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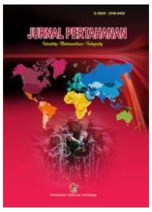

THE BIOMIMETIC FIN PERFORMANCE EVALUATION FOR AN EFFICIENT AUTONOMOUS UNDERWATER VEHICLE (AUV) TO SUPPORT THE REVOLUTION IN MILITARY AFFAIRS (RMA) IN UNDERWATER DEFENSE

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Abstract

The world is facing the global trend of Industry 4.0 in the manufacturing sectors. The concept of the Internet of Underwater Thing (IoUT) presents the trends in the underwater region. The Autonomous Underwater Vehicle (AUV) as a data collector and transmitter becomes the central component in the connected system of the IoUT. The efficiency of the platform is crucial to lengthening the range and duration of the mission. The biomimetic method of utilizing the caudal fin propulsion could enhance the efficiency of the small and low-speed AUV. From the defense perspective, there is a concept of Revolution in Military Affairs (RMA) that supports technological modernization for defense purposes. Technically, this study aims to combine the technical aspects of mechanical engineering and the defense concept of RMA in the technological advancement of AUV for the advanced and efficient defense strategy in the underwater region. The evaluations involved numerical simulation with Computational Fluid Dynamics (CFD) method. The simulation results show that the fully tapered flexible fin enhances the efficiency by 25%, while the narrow flexible fin enhances the efficiency by 30%. These results indicate that a flexible tapered fin should be the primary consideration in designing the high-efficiency biomimetic fin. The visualization of the force vectors shows that the flexibility of the fin acts as a thrust vectoring factor that directs more force vectors in the thrust direction. This study supports the RMA concept implementation by technological modernization, such as efficient biomimetic AUV development, to develop doctrines in the State's defense in the underwater region.

INTRODUCTION

The world is facing the fourth Industrial Revolution with the development of cyber-physical systems (Rojko, 2017). The industrial revolution is famously called Industry 4.0. The characteristics of Industry 4.0 include digitalization, automation and adaptation, human-machine interaction, and advanced internet technology and algorithm. The potential advantages of Industry 4.0 include highly flexible systems, reduction in lead times and cost, and customized small batch size enhance. This phenomenon leads the world to enter the ‘smart’ and automation era.

According to Asian Development Bank (2013), the marine area of Indonesia is about 580 million ha. Indonesia is one of the largest maritime countries in the world. For an archipelagic country like Indonesia, the possible implementation of automation was the concept of the Internet of Underwater Things (IoUT) (Heidemann, Stojanovic, & Zorzi, 2012; Kao, Lin, Wu, & Huang, 2017; Mary et al., 2020). The concept introduced connectivity between underwater objects. The connectivity could enhance the degree of efficiency and effectiveness of the underwater mission. Furthermore, the connectivity should also include the solution to the problem of underwater localization and navigation (González-García et al., 2020). Hence, the development of an intelligent underwater platform such as an Autonomous Underwater Vehicle (AUV) is crucial in the success of the IoUT.

From the technological perspective, an AUV is the prominent and intelligent underwater tool to collect critical underwater data such as biochemical oxygen, pH, conductivity, temperature, and depth. The AUV performed underwater missions with a vehicle speed of generally less than 3.0 m/s (Aguirre, Vargas, Valdés, & Tornero, 2017). Another study by Khalin & Kizilova (2019) stated that the speed range of low-speed AUV is typically from 0.2 m/s to 0.5 m/s. In a low-speed and relatively small underwater vehicle, such as AUV, efficiency is the significant factor to achieve the high-performance range and duration of the underwater mission (Jaya & Kartidjo, 2017, 2019).

One of the ways to improve the efficiency of the AUV is to reduce the controller size and weight of the AUV (Fiester et al., 2019). Other studies suggested that underwater locomotion highly relies on the forces generated by the propeller (Edge et al., 2020; Zhang et al., 2017). The utilization of permanent magnet synchronous motors (Paolucci et al., 2019) and the thrust vectoring ducted propeller in AUV (Xia, Wang, Jin, An, & Ding, 2020) could enhance the reliability and efficiency of the underwater propeller, increasing the overall efficiency of the vehicle.

