

Artificial Intelligence and Maritime Governance: Policy Challenges in Combating Illegal Fishing in the Natuna Exclusive Economic Zone

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Abstract

The Natuna Exclusive Economic Zone (EEZ) is one of Indonesia's most strategic maritime areas, facing persistent threats from illegal, unreported, and unregulated (IUU) fishing that undermine national sovereignty, food security, and marine sustainability. Conventional maritime patrols have proven inadequate due to limited resources, adverse weather, and the vastness of the region. This study explores the role of artificial intelligence (AI) in strengthening maritime governance, with particular attention to policy challenges in addressing IUU fishing in the Natuna EEZ. Using a qualitative-analytical case study approach, the research identifies major issues such as inter-agency coordination, legal recognition of digital evidence, and community participation in surveillance efforts. The findings show that AI can enhance maritime monitoring through multisensor data integration, trajectory prediction, and anomaly detection in vessel movements. However, the effectiveness of AI systems depends on institutional interoperability, legal adaptation, and inclusive governance mechanisms. The study concludes that AI integration in maritime governance represents a multidimensional reform rather than a purely technical advancement. It bridges technology, law, and environmental management, positioning AI as a strategic instrument to safeguard Indonesia's maritime sovereignty and strengthen its contribution to Indo-Pacific security cooperation.

Keywords: Artificial Intelligence, Maritime Governance, Illegal Fishing, Natuna Exclusive Economic Zone, Policy Challenges, Maritime Security, Sustainability.

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INTRODUCTION

The Natuna Exclusive Economic Zone (EEZ) stands as a vital maritime frontier for Indonesia, combining significant economic prospects with exposure to transnational security threats. Positioned at the edge of the South China Sea, Natuna not only serves as a zone of geopolitical rivalry but also faces persistent challenges such as piracy and IUU fishing. Traditional approaches that depend largely on naval patrols have reached a point of declining effectiveness, underscoring the urgency of integrating artificial intelligence (AI) as a key instrument for maritime governance and national security.

AI has transformed both industry and defense sectors by enabling large-scale data processing, anomaly recognition, and predictive modeling. Within the maritime sphere, these capabilities facilitate surveillance systems that can detect unusual navigation routes, monitor vessels operating without AIS signals, and anticipate illegal vessel paths using combined real-time and historical data from AIS, satellites, and underwater sensors (Munim et al., 2020). For Natuna, a region characterized by vast territorial waters and limited infrastructure, such semi-automated systems are highly relevant to strengthen governance mechanisms.

The broader maritime industry is already undergoing a digital transformation, with AI, sensor integration, and autonomous platforms becoming core tools for enhancing efficiency and security (Ichimura et al., 2022). For Indonesia, the adoption of these innovations in strategic zones such as Natuna is not optional but necessary, especially given regional tensions and ecological pressures.

One of AI's main contributions is its resilience under operational constraints. Unlike conventional patrols limited by vessel availability, sea conditions, and weather disturbances, AI platforms can synthesize information from radar, acoustic devices, and drones to generate a real-time situational overview (Thombre et al., 2022). This ability ensures early recognition of vessels disabling tracking systems or maneuvering in unauthorized routes.

Trajectory prediction is another core aspect of AI-based maritime governance. Murray and Perera (2020) proposed a dual linear autoencoder that analyzes historical AIS data to project vessel movements. Their method is able to highlight deviations from standard shipping lanes and thereby signal possible infractions (Murray & Perera, 2020). Such predictive capacity is particularly important in Natuna, where foreign vessels often deviate from regulated navigation corridors.

Nevertheless, the value of AI is not determined by algorithms alone. Effective maritime governance requires human-AI collaboration. The "human-in-the-loop" configuration emphasizes the role of human oversight, allowing operators to evaluate machine outputs, contextualize



ambiguous readings, and ensure decisions remain consistent with legal and ethical frameworks (Grønsund & Aanestad, 2020). Complementarily, systems must be designed with transparency and human-centered interfaces to guarantee operational trust and accountability (Veitch & Alsos, 2022). For Indonesia, this translates into investing in training for maritime personnel who must not only master AI tools but also understand their implications within national and international law.

Environmental conditions further complicate governance efforts. Research shows that marine pollution and ecological variability can distort sensor accuracy and affect AI reliability (Siddiqua et al., 2022). For Natuna, this means that digital surveillance systems must be adaptable to fluctuating oceanic conditions and resilient to disturbances caused by human activities.

