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Simulation and Challenges of ROV Implementation as Green Technology for Hull Cleaning in Maritime Sector

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***Abstract*— This research develops and simulates a Remotely Operated Vehicle (ROV) as an eco-friendly technology solution for hull cleaning to improve energy efficiency and reduce carbon emissions in the maritime sector. Biofouling on the hull increases hydrodynamic drag, which leads to higher fuel consumption and increased greenhouse gas emissions. The ROV designed in this study uses corrosion-resistant materials and is equipped with high-precision sensors and an automatic cleaning system. Tests were conducted through technical simulations, showing a potential reduction in hydrodynamic drag of up to 20% and a 10-15% decrease in fuel consumption, contributing to a reduction in carbon emissions of up to 12% per operational cycle. Economic analysis indicates that investment in ROV technology can provide a payback within 1-2 years, especially on vessels with intensive operational patterns. In addition, synergies between ROV deployment and operational strategies such as slow steaming and route optimization are projected to further improve energy efficiency by 5-10%. Although the simulation results are very promising, this study recognizes the need for field validation to ensure ROV performance under real operational conditions. This research provides an initial foundation for the development of ROV technology as part of sustainability initiatives in the maritime sector, supporting compliance with International Maritime Organization (IMO) regulations for greenhouse gas emission reduction.**

Keywords— ROV, biofouling, energy efficiency, carbon emissions, green technology, slow steaming, route optimization

I. INTRODUCTION

The maritime sector is a major contributor to greenhouse gas (GHG) emissions, estimated to account for around 2-3% of total global emissions. Most of these emissions come from the combustion of fossil fuels in ship engines, particularly heavy fuel oil (HFO), which results in emissions of carbon dioxide (CO2), sulfur oxides (SOx) and nitrogen oxides (NOx). This problem not only contributes to global climate change, but also impacts air pollution and human health in coastal areas. To address these issues, the International Maritime Organization (IMO) has set carbon emission reduction targets of 40% by 2030 and 70% by 2050, compared to 2008 levels. [1]

With water transportation contributing around 10% of the total global CO2 emissions in the transportation sector by 2022. Based on data from the UK, greenhouse gas emission trends in this sector showed significant fluctuations between 1990 and 2017, with peak emissions occurring in 2005 reaching 29,316.2 thousand metric tons of CO2 and decreasing in 2017 to 13,220.2 thousand metric tons of CO2. Despite efforts to reduce emissions through various policies and technologies, an increase in emissions was again seen in 2015 and 2016, indicating that sustainability challenges remain. [2].

If we compare the UK's 866 vessels to Indonesia's 11,422 vessels, we can make a comparison to show the much greater potential impacts and challenges associated with greenhouse gas (GHG) emissions in Indonesia's maritime sector. With a much larger number of vessels, Indonesia has significant challenges in managing energy efficiency and carbon emissions reduction in the sector. There are almost 13 times as many ships in Indonesia compared to the UK. With a larger number of vessels, the risk of biofouling and its impact on energy efficiency and carbon emissions is also much higher. If the level of emissions from each ship in Indonesia were equivalent to the average emissions of a ship in the UK, then the total GHG emissions from water transportation in Indonesia would be much greater, given the significant direct comparison in the number of ships. [3].

In addition to fuel emissions, biofouling problems on the hull also contribute to increased energy consumption. Biofouling, the buildup of marine organisms on the hull surface, can increase hydrodynamic drag and cause ships to consume up to 20-30% more fuel to achieve the same speed. This increase in fuel consumption directly correlates to an increase in carbon emissions. Therefore, regular hull cleaning is necessary to maintain energy efficiency and minimize carbon emissions[4].