Another way to enhance the efficiency of the underwater vehicle is by developing a biomimetic AUV (Fish, 2013). Generally, biomimetic AUV utilized fin propulsion that mimics the caudal fin of fishes. In nature, the flexibility of the natural body of the fishes determined the swimming mode of the fishes. Flexible fin should have a better efficient performance than rigid fin (Quinn, Lauder, & Smits, 2015). The development of efficient biomimetic fin propulsion could consider the flexible fin in the initial stage of design. The development of a biomimetic AUV becomes the state-of-the-art of efficient underwater platform in a low-speed regime.

From the defense perspective, the growth of industrial automation could revolutionize the overall defense technology and industries. According to Metz & Kievit (1995), the early military revolution was in terms of the Military-Technical Revolution (MTR) and continues to evolve into a holistic concept of Revolution in Military Affairs (RMA). The RMA characterized the revolutionary change in warfare with three pillars of military technology, doctrine, and organizational reform (Aini & Triantama, 2021; Gray, 2006; Metz & Kievit, 1995). The combination of the pillars in RMA leads to an advanced and efficient defense strategy. Recently, the RMA related to modern technological terms such as stealth, precision, digitization, smart weapons systems, robotics, non-lethality, cyber defense, and nanotechnology (Metz & Kievit, 1995).

The RMA changed the structure, institution, and concept of military preparation of war by involving significant innovations in the combination of doctrine, tactics, and organization (Bitzinger, 2008). Another study by Rafikasari (2021) proposed that technology advancement, in terms of modernization of the primary weapon systems (*Alat Utama Sistem Senjata, Alutsista*), strengthened the defense system and became part of the RMA. Aini & Triantama (2021) provided South Korea as an example country that initiates the RMA through defense reform policies. The study highlighted that South Korea performed the revolution in military technology through modernization rather than any other aspects.

In the field of maritime security, such as in the South China Sea region, Herdijanto, Mulyadi, & Susilo (2019) suggested an RMA concept strategy with six sub-strategy steps to develop Indonesia Armed Forces (*Tentara Nasional Indonesia*, TNI) capabilities in the region. One of the steps was to increase monitoring and detection through the modernization of intelligence technology. Although these studies included the RMA concept to strengthen the defense capability, the relation between the concept and the advanced technical aspect of the intelligence technology that supports the strategy is rarely discussed.

This study aims to combine the technical aspects of mechanical engineering and the defense concept of RMA in the technological advancement of AUV for the advanced and efficient defense strategy in the underwater region. In the present study, the flexible biomimetic fin propulsion characterized the technical aspects of the AUV model. The numerical method of Computational Fluid Dynamics (CFD) evaluated the efficiency of the fin. By varying the geometrical parameters of the fin, such as variable thickness position and fin base thickness, this study analyzed the efficiency performance of the biomimetic fin. This study hypothesized that variable thickness position and fin base thickness affect the efficiency of the fin significantly. An efficient AUV with extended range and duration capability supports the underwater mission of Intelligence, Surveillance, and Reconnaissance (ISR). The efficient AUV reflected the implementation of RMA to support the strategic defense strategy and diplomacy in the underwater region.

METHODS

To evaluate the efficiency performance of the flexible biomimetic fin, as the propulsor of the AUV, quantitative research by using numerical simulation was performed in this study. This study utilized the state-of-the-art of numerical simulation of the Computational Fluid Dynamics (CFD) method. The numerical simulation method has several advantages, including lower cost, faster analysis time, completeness of data, and the ability to simulate a complex environment in ideal conditions (Mi & Zhan, 2020; Pourshahbaz et al., 2020; Yang, Ouyang, Zhang, Yu, & Arowo, 2019).

CFD has been shown as the efficient and reliable method in evaluating a comprehensive design of an object surrounded by fluid. A study by Ariffin & Ahmad (2020) highlighted the importance of CFD in synthetic jet product enhancement. Demeke, Asfaw, & Shiferaw (2019) emphasized the utilization of CFD in complex problems of hydraulic engineering. Other studies utilized CFD to analyze the fin performance, such as motion parameters of the biomimetic caudal fin, fin drag force, and variable stiffness of tuna-like fish bodies (Liu, Liu, Xie, Leng, & Li, 2020; Luo, Xiao, Shi, Pan, & Chen, 2020; Piskur, Szymak, Kitowski, & Flis, 2020).