Institutional integration is equally essential. Liu (2022) demonstrated that high-tech surveillance cannot succeed without coordination across state and non-state stakeholders, effective policy oversight, and enforcement guarantees. Applied to Indonesia, this necessitates cohesive collaboration among the Navy, Bakamla, the Ministry of Marine Affairs and Fisheries, and other agencies under a unified data-driven framework.

Data management also plays a central role. Inconsistent, insecure, or fragmented datasets undermine digital systems (Sánchez-González et al., 2019). Hence, the foundation of Indonesia's AI-enabled governance must include a robust national maritime data infrastructure that ensures secure, standardized, and real-time information exchange.

Moreover, AI provides operational advantages under extreme conditions. Smart sensor-based systems maintain detection reliability during poor visibility, such as storms or heavy fog, conditions under which conventional patrols are hindered (Ranyal et al., 2022). Given the volatile maritime environment of Natuna, this capability supports continuous surveillance essential for governance and law enforcement.

Failure to modernize Indonesia's maritime governance structure with advanced digital systems risks widening the technological gap with neighboring states that have already begun AI integration (Munim et al., 2020). This imbalance could weaken national sovereignty enforcement and allow external actors to exploit Indonesia's vulnerabilities in Natuna.

Beyond economic losses from IUU fishing, environmental degradation accelerates when enforcement mechanisms fail to address ecological pressures. AI-enabled systems, therefore, must also be aligned with conservation policies, acting not only as deterrence tools but as preventive mechanisms to safeguard marine ecosystems (Siddiqua et al., 2022).

To achieve robust maritime domain awareness, AI must integrate multidimensional



datasets into a framework that allows human auditing while ensuring automation (Thombre et al., 2022). This dual structure—automation with accountability—addresses the dynamic and adaptive nature of illegal maritime activities.

Institutional readiness remains the linchpin. Liu (2022) stresses that inter-agency collaboration, legal clarity, and policy coherence determine the extent to which technology enhances governance. For Indonesia, building a cooperative structure that shares responsibility among agencies is vital to ensure accountability and transparency.

Human capital development is the final but most critical pillar. Operators and policymakers must be well-trained to operate AI tools, manage cyber risks, and interpret outputs accurately (Veitch & Alsos, 2022). With adequately prepared human resources, Indonesia's maritime governance can leverage AI not only to detect threats but also to enforce sovereignty with agility.

Ultimately, integrating AI into the governance of the Natuna EEZ supports the creation of a centralized maritime command and control framework. Such a system would enable simultaneous monitoring, analysis, and operational direction, aligning Indonesia with global trends in maritime digitalization (Ichimura et al., 2022). By combining technology, law, institutional coordination, and environmental awareness, Indonesia can establish an adaptive and sustainable maritime governance model. This approach ensures that Natuna is not only secured from illegal fishing but also strengthened as a cornerstone of Indonesia's sovereignty in the Indo-Pacific region.

METHODOLOGY

This study employs a qualitative-analytical case study approach to investigate the governance and policy dimensions of artificial intelligence (AI) implementation in combating illegal, unreported, and unregulated (IUU) fishing in Indonesia's Natuna Exclusive Economic Zone (EEZ). The qualitative nature of this research enables an in-depth interpretation of institutional processes, legal frameworks, and technological transformations that shape maritime governance. The analytical orientation complements this by synthesizing multidisciplinary perspectives—ranging from maritime law and environmental studies to defense technology—allowing for a holistic understanding of AI as both a strategic and policy instrument (Liu, 2022).

The qualitative approach is chosen to capture the complexity of maritime governance, where conventional quantitative models often fail to address the interplay between political, ecological, and legal factors. In Natuna, where sovereignty issues intersect with technological modernization, qualitative inquiry allows the researcher to analyze how state and non-state actors



interpret and adapt to AI-driven surveillance systems. Through thematic analysis, patterns are identified around interoperability between institutions, legitimacy of digital evidence, and ethical challenges in human-machine collaboration (Veitch & Alsos, 2022).

The case study design focuses specifically on the Natuna EEZ because it represents both a geopolitical hotspot and a testing ground for Indonesia's maritime governance reforms. This method allows an in-depth contextual exploration of how AI technologies—such as predictive vessel tracking, satellite imagery, and autonomous surveillance—are integrated into national law enforcement mechanisms (Murray & Perera, 2020). The Natuna case also reflects broader regional dynamics in the South China Sea, providing comparative insights into how technology and diplomacy interact in contested maritime zones (Son, 2023).

