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151 АВТОМАТИЗАЦІЯ ТА КОМП'ЮТЕРНО-ІНТЕГРОВАНІ ТЕХНОЛОГІЇ

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DESIGN OF DISTRIBUTED AUTOMATED SHIP'S CONTROL SYSTEMS BASED ON OPC UA TECHNOLOGY

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The OPC Unified Architecture (OPC UA) is a platform-independent, secure, and scalable communication protocol for industrial automation and control systems. It provides a standardized way for devices from different manufacturers to communicate and exchange data, regardless of their underlying technology or operating system. This interoperability enables the seamless integration of various components within a distributed automated control system (DACS), leading to improved efficiency, reliability, and flexibility. In the maritime industry, the adoption of OPC UA technology has the potential to revolutionize the design and operation of ships. By implementing OPC UA, shipyards and ship owners can achieve greater control over their vessels, optimize operations, and reduce maintenance costs. OPC UA can be used to connect a wide range of devices and systems on a ship, including sensors, actuators, controllers, and human-machine interfaces (HMIs). This enables the collection and analysis of real-time data from various sources, providing valuable insights into the ship's performance and health. One of the key benefits of using OPC UA in the design of DACS is its ability to facilitate remote monitoring and control. By integrating OPC UA with cloud-based technologies, ship operators can access and manage their vessels from anywhere in the world. This allows for proactive maintenance, timely troubleshooting, and remote diagnostics, reducing downtime and increasing operational efficiency. Another significant advantage of OPC UA is its support for information modelling. This allows for the creation of standardized data models that can be used to describe the physical components and processes on a ship. By using these models, engineers can design and implement DACS more efficiently, reducing the risk of errors and inconsistencies.
Keywords: *OPC UA, distributed automated control systems, maritime industry.*

Statement of the problem

Advancing beyond traditional centralized systems, Distributed Automated Control Systems (DACS) [1, 2] utilize a network of controllers to monitor and manage industrial operations. This distribution of control functions provides a multitude of advantages:

– Reliability: If one controller fails, the system can continue to operate, minimizing downtime.

– Scalability: DACSs can easily be expanded to accommodate new processes or increased production capacity.

– Flexibility: Individual controllers can be tailored to specific process requirements, enhancing efficiency.

Key components of a DACS:

– Controllers: These devices perform the actual control functions, such as regulating temperature, pressure, or flow.

– I/O Modules: These modules connect the controllers to sensors and actuators, allowing them to receive data and send control signals.

– Communication Network: This network links the controllers, I/O modules, and other system components, enabling data exchange and coordination.

– Operator Interface: Human-machine interface (HMI) make possible to monitor the process, make adjustments, and respond to alarms for operators.

Common applications of DACS:

– Manufacturing: Chemical plants, refineries, food processing facilities

– Power generation: Power plants, hydroelectric stations

– Water and wastewater treatment: Treatment plants, distribution networks

– Oil and gas: Exploration, production, and refining

– Pharmaceutical: Manufacturing and packaging

Advantages gained by implementing a DACS are the following:

– Improved efficiency: Optimized process control can lead to increased productivity and reduced waste.

– Enhanced safety: Automated monitoring and control can help prevent accidents and minimize risks.

– Reduced costs: Efficient operations and lower maintenance requirements can result in significant cost savings.

– Better decision-making: Real-time data and analytics can support informed decision-making.

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By distributing control functions and leveraging advanced technology, DACSs provide a reliable, scalable, and flexible solution for automating industrial processes.

Research Relevance.

The maritime industry is undergoing a significant transformation driven by the need for increased efficiency, safety, and environmental sustainability. Distributed Automated Control Systems (DACS) play a crucial role in achieving these goals by enabling the monitoring and control of complex onboard systems, such as propulsion, power generation, and cargo handling. However, traditional maritime DACS architectures often suffer from interoperability issues, limited scalability, and inadequate security, hindering their ability to meet the demands of modern maritime operations.