Figure 1 shows the schematic diagram of

the present efficiency performance evaluation. As shown in the figure, the initial stage is the simulation model preparation for the biomimetic AUV. Next, the study should identify the flexibility parameters that affect the efficiency performance of the fin. The parameters consist of the variable thickness position and fin base thickness.

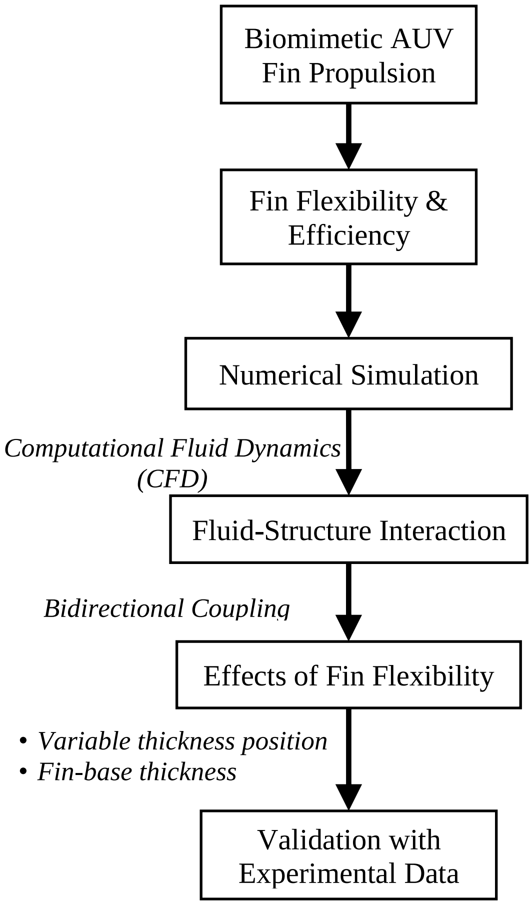

Figure 1. Schematic diagram of the efficiency performance evaluation
Source: Proceed by the Authors, 2021

The efficiency, η, is the ratio between the generated thrust (positive value of the average net-force) to the mechanical power that creates the thrust and can be expressed as:

$$\eta = \frac{\overline{F_{XNet}}}{Q_{Net} \times \omega} \tag{1}$$

$$\eta_{norm} = \frac{\eta}{\eta_{max}} \tag{2}$$

where $\overline{F_{XNet}}$ is the positive average net force, Q_{Net} is the maximum net torque during the fin motion, and ω is the angular velocity of the fin. The simulation results provide these values. The normalized efficiency, η_{norm}, in Equation (2) is the ratio between the efficiency performances in Equation (1) to the maximum value of the efficiency.

The present CFD utilized Fluid-Structure Interaction in terms of bidirectional coupling simulation. The present numerical simulation involved a two-way Fluid-Structure Interaction (FSI) in ANSYS Workbench. The present case of the biomimetic fin motion was considered as a strongly coupled category in which the alteration force by the fluid to the moving structure cannot be neglected. The motion of the biomimetic fin was set up in the Transient Structural system while the fluid analysis was performed in the CFX system (Afanasyeva & Lantsova, 2017; Badshah et al., 2019; Junaidin, 2017). The fin motion was an oscillating motion with a certain degree of amplitude. By considering that flow separation might occur during the interaction between the fin and fluid, this study involved Shear Stress Transport (SST) turbulence model.

The simulation setup of the present study conforms to another research by Khalid et al. (2013). In this study, the modulus elasticity of the fin was fixed at 60 MPa, which was close to the properties of synthetic rubber. As mentioned in the previous passage, two parameters of variable thickness position and fin-base thickness evaluate the effect of flexibility on efficiency performance. Figure 2 shows the generated Biomimetic AUV model with fin propulsion. Figure 2 (a) and Figure 2 (b) present the side and top views of the model, respectively. The model represents the submerged part of the components involved in the previous experimental activities, including dynamometer rod, fixed body, and flexible oscillating fin. Figure 2 (c) shows the generated unstructured mesh in the present simulation. The fluid is water and flowing from the right side of the inlet to the left side of the outlet.

