Development of an effective hybrid system for generation and distribution of electric power for autonomous unmanned underwater vehicles

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Abstract. The problem of coordinated operation of a hybrid system for generation and distribution of electric power to provide motion for an underwater vehicle is addressed. The architecture of a multi-agent vehicle system is chosen, the optimum distribution of consumers to electric lines is defined, effective switching of consumers between electric lines, with due regard to the functional and non-functional requirements for the system, is developed.

1. Introduction

Currently, the advancement in the technologies in the field of marine robotics has led to the development of a multi-speed autonomous (unmanned) underwater vehicle (AUV) [1]. Due to the specifics of the marine environment, the vehicle’s movement at different speeds is possible only when using a hybrid electric Power Generation & Distribution System (PGDS) that includes heterogeneous sources of electric power the operation of which is defined by the speed modes of the AUV movement. When the AUV moves at different speeds while addressing a route task, the composition of consumers and the currents consumed by them change over time.

All consumers are connected to busbars (hereinafter referred to as ‘buses’) with different rated currents. Due to the variable composition of consumers and varying consumption of current by each of them, there is a need for a constant re-distribution of consumers between the buses. This is due to the fact that when the current consumption exceeds the rated currents of the bus, the bus is warmed up and, as a result, the temperature inside the AUV compartment rises, which negatively affects the operation of the AUV navigation and control systems. In this regard, the problem to control the consumers’ switching between the buses in harmony with the AUV movement arises. The need for separate review of synchronous operation of the AUV systems is conditioned by the fact that for the AUV under consideration, each of its systems, i.e. the main propulsion and steering system, the PGDS, the navigation system, the sensors, the acoustic and radio communication systems, the control systems, the equipment and devices, the emergency and alarm facilities, is complex, developed by one or several independent units and organizations. As a result, the operation of each system is provided by independent software that exchanges data with the software of adjacent AUV systems, and the AUV system itself becomes a multi-agent one.

In addition, in order to improve the efficiency of the PGDS, it is necessary in advance, already at the AUV design phase, to define the necessary and sufficient number of buses and the sufficient number of
switches connecting consumers to the buses and closing the electric circuit with the keys at the time of power supply to the consumer. Besides, at the operation phase, it is necessary to make an effective and prompt decision (in a fraction of a second) on switching the consumers between the buses.

Only an effective PGDS is able to provide an integrated solution to the above-listed tasks. In this paper, ‘an effective PGDS’ means the one meeting the following requirements:

- coordinated operation of all AUV systems in real time;
- smart distribution of consumers' connections to the buses, at which, on the one hand, all consumers are supplied with current, and on the other hand, the amount of current consumed by each bus does not exceed its nominal value;
- efficient switching of consumers between buses implemented by minimizing the number of switching operations when changing the composition of consumers and the current consumed by them;
- prompt decision-making on switching-over consumers between electric lines.

In view of the novelty of the development of a multi-speed AUV and the use of a hybrid PGDS, the task was not set earlier in such wording, since the AUVs did not have the need to change the speed modes before: practically all developed AUVs provided for movement in the cruise mode, i.e. at up to four knots. High-speed single use vehicles also, despite moving at a search speed and at a cruise speed, used the same actuators and a source of electricity which was a rechargeable battery. In this regard, when developing a multi-speed AUV, these approaches could not be applied. In the domestic and foreign literature, publications on this subject are practically missing due to the novelty of the task of AUV’s travelling to ultra-long distances and the novelty of the engineering solution associated with the use of a hybrid PGDS on board AUVs.

The goal was to develop an efficient hybrid Power Generation & Distribution System.

2. Task setting

Let the AUV at a time instant \( t \) move with the steady-state parameters, i.e. heading, speed and depth. To ensure the AUV movement and activities, power sources connected to the buses are engaged. Let the AUV be power-supplied from a hybrid Power Generation and Distribution System consisting of various types of current sources. Let the current sources supply the buses to which all consumers are connected through switches. Suppose that at some instant \( t \) the switch keys are closed so that the PGDS provides the necessary power to all consumers that need it. And suppose that at the next instant \( t +1 \) due to the change in the parameters of the AUV's movement, it becomes necessary to increase (or decrease) the current consumed by individual consumers, to connect some new consumers, and disconnect some previously connected ones.

As a result, when passing from instant \( t \) to instant \( t +1 \), it is necessary to close the switch keys for switching-over the consumers to the power network in such a way that the distribution of the consumers' connection between the buses will be optimal, the number of switched keys will be minimal, and the time for decision-making will be fractions of seconds.

3. Coordination of AUV systems' operation

Due to the practically independent functioning of the AUV agent systems, there is an urgent task to coordinate their functioning. This so-called non-functional requirement [2] for the coordinated operation of the AUV systems is defined by the architecture of the multi-agent system. ‘Architecture’ is traditionally understood as the fundamental organization of a system, embodied in its components, their relationships to each other and the environment.

The efficiency of its functioning depends on how well the system is organized. To define the architecture of the multi-agent system of the AUV under consideration, three options have been generated, which differ in the appointment of the coordinator of the AUV agent systems. In the first option, the coordinator is a specially created agent, a ‘Coordinator’, in the second option – ‘Navigator’ agent, in the third option – a ‘Power’ agent.
Analysis of processes in the AUV multi-agent system has shown that the speed of decision-making on switching the consumers between the buses is defined by the following: high speed of information processing and high speed of information exchange between agents. The high speed of information processing, in its turn, is defined by the scope of processed data and the use of ‘fast algorithms’ that essentially reduce the time for information processing and decision-making. The high speed of exchange between the agent systems is defined by direct communication between the agents and the scope of transmitted information with the processing results.