OPC Unified Architecture (OPC UA) emerges as a promising solution to address these challenges. Its platform-independent, service-oriented architecture provides a standardized framework for secure and reliable data exchange, enabling seamless integration of diverse onboard systems and devices. The relevance of OPC UA in the context of maritime DACS is evident in the following aspects:

1. Enhanced Interoperability: OPC UA facilitates the integration of systems from different manufacturers, eliminating vendor lock-in and enabling the creation of more flexible and cost-effective maritime DACS [3]. This is particularly important in the maritime industry, where vessels often incorporate a wide range of equipment from various suppliers.

2. Improved Data Accessibility and Exchange: OPC UA provides a unified data model that enables seamless access to real-time and historical data from various onboard systems [4]. This capability is crucial for advanced monitoring, diagnostics, and predictive maintenance, leading to improved operational efficiency and reduced downtime.

3. Strengthened Cybersecurity: OPC UA incorporates robust security mechanisms, including authentication, authorization, and encryption, to protect critical control systems from cyber threats. This is particularly important in the maritime industry, where vessels are increasingly connected to shore-based networks and vulnerable to cyberattacks.

4. Scalability and Flexibility: OPC UA's service-oriented architecture enables the easy addition and removal of devices and systems, facilitating the scalability and flexibility of maritime DACS. This is essential for adapting to changing operational requirements and integrating new technologies, such as IoT and cloud computing.

Support for Autonomous Shipping: As the maritime industry moves towards autonomous shipping, OPC UA's ability to provide secure and reliable data exchange is crucial for enabling the integration of autonomous navigation, collision avoidance, and remote monitoring systems.

By leveraging OPC UA's capabilities, maritime DACS can achieve higher levels of interoperability, security, and scalability, leading to improved operational efficiency, safety, and environmental sustainability. This research aims to demonstrate the practical application of OPC UA in maritime DACS and highlight its potential to revolutionize the maritime industry.

Problem Statement.

Distributed Automated Control Systems (DACS) are integral to modern industrial operations, enabling the control and monitoring of complex processes across geographically dispersed locations. However, the inherent complexity and heterogeneity of DACS present several challenges that hinder their efficiency, interoperability, and scalability. Traditional DACS architectures often rely on proprietary communication protocols, leading to vendor lock-in and difficulties in integrating devices and systems from different manufacturers. This lack of standardization results in fragmented data exchange, limited real-time capabilities, and increased maintenance costs.

Furthermore, the increasing demand for real-time data analysis and predictive maintenance in Industry 4.0 environments necessitates a robust and secure communication infrastructure. Existing solutions often struggle to provide the required level of security, reliability, and performance for critical control applications. The need for seamless integration with enterprise-level systems, cloud platforms, and IoT devices further exacerbates these challenges.

To address these limitations, this paper investigates the application of OPC Unified Architecture (OPC UA) as a solution for enhancing the interoperability, security, and scalability of DACS. OPC UA is a platform-independent, service-oriented architecture that provides a standardized framework for industrial communication. By leveraging OPC UA's capabilities, this research aims to demonstrate how it can overcome the limitations of traditional DACS architectures and enable the development of more efficient, secure, and future-proof industrial control systems.

Analysis of the latest achievements on the identified problem

OPC UA (Open Platform Communications Unified Architecture) [4] continues to be a cornerstone for industrial interoperability. Recent research and publications have focused on expanding its capabilities, addressing emerging challenges, and exploring new applications. The publication [5] provides an up-to-date overview of the field, as well as identifies several potential research directions, challenges, and opportunities for further research on OPC UA. An example of OPC UA usage in the marine industry is given in [6], where a control system based on the OPC UA for the requirements of the deep-sea dry recovery unit was designed and verified through prototype testing. In the study [7] the authors proposed the use of OPC UA to increase interoperability of communication and the utilization of Arrowhead Framework to enhance interoperable service compositions of control applications implemented in IEC 61499. The paper [8] presents an Open Platform Communications Unified Architecture (OPC UA)-based cloud system designed for managing distributed microgrid networks. The paper proposes a three-layer model specifically tailored to manage microgrids within cloud environments and defines an appropriate level of the information model for each layer. The research [9] demonstrates the mapping of the resource, device, and the system model to OPC UA and deals with the IEC 61499-based distributed control model that gaining popularity among the stakeholders involved in the field of cyber-physical production systems.