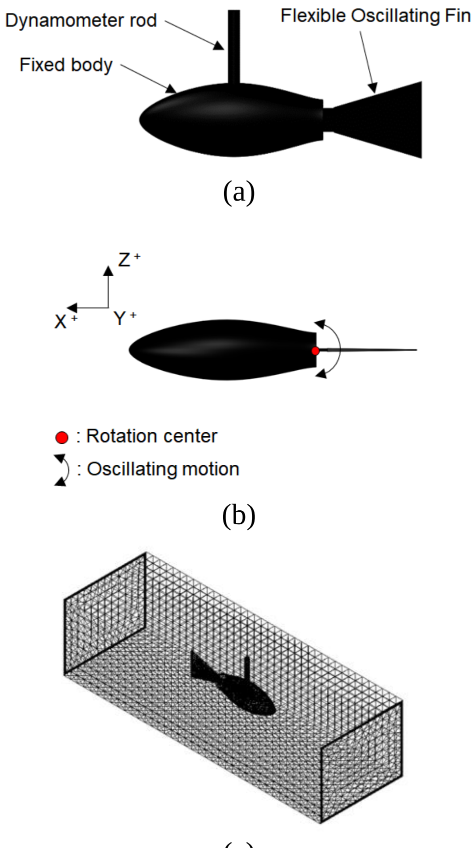

Figure 2. Simulation model of the Biomimetic AUV (a) Side view, (b) Top view, (c) Generated unstructured mesh
Source: Proceed by the Authors, 2021

There were five configurations of the variable thickness position from 0% (fully tapered fin) to 100% (rectangular fin) in intervals of 25% with a similar fin-base thickness of 4 *mm*. The kinematic parameters were fin frequency $f = 1$ *Hz*, flow velocity $V = 0.1$ *m/s*, and fin amplitude $\theta = 10^{\circ}$. The effect of fin-base thickness was divided into five thickness configurations from 4 *mm* to 10 *mm* with a fully tapered fin. The kinematic parameters were $f = 1$ *Hz*, $V = 0.1$ *m/s*, and $\theta = 10^{\circ}$. The previously obtained experimental data in a water tunnel facility validated the present simulation results.

RESULT AND DISCUSSION

Biomimetic Fin Performance

This section describes the results of the present study. Figure 3 shows the detailed visualization results of the CFD simulation. Figure 3 (a) presents the contour map visualization of the generated force in the fin surface. The color bar indicates that the red color region generates a higher thrust than the blue color region. Therefore, as shown in the figure, a higher thrust is generated at the rear part region of the fin surface.

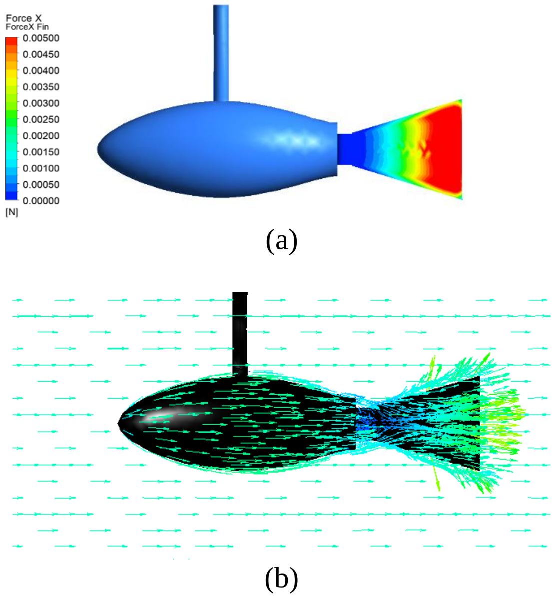

Figure 3. Visualization results of the CFD simulation (a) Contour map of thrust, (b) Velocity vector of the flow
Source: Proceed by the Authors, 2021

The result indicates that about 30% of the rear-fin surface contributes significantly to the thrust generation of the fin. Since the rear-fin surface is the most flexible part of the fin, the flexibility acts as the thrust vectoring that directs more thrust in the thrust direction. Since the generated force could be related to the momentum transfer in the interaction of the fluid and model, the velocity vectors of the flow could represent the generated thrust vectors, as shown in Figure 3 (b). The figure shows a significant divergent pattern of the vectors at the rear-fin surface. Since more vectors deviate from the thrust direction, the fin could suffer a low thrust generation and efficiency.

