real operational conditions.

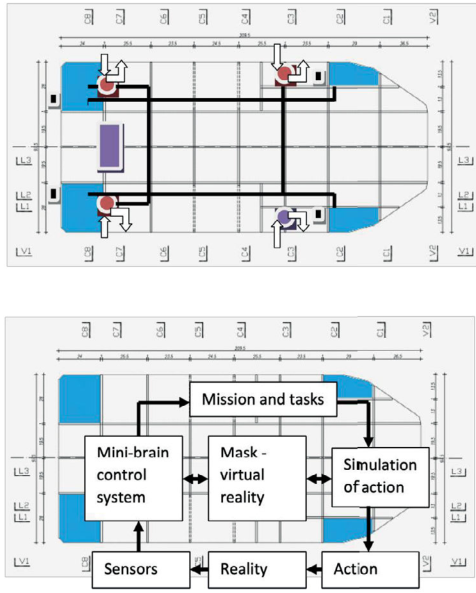

Figure 1. Some elements of the AUV-AI-based control system including the ballast system and elements of the AUV-AI-based Mask systems.

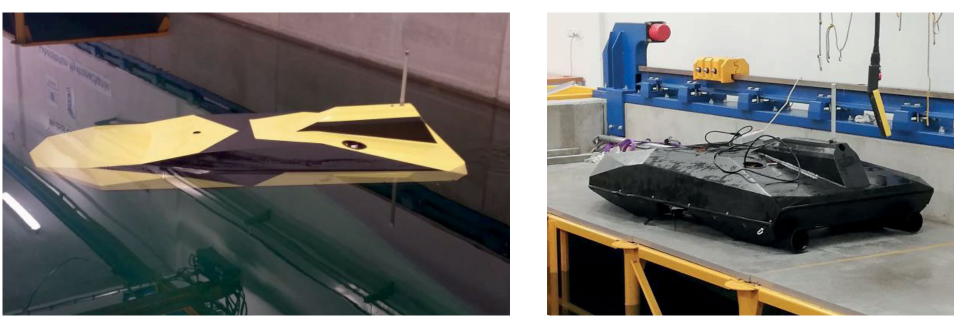

Figure 2. An advanced AUV-AI-based demonstrator during the towing tank test.

5. CONCLUSIONS

The last decade has been devoted to further development of the UUVs, or unmanned underwater vehicles, and AUVs – autonomous underwater vehicles. There is a growing interest to obtain successful implementations of a fully autonomous underwater vehicle[9]. The main drivers for further development of AUVs

[9] M. K. Gerigk, Modelling 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.

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. Such developments may bring to life a vision of fully autonomous AUVs. It is possible to let the AU-AI-based vehicle to be an intelligent vehicle if the functional, performance, operational (mission, tasks) and safety standards, limitations and criteria are supervised by the AI-based mini-brain control system[10].

The AUV-AI-based vehicle concept has been worked out where the combined sensor and AI-based control systems enable to compare the reality and on-board virtual reality in operation. According to this concept, basic functional, performance, operational and safety features, characteristics and parameters of the AU-AI-based vehicle have been investigated. Obtaining an intelligent AU-AI-based vehicle does not mean to equip her with:

– steering system consisting of the advanced hardware and
– AI-based software.

The intelligent AUV-AI vehicle requires an innovative hardware and software (hull form, etc.) which all together contribute to the fact that an AU-AI vehicle is keen on behaving (diving, etc.) in an "intelligent way"[11].

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