Purpose and task statement

The purpose of the study is to connect two automated control systems in the maritime industry into common distributed control system with application of the OPC UA technology.

Summary of the main material

The development of robust and efficient Distributed Automated Control Systems (DACS) requires powerful tools that facilitate seamless integration, modeling, and deployment. In this study, we have selected Simulink/MATLAB and CODESYS [10] as the primary platforms for the following reasons:

Simulink/MATLAB:

– Advanced Modeling and Simulation: Simulink provides a graphical environment for modeling and simulating dynamic systems, enabling the creation of complex control algorithms and the analysis of system behavior under various operating conditions. MATLAB offers a wide range of toolboxes for signal processing, control design, and optimization, which are essential for developing sophisticated control strategies.

– Rapid Prototyping and Testing: Simulink allows for rapid prototyping and testing of control systems, reducing the time and cost associated with traditional development methods. The ability to simulate systems in a virtual environment enables early detection and correction of design flaws, improving the overall reliability of the DACS.

– Code Generation and Hardware Integration: MATLAB Coder and Simulink Coder facilitate the automatic generation of C/C++ code from Simulink models, which can be deployed on a variety of hardware platforms. This capability simplifies the integration of control algorithms with real-world systems, including programmable logic controllers (PLCs) and embedded devices.

CODESYS:

– IEC 61131-3 Compliance: CODESYS is a comprehensive software platform that supports all five IEC 61131-3 programming languages, providing flexibility and interoperability for PLC programming. This standard ensures that control logic can be easily transferred between different hardware platforms, reducing vendor lock-in and simplifying system maintenance.

– Integrated Development Environment (IDE): CODESYS offers an intuitive IDE that streamlines the development, debugging, and deployment of PLC applications. The IDE includes powerful features such as online monitoring, debugging tools, and version control, which enhance the productivity of control engineers.

– Communication and Networking Capabilities: CODESYS supports a wide range of communication protocols, including OPC UA, EtherCAT, and Modbus, enabling seamless integration with other industrial devices and systems. This flexibility is crucial for building distributed control systems that require reliable data exchange and interoperability.

– SoftPLC Functionality: CODESYS SoftPLC enables the execution of PLC programs on standard PC hardware, providing a cost-effective and flexible alternative to traditional hardware PLCs. This capability facilitates the development of virtual control systems for simulation and testing purposes, as well as the deployment of control applications on edge devices and cloud platforms.

By combining the strengths of Simulink/MATLAB and CODESYS, we can effectively address the challenges associated with the development of DACS. Simulink/MATLAB provides a powerful environment for modeling, simulation, and code generation, while CODESYS offers a robust platform for PLC programming, communication, and deployment. This integrated approach enables the creation of highly efficient, reliable, and scalable distributed control systems.

OPC UA was integrated to facilitate the development of a distributed control architecture, bridging two distinct automated control systems. The first system, controlling the ship's diesel-electric propulsion plant, was built using Simulink/MATLAB at the equipment layer. This hierarchical control system accepts the desired propeller rotation speed as its primary input. System parameters are determined via mathematical modeling, utilizing classical and optimal control algorithms, to minimize energy losses. The output provides the objective function value, and all parameters are in per-unit (p.u.). A visual representation of the upper-level hierarchical control system for the ship's diesel-electric propulsion plant is shown in Figure 1.

Simulink's Industrial Communication Toolbox offers an OPC UA client, enabling connections to OPC UA servers. This client allows users to monitor server status, explore the server's data structure, read and write real-time data, and retrieve historical data. Historical data is presented as OPC data objects, facilitating analysis. The toolbox provides «OPC UA Read» and «OPC UA Write» blocks for seamless data exchange with OPC UA servers. It should be noted that OPC UA Read & Write blocks are presented since the newest Simulink version – R2024a.