Figure 4 shows the quantitative simulation result of the effect of the variable thickness position on the normalized efficiency. The result indicates that the flexible fin with a rectangular cross-section (100% fin length) has the lowest normalized efficiency than the tapered flexible fins. On the other side, a fully tapered fin (0% variable thickness position) achieves the maximum normalized efficiency. A fully tapered fin enhances efficiency performance by 25% compared to the non-tapered fin. Therefore, a fully tapered flexible fin should be the primary consideration in designing the high-efficiency biomimetic fin propulsion.

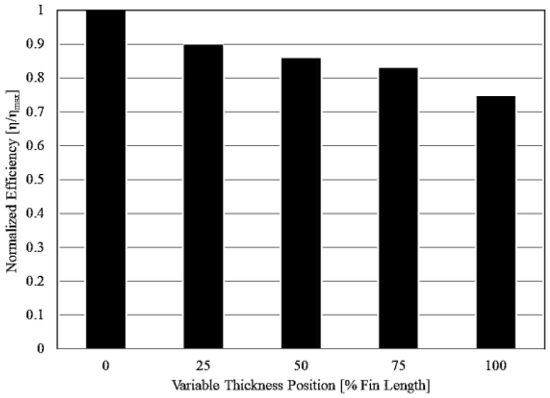

Figure 4. Effect of variable thickness position on the normalized efficiency
Source: Proceed by the Authors, 2021

Figure 5 shows the effect of the fin-base thickness on the thrust generation efficiency. With the present simulation setup, narrow fin-base thickness enhances the normalized efficiency value. There is an increasing about 30% of the efficiency by reducing the fin-base thickness. Since the narrow fin-base thickness represents a higher degree of fin flexibility, the result indicates that flexible fin enhances the efficiency of the biomimetic fin. The result supports the proposed advantage of the flexibility of the biomimetic fin in a low-speed regime by other studies such as Jaya & Kartidjo (2019), Liu et al. (2020), Pfeil et al. (2020), and Shi, Li, & Xiao (2019). However, since this study is only limited to a single value of modulus elasticity, the value of efficiency enhancement could be different at varying modulus of elasticity.

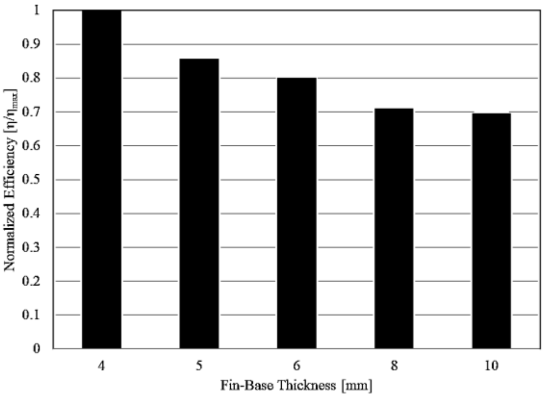

Figure 5. Effect of the fin-base thickness to the normalized efficiency
Source: Proceed by the Authors, 2021

Figure 6 shows the effect of fin-base thickness on the thrust generation of the tapered fin. The narrow fin-base thickness creates a more flexible fin, as shown in the top image, while the bottom image shows a more rigid fin by the wider fin-base thickness. The thrust vector visualization indicates that the flexible fin generates a higher thrust vector than the rigid fin. The figure shows that the flexible fin directs more vectors in the thrust direction, thus acting as a thrust vectoring factor.

Figure 6. Comparison of the thrust vector at the flexible fin (top) and rigid fin (bottom)
Source: Proceed by the Authors, 2021

Table 1. Summary of experimental validation

Parameter	Exp.	Sim.	Diff.[%]
Avg. Thrust [N]	0.058	0.061	4.6
Avg. Torque	0.054	0.053	2.5
Efficiency, η [%]	15.42	16.54	7.3

Exp.: Experiment
Sim.: Simulation
Diff.: Difference.

Source: Proceed by the Authors, 2021

Table 1 presents the average values of the thrust, torque, and efficiency during a single periodic motion of the fin. With a difference of less than 10% between simulation and experiment, the present result is comparable with (Khalid et al., 2013). This study shows that the CFD method could support further efficiency performance optimization of the biomimetic AUV.