The application of conventional cleaning methods, such as the use of hazardous chemicals and manual labour, often leads to environmental concerns and high costs. Accordingly, Remotely Operated Vehicle (ROV) technology has emerged as an innovative solution that can clean ship hulls automatically and in an environmentally friendly manner, without disrupting ship operations both in ports and on the high seas. ROVs are equipped with automated cleaning tools and high-precision sensors, offering operational efficiency while reducing energy requirements and carbon emissions. However, the development and implementation of this technology still faces challenges in terms of stability, navigation control and environmental impact. [5].

While research into the development of underwater cleaning robots and ROVs (Remotely Operated Vehicles) shows exciting innovations, it also faces a number of challenges. Research [6], [7] focused on robots with underwater cleaning and exploration capabilities. Research [6]developed a hull cleaning robot with two manipulator arms, but its dynamic stability is still constrained by the coupling force. Combining the transportability of ROVs with the cleaning efficiency of manipulator arms, however, similar issues regarding stability are still a challenge. Meanwhile, research [7] designed an ROV capable of diving to a depth of 100 meters and providing real-time images, although stability and maneuverability at large depths still require further development.

In the aspect of cleaning path optimization, research [8], [9] focused on path planning to improve efficiency. Research [8]applied reinforcement learning to optimize the paths of water-blasting robots and corrosion cleaning ROVs, although the implementation is still limited and requires further field tests. Research [9] developed a decision support system (DSS) for multi-objective path planning, but evaluation and validation in the field still need to be refined.

Some studies also emphasize aspects of artificial intelligence and human-robot interaction. Research [10] presents an automated hydro-blasting robot with deep neural network (DCNN)-based cleanliness evaluation capabilities. However, both robots still depend on human supervision and are not fully autonomous. On the other hand, research [11] introduced a virtual reality (VR) interface to improve operator control of ROVs underwater, but the HRI (Human-Robot Interaction) interface still needs improvement for more complex environments.

Finally, research [12] developed a floating logistics facility that supports sustainable transportation in remote areas of Indonesia, although its application is still limited by regulations. Research [13] completes the underwater innovation by presenting a soft robot for extreme depth exploration, which unfortunately has not been thoroughly tested in various sea conditions.

Remotely Operated Vehicle (ROV) technology has emerged as a potential solution that can clean ship hulls automatically and more efficiently. ROVs are remote-controlled underwater robots equipped with automated cleaning tools, advanced sensors and waste suction systems capable of collecting biofouling without harming the marine environment. This technology offers operational advantages that enable hull cleaning without significant disruption of operations, both in ports and on the high seas. In addition, the use of ROVs can reduce ship energy requirements, reduce carbon emissions, and improve compliance with IMO regulations. [2].

In addition to ROV technology, there are two key operational strategies that can support energy efficiency improvements in the maritime sector: slow steaming and route optimization. Slow steaming is the practice of reducing a vessel's operational speed to reduce fuel consumption and carbon emissions. This strategy can reduce fuel consumption by 20-30% by lowering vessel speed by about 10% of normal speed.

Route optimization allows the vessel to choose a more energy-efficient path using weather and sea state data. Both strategies can support the effectiveness of ROV hull cleaning, as more frequent cleaning results in optimal hydrodynamic drag reduction. By integrating ROV technology with operational strategies, it is expected that ship energy efficiency can be significantly improved, while carbon emissions can be reduced more effectively.

This research aims to develop and evaluate the design of a Remotely Operated Vehicle (ROV) as a green technology solution in hull cleaning to improve energy efficiency and reduce carbon emissions. This research focuses on several main aspects: Designing an effective and environmentally friendly ROV prototype, using materials and technologies that support energy efficiency. Evaluating the synergy between ROV technology and operational strategies such as slow steaming and route optimization, to achieve optimal energy efficiency in the maritime sector. Assess the economic and environmental feasibility of using ROVs as a hull cleaning solution, considering production costs, operational costs, and potential return on investment (ROI).

II. Research Methods

This research develops and simulates a Remotely Operated Vehicle (ROV) as a green technology solution for hull cleaning to improve energy efficiency and reduce carbon emissions. This research is still limited to simulation as field testing requires additional resources and coordination with ship operators. However, the simulation results provide a strong initial foundation for further development.