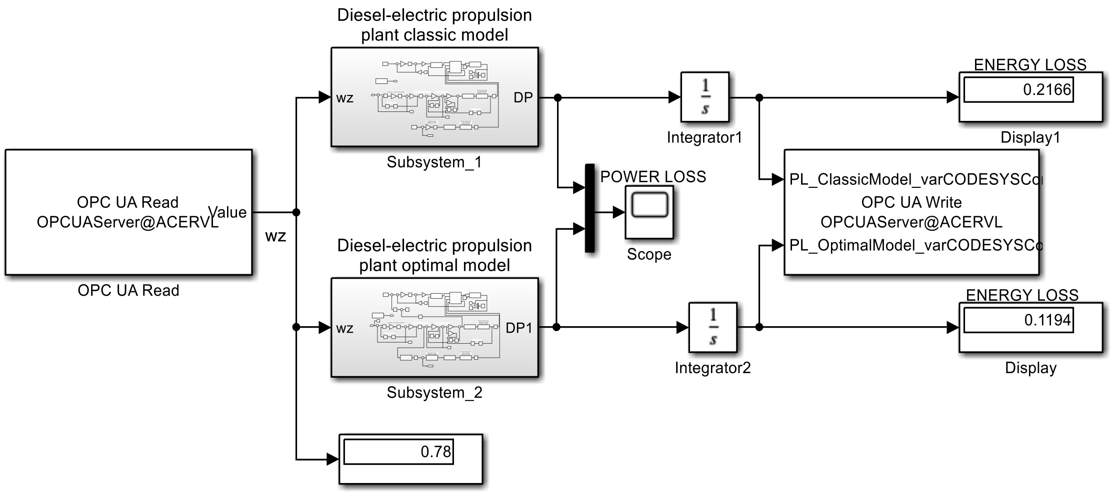

Fig. 1 – The Simulink/MATLAB block diagram illustrating the upper-level structure of the ship's diesel-electric propulsion plant's hierarchical control

To integrate live data from an OPC UA server into a Simulink model, the OPC UA Read block was used in the research. This block reads data from specified server nodes at a set rate, and then organizes that data into a Simulink bus signal. For more comprehensive data analysis, timestamps and quality statuses can be output separately. The block ensures that the data types read from the server are faithfully represented in Simulink, and timestamps are provided in either real or simulation time. The parameters for the OPC UA Read block, as utilized within this investigation, are depicted in Figure 2.

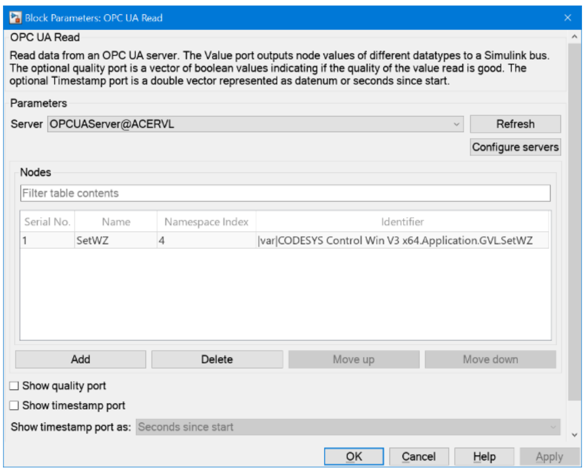

Fig. 2 – The OPC UA Read block parameters used in study

Parameter «Server» contains the OPC UA server name. OPC UA server connection is done via «Configure servers», which opens the «Configuration parameters window». OPC UA server parameters use in the study is shown in Fig. 3.