Biomimetic Fin and RMA

Military technology is one of the pillars of the Revolution in Military Affairs (RMA) in modern warfare (Aini & Triantama, 2021; Gray, 2006; Metz & Kievit, 1995). The recent terms of unmanned systems and unmanned vehicles have a strong relationship with the modern revolutionary change in RMA as has been stated in Metz & Kievit (1995). In the maritime field, the operation of unmanned vehicles has been extended to the underwater region by the presence of Unmanned Underwater Vehicle (UUV) and Autonomous Underwater Vehicle (AUV). Many countries have been developed and manufactured these kinds of advanced vehicles, including the United States of America with Echo Voyager by Boeing Phantom Works and MRUUVS (Mission Reconfigurable UUV System) by Lockheed Martin, the United Kingdom with Talisman by BAE Systems, Norway with HUGIN and Remus 600 by Kongsberg Maritime, Germany with ATLAS SeaFox MK II by ATLAS Elektronik, and other countries such as Japan and China (Heo, Kim, & Kwon, 2017). Since the vehicles have been utilized for military operations such as Intelligence, Surveillance, and Reconnaissance (ISR), mine countermeasure (MCM), and anti-submarine warfare (ASW), this technology should be considered as the embodiment of the RMA concept for defense purposes in the underwater region.

For archipelagic countries such as Indonesia, most potential threats might come from the sea (Santosa, Budiarto, & Azhari, 2021). The potential threats might include Chemical, Biological, Radiological, and Nuclear (CBRN). These potential treats should be fully monitored for national security. Therefore, due to its functionality, it is crucial to develop and build the AUV technology as one of the future primary weapon systems (*Alat Utama Sistem Senjata, Alutsista*) to prevent potential threats from the sea. Despite its strategic function, this technology is relatively hard to acquire due to the complex nature of its technical aspect, not to mention the legal issues as stated in Nainggolan (2018).

The present research should bridge the gap between the technical aspects of the AUV with the concept of technological modernization in RMA to promote an efficient defense strategy in the underwater region. Since the AUV mission is mainly performed in a low-speed regime, efficient underwater propulsion should be developed to lengthen the range and duration of the mission. This study, along with previous related studies by Jaya & Kartidjo (2017) and Jaya & Kartidjo (2019), suggests the utilization of biomimetic fin propulsion as the efficient low-speed underwater propulsion for AUV. The present numerical simulation with the CFD method shows that a flexible biomimetic fin with a fully tapered shape and low fin base thickness allows the creation of efficient propulsion for AUV in a low-speed regime.

From the defense perspective, this study encourages the establishment of a particular research laboratory and the industrial-scale production of the AUV for military purposes. Furthermore, the collaboration between government, academic institutions, defense industries, and Indonesia Armed Forces (*Tentara Nasional Indonesia*, TNI) should be essential to consider the RMA concept to direct the technical, tactical, and strategical aspects in developing doctrines in the State's defense in the underwater region.

CONCLUSIONS, RECOMMENDATIONS, AND LIMITATIONS

Numerical simulation in the present study shows that the flexibility properties of the fin affect the thrust generation efficiency performance of the biomimetic fin. The variable fin base position and fin-base thickness parameters affect the flexibility of the fin. Flexible biomimetic fin enhances the efficiency performance of the biomimetic Autonomous Underwater Vehicle (AUV). Moderate fin-base thickness with a tapered shape should be the primary configuration of the high-efficiency biomimetic fin. Higher efficiency of the biomimetic AUV should enhance the range and duration of the underwater mission. For the design and development of the AUV, the numerical simulation with the Computational Fluid Dynamics (CFD) method could be a beneficial tool to obtain more detailed flow physics information, such as in the fluid-structure interaction. An efficient AUV is an embodiment of the Revolution in Military Affairs (RMA) concept in the field of underwater defense.

This study urges the development of AUV for defense purposes. The AUV should be able to be mass-produced on a defense industrial scale. The benefits of AUV in support the defense and security task in anticipating attacks of Chemical, Biological, Radiological, and Nuclear (CBRN) weapons through the underwater region. Furthermore, the AUV has the capability in monitoring territorial issues such as illegal fishing, trafficking, piracy, and the movement of manned or unmanned underwater vehicles. The RMA should direct the technical, tactical, and strategical aspects in developing doctrines in the State's defense through technological modernization especially in defense in the underwater region.

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