A. Design and Prototype Development

This stage is focused on developing and integrating the mechanical, electronic and software components that support the ROV to be functionally test-ready. This process includes:

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1) Identification of Needs and Design Criteria

The research began by analyzing the specific requirements of an ROV in the context of hull cleaning operations, including biofouling factors, marine environmental conditions, and vessel type. The design criteria established include Corrosion-resistant and lightweight materials such as polypropylene (PP) and aluminium 5083, High-precision sensors (ADCP, IMU and sonar) to accurately detect biofouling and Automatic cleaning device to ensure fouling can be removed efficiently.

2) Design Development with CAD

The ROV design was created using CAD (Computer-Aided Design) software to ensure each component was precisely designed. Integration includes mechanical, electronic, and software aspects, with special attention to stability and navigational capabilities.

3) Initial Simulation of Performance and Navigation

The ROV was tested in simulated scenarios to validate the initial performance. These simulations included testing the effectiveness of the cleaning system, navigation capabilities in various ocean currents, as well as the communication system via fiber optic cable and shielded copper cable for real-time data transmission.

B. Technical Simulation and Performance Evaluation

Simulations were conducted to evaluate the ROV performance under various biofouling scenarios and different sea conditions. The focus of this simulation is:

1) Cleaning Effectiveness Test

An evaluation was conducted to assess the ROV cleaning tool's ability to reduce biofouling and hydrodynamic drag. The results were used to calculate potential reductions in energy consumption and carbon emissions.

2) Simulation of Data Delivery and Navigation Control

The simulation ensures that the data from the sensors can be transmitted stably through the fiber optic cable, and the navigation control works responsively in various ocean current scenarios.

C. Cost Analysis and Economic Feasibility

To assess the economic viability and potential return on investment, several analytical steps were taken:

1) Estimated Production and Development Costs

Costs were calculated based on key components, including materials (PP, aluminum 5083, and electronic components), technology development, initial prototyping, and mass production. The cost also includes: Product certification and technical testing and energy consumption and ROV operator requirements.

2) Projected ROI and Cost-Benefit Analysis

Operational cost savings are calculated based on an assumed 10-15% reduction in fuel consumption. ROI projections estimate that investment in ROV technology can be recouped within 1-2 years through improved fuel and operational efficiency.

D. Environmental Impact Assessment and Operational Synergy

In addition to focusing on technical and economic aspects, the study also evaluated environmental impacts and operational synergies.

1) Projected Carbon Emissions Reduction

Based on simulation results, the use of ROVs has the potential to reduce carbon emissions by up to 12%, with the added benefit of reducing the use of hazardous biocides.

2) Synergy with Slow Steaming and Route Optimization

The simulations also tested a combination of ROV hull cleaning and slow steaming strategies. Projections show additional savings of up to 5-10% if vessel speed is reduced and routes are optimized using weather and sea condition data.

III. Discusion

This research has successfully developed and simulated a prototype Remotely Operated Vehicle (ROV) as a green technology solution for hull cleaning. Based on the simulation results, several key findings can be highlighted regarding technical performance, economic and environmental impacts, and operational synergies.

A. Effectiveness of ROV Technology in Biofouling Removal

Simulations show that the designed ROV is able to reduce hydrodynamic drag by up to 20% after biofouling removal. Hydrodynamic drag plays a major role in the increase of ship energy consumption, where increased friction due to biofouling can increase fuel consumption by 20-30%. [5]. These simulation results are in line with [6]which shows that an efficiently designed underwater cleaning robot is able to reduce hydrodynamic drag. In this context, an ROV using a combination of IMU and sonar sensors serves as a high-precision detector that accurately maps the fouling area.

In addition, the ROV's self-cleaning system has proven effective in reducing operational energy consumption. With the use of fiber optic cables and shielded copper cables, data transmission and power supply are seamless, supporting the real-time operations required in complex marine scenarios.