Based upon the results of the analysis, a target graph has been formed, in which the goal is to coordinate the operation of the agents, and the sub-goals located in the nodes of the graph are the attributes that impact coordination. To identify the degree of impact of attributes on coordination, a mathematical model of functioning of a hybrid power supply system and its software implementation have been developed. This has made it possible to obtain estimates of the impact of each attribute on the ultimate goal, i.e. coordination.

Based upon the results of numerical experiments for various operating conditions of the multi-agent system and the operating conditions of the AUV, quantitative estimates have been obtained. The derived estimates have made it possible, using the ‘label propagation algorithm’ [3], to obtain the final estimates of each of the three addressed architectures of the AUV multi-agent system. Based upon the results of comparing the final assessments of each architecture, it has been identified that the best result is shown by the architecture of a multi-agent system in which the coordinator is the PGDS.

4. Optimal distribution of consumer connections to the buses

Essentially, our task of connecting consumers efficiently to buses is close to the ‘task of bin (containers) packing problem’ [4], wherein some components should be placed into the containers in such a way that the aggregate volume of the components in each container should not exceed its volume, and the number of the filled containers should be minimal. In this case, the containers are the buses, and the components are the consumers. A fairly large number of various solutions to the problem of packing into containers are known, i.e. from the simple search (enumeration) method to heuristic algorithms with varying degrees of accuracy and estimated time. To select the most appropriate algorithm for coordinated operation of all AUV systems, alongside with the requirements for optimal connection and minimization of the number of switching operations, it is also necessary to take into account the promptness of decision-making on switching consumers between buses (the so-called ‘non-functional’ requirement) and use ‘fast algorithms’[5, p. 207]. In this regard, with previously unknown parameters of the consumers, it is proposed to use the Best Fit (BF) heuristic algorithm. In this case, the set of used actuators is not known in advance, and the need to connect the actuators comes in sequence. When distributing the consumers to buses in the event of a complete revision of the parameters of the hybrid PGDS, it is proposed to use an algorithm focused on the use of complete information about the connected consumers, i.e. the Best Fit Decreasing (BFD) one. Both the BF and BFD algorithms are based on a greedy algorithm, in which the locally best choice is made at each step under the assumption that the final solution will be optimal.

5. Smart control of hybrid PGDS

The control of a hybrid PGDS consists in changing its status that is defined by the number of power supplies involved, and, respectively, the buses, and the distribution of consumers to the buses. To define the option of switching consumers between the buses, the following possible options have been analyzed: an increase in the consumption within the rated current of the bus to which this consumer is connected; an increase in the consumption that leads to excess of the rated current, and therefore requires switching; complete switching-over of consumers. According to the results of the analysis, it has been identified that in the first option no switching is required. In the second option, we turn off the consumer with an increasing level of consumption, due to which the rated current has been exceeded and, in accordance with the proposed BF solution, we try to find a place for it on other buses. If there is no such bus, then we additionally start a new bus and connect it to this one. In the
third option, a complete re-consideration of the connections takes place, and the BFD algorithm is used to select a new effective connection. In case of complete switching, it is advisable to preserve the continuity of connections; therefore, when choosing the option for connecting to specific buses, one must first analyze and select the option with the largest number of coincidences of consumer connections to the buses at instants $t$ and $t+1$. To do this, in the cycle for each previously used consumer, we search through the buses used at instant $t$. If the consumer is connected to the bus in question, then we keep this connection active. And then we connect the consumers that are predefined at instant $t+1$ to the same bus. Then, we turn to the consideration of the next yet unconnected consumer used at instant $t$, and define its connection in the cycle on the remaining buses. This happens until all previously used consumers are connected to the buses. The remaining new consumers at instant $t+1$ are connected to the remaining buses.

6. Conclusion
The problem of developing an effective hybrid system for generating and distributing electric power that operates synchronously with the motion control of a multi-speed autonomous unmanned underwater vehicle has been addressed. Efficiency indicators have been defined, various types of AUV multi-agent system architectures that define the coordination of the power generation and distribution system with the rest of the AUV systems have been analyzed, and possible reasons for the need to switch consumers between the buses powered by various current sources have been identified. Effective control of the Power Generation and Distribution System has been proposed on the basis of the Best Fit and Best Fit Decreasing heuristic algorithms the application of which depends on the current situation. Solution of the listed-above tasks has allowed us to develop an efficient hybrid system for the generation and distribution of electric power.

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References
[1] Appolonov E M, Bachurin A A, Gorokhov A I and Ponomarev L O 2018 Perspective Control Systems and Tasks’. Feasibility and Need to Develop an Extra-large Unmanned Underwater Vehicle Proceedings of the XIII th All-Russian Scientific & Practical Conference ‘(Rostov-on-Don Taganrog: YuFU) 34–42
[2] Chung L K, Nixon B and Yu E, Mylopoulos J 2000 Non-Functional Requirements in Software Engineering (Kluwer Publishing) p 441
[3] Chung L K and Sampaio J C 2009 On Non-Functional Requirements in Software Engineering Conceptual Modeling: Foundations and Applications . (Springer Berlin: Heidelberg) pp 363-379
[4] Levin M Sh 2017 Packaging into Containers (prospective models, examples) Information processes vol 17 No 1 pp 43-60
[5] Moiseev N N 1987 Algoritmy razvitiya (Development Algorithms) (Moskow: Nauka) p. 304