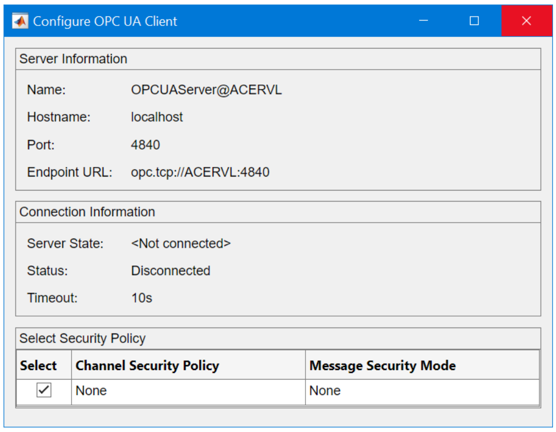

Fig. 3 – OPC UA server parameters

To enable data exchange between an OPC UA client and Simulink, using the OPC UA Read or Write blocks, configuration can be accomplished through two methods: either by adjusting *Model Settings* within the *Modeling* tab, or directly via the *Configure servers* option within the OPC UA Read or Write blocks. Figure 4 depicts configured OPC UA clients for the research model at the *OPC Configuration* pane.

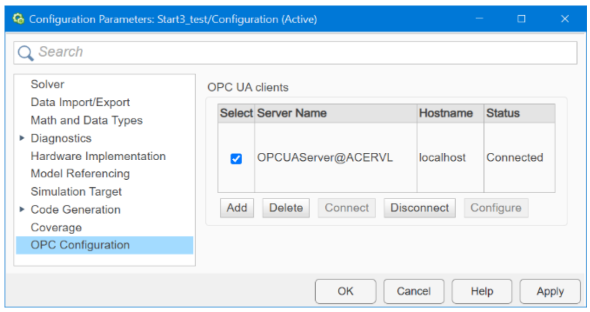

Fig. 4 – OPC UA Client Configuration

Adding an OPC UA Read or OPC UA Write block to a model automatically activates the OPC Configuration pane within the model's Configuration Parameters dialog box, which allows configuring an OPC UA client for a Simulink model.

In the study the desired propeller speed is configurable, either through direct operator input or via a CODESYS project functioning as a higher-level automated controller. To configure variables which is exported to control system in Simulink model, the two CODESYS project components was added in the research.

The first component «Global variable list» (GVL) is optional and creates the global variables to export in Simulink Model; local variables could be also exported. A global variable list is used for the declaration, editing, and display of global variables. The REAL type global variables SetWZ, PL_OptimalModel, PL_ClassicModel were added to the project developed in the study.

The second component «Symbol Configuration» is necessary for this research and was used to create a list of existed variables of the project and setup its access parameters, which was exported to the Simulink model editor (Fig. 5). The work described was performed using a new version of the automation platform with the latest service pack – CODESYS 3.5 SP20 for providing symbols to an OPC UA Server. To download necessary information to the controller the Support OPC UA features ☑ option was applied. The following information is necessary for operating the OPC UA Server: base types of inherited function blocks, contents of attributes that were assigned via compiler pragmas, and variable scopes (VAR_INPUT, VAR_OUTPUT, VAR_IN_OUT).

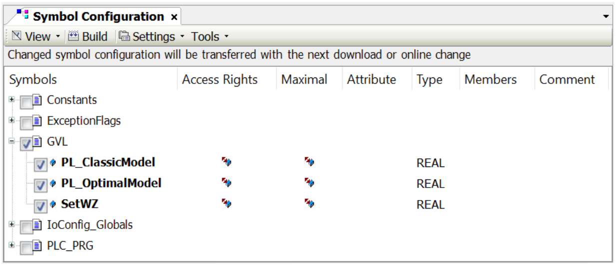

Fig. 5 – CODESYS Project Symbol Configuration

After «Symbol Configuration» had been added, the corresponding variables were added in the Simulink model by clicking the "Add" button in the OPC UA Read/Write block and the appropriate variables under DeviceSet/CODESYS Control Win V3 x64/Resources/Applacation/Global Vars/GVL node were selected (Fig. 6).