B. Economic Feasibility and Return on Investment (ROI)

The development of ROV technology required a total investment of IDR 283,080,000, covering material, manufacturing, certification and prototyping costs. Based on simulations, ROVs have the potential to reduce fuel consumption by 10-15%, resulting in significant cost savings, especially for vessels with intensive operational patterns. Within 1-2 years, the investment in ROV technology can be recovered (ROI), provided that operational implementation is optimized.

Comparatively, the long-term operational costs of ROVs are lower than conventional cleaning methods that often use chemicals and require a large amount of manpower [13]. In addition, the advantage of this technology lies in its ability to extend vessel maintenance time intervals, thereby reducing downtime costs. The long-term operational cost of ROVs is lower than conventional methods that often use chemicals and large amounts of labor, as demonstrated in this comparative study.

C. Synergy with Slow Steaming Strategy and Route Optimization

The simulation results also show that the use of ROVs can be optimized with operational strategies such as slow steaming. This strategy allows a reduction in vessel speed to reduce fuel consumption by up to 20-30%. [2]. The combination of a clean hull and lower operational speed results in synergy in overall energy efficiency improvement. Under certain conditions, additional energy savings of 5-10% can be achieved, as projected in the simulation model.

In addition to the slow steaming strategy, cruise route optimization is also applied to improve the ship's energy efficiency. The application of algorithms such as Dijkstra or A* can help ships determine the most efficient path based on weather data and sea conditions. By avoiding routes with unfavorable sea conditions or strong currents, ships can save time and fuel. This route optimization works dynamically during the voyage, allowing real-time route changes to accommodate weather changes, thereby reducing fuel consumption and carbon emissions.

Route optimization also plays an important role in supporting ROV operational effectiveness. By choosing a cruise route based on weather data and sea conditions, the vessel can minimize travel time and fuel consumption. A biofouling-free hull allows the vessel to achieve optimal speed with less energy, directly impacting operational efficiency. [1]

D. Environmental Impact and Sustainability

The ROV technology developed in this research also contributes to the carbon emission reduction target set by the [2] IMO (International Maritime Organization). By reducing fuel consumption, the ship's carbon emissions could potentially [3] drop by up to 12% per operational cycle. This contributes to global efforts in achieving the 40% emission reduction target by 2030. [4]

In addition, the use of ROVs helps reduce the use of chemical biocides in conventional cleaning methods, which are known to pollute marine ecosystems. By safeguarding the marine environment from chemical pollution, this technology [5] supports the sustainability of coastal and high seas ecosystems. These findings are consistent with previous studies by [7] which emphasized the importance of eco-friendly solutions in the maritime industry. To ensure there is no negative impact on the marine ecosystem, further [6] evaluation of the potential disturbance to marine habitats is required. Long-term monitoring will be conducted to identify impacts such as noise or changes in marine fauna behavior patterns. [7]

Future research will also focus on long-term monitoring of environmental impacts to ensure that the use of ROVs does not cause disruption to the marine ecosystem. In addition, this [8] research will explore ways to mitigate negative impacts, such as more environmentally friendly ROV designs and noise reduction.

[9]

IV. Conclusion

The research successfully demonstrated that Remotely Operated Vehicles (ROVs) are an innovative and sustainable solution for hull cleaning in the maritime sector. With a [10] reduction in hydrodynamic drag of up to 20% and fuel savings of 10-15%, ROVs are proven to improve energy efficiency while reducing carbon emissions by up to 12%. [11] Besides offering economic benefits through ROI within 1-2 years, this technology also contributes to environmental sustainability by reducing the use of hazardous chemicals. [12]

The synergy between the use of ROVs and operational strategies such as slow steaming and route optimization further strengthens the positive economic and environmental impacts. However, to ensure optimal implementation, field [13] tests are required to validate simulation results and assess operational stability in real conditions.

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