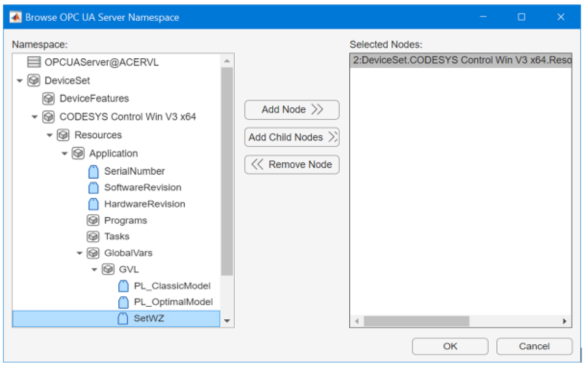

Fig. 6 – Variables selection in Simulink OPC UA Read/Write block namespace browser

Figure 7 illustrates the Human-Machine Interface (HMI) [11, 12] of the higher-level control system of this study, built on the CODESYS automation platform. This interface enables users to modify the desired propeller rotation speed of the ship. Special feature of the designed HMI is 'Donut Gauge' visual HTML5-based control element to monitor current set speed, which is the extension of the standard CODESYS visualization library.

The ship's desired propeller rotation speed is sent to a Simulink-based lower-level control system. Utilizing OPC UA, the resulting control objective function values – representing power loss under both classic and optimal control – are retrieved. These values, converted to energy losses, are then dynamically graphed in real time, allowing for the observation of energy savings in the main power plant.

The experimental setup utilized in this research was an Acer Aspire 5 laptop (Model: A515-44-R5QE) as the central processing unit and data acquisition system. The laptop specifications are as follows:

– Processor: AMD Ryzen 4500U @ 2.3-4.0GHz
– Memory: 8GB DDR4 RAM
– Storage: 256GB NVMe SSD
– Operating System: Windows 10 Pro

The AMD Ryzen 4500U processor provided sufficient computational resources for data processing and analysis, while the 8GB of RAM allowed for efficient multitasking. The NVMe SSD ensured fast data access and system responsiveness. At this experimental setup, the distributed control system has low latency up to 20 ms. In the conditions of scaling of the studied distributed control system within the local network of the Ethernet TCP/IP 1Gbs standard, the delay value estimate will be up to 25 ms, which is acceptable for real-time systems. Monitoring of the system developed in this study over a sufficient period of time (more than 24 hours) revealed no problems in data exchange between subsystems, which shows its sufficient reliability.

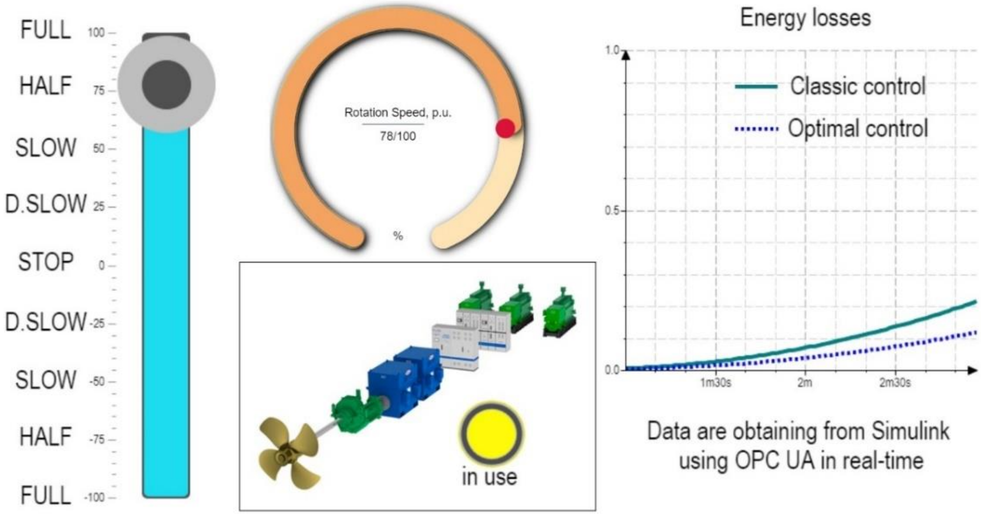

Fig. 7 – The HMI interface for the upper-level control system, developed within the CODESYS automation environment

Conclusions

This research has successfully demonstrated the feasibility and efficiency of integrating two different ship automated control systems through the implementation of OPC UA. The findings confirm the assumption that OPC UA provides a robust and standardized framework for achieving seamless, real-time interoperability between heterogeneous automation platforms, a critical prerequisite for the development of advanced distributed control systems in maritime environments. Specifically, the study has shown that:

1. The implementation of OPC UA facilitated the consistent and low-latency exchange of critical operational data between the integrated systems, ensuring synchronized and responsive control actions. This is essential for maintaining operational safety and efficiency in dynamic maritime scenarios.

2. Enhanced System Interoperability: The adoption of a platform-independent communication protocol like OPC UA significantly reduced the complexities associated with integrating systems from different vendors, thereby promoting greater flexibility and scalability in maritime automation design.

3. The architecture developed in this research, leveraging OPC UA's inherent security and redundancy features, contributes to the enhanced resilience of ship control systems. This is vital for mitigating the risks associated with system failures and ensuring uninterrupted operation in demanding conditions.

4. The successful integration achieved in this study lays a foundation for the implementation of more sophisticated automation functionalities, such as predictive maintenance, remote diagnostics, and autonomous navigation, which are increasingly relevant in the evolution of maritime technology.

5. This research underscores the importance of adopting open standards like OPC UA in maritime automation, fostering a more unified and interoperable ecosystem. Future work should focus on exploring the scalability of this approach for larger and more complex ship systems, as well as investigating the integration of emerging technologies such as artificial intelligence and machine learning within the OPC UA framework.

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ПРОЄКТУВАННЯ РОЗПОДІЛЕНИХ АВТОМАТИЗОВАНИХ СУДНОВИХ СИСТЕМ КЕРУВАННЯ НА БАЗІ ТЕХНОЛОГІЇ OPC UA

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Стаття досліджує застосування технології OPC Unified Architecture (OPC UA) у розробці розподілених автоматизованих систем керування (АСК) на морських суднах. OPC UA є відкритим стандартом, що забезпечує безпечний та масштабований обмін даними між різноманітними промисловими пристроями. Впровадження OPC UA в морській галузі відкриває нові можливості для оптимізації роботи суден, підвищення надійності та зменшення витрат на обслуговування. Завдяки OPC UA можна об'єднати в єдину систему різні датчики, виконавчі механізми, контролери та інші технічні засоби судна, що дозволяє збирати та аналізувати дані в реальному часі. Це, в свою чергу, дає змогу здійснювати дистанційний моніторинг та керування суднами, а також виконувати проактивне технічне обслуговування. До основних переваг використання OPC UA в морській галузі відносять: міжплатформність: забезпечує сумісність різних виробників обладнання; безпека: надійний захист даних завдяки різним механізмам шифрування та аутентифікації; масштабованість: адаптація до систем різного розміру та складності; інтеграція: спрощує об'єднання різних систем автоматизації; надійність: гарантує безперебійну роботу в складних умовах морського середовища. Одним із ключових переваг технології OPC UA є її здатність до інформаційного моделювання, що дозволяє створювати стандартизовані моделі даних для опису фізичних компонентів та процесів на судні. Це спрощує процес проектування та впровадження АСК, зменшуючи ризик помилок. Крім технічних переваг, OPC UA також має економічні переваги. Завдяки спрощенню інтеграції та обслуговування систем, OPC UA може знизити загальну вартість володіння для суднобудівних компаній та судновласників. Крім того, підвищуючи ефективність та надійність експлуатації суден, OPC UA сприяє збільшенню прибутковості. Таким чином, впровадження технології OPC UA в морській галузі є перспективним напрямком розвитку, який дозволяє підвищити рівень автоматизації та інтеграції систем на суднах, забезпечити безпеку та ефективність їхньої експлуатації.

Ключові слова: *OPC UA, розподілені автоматизовані системи керування, морська галузь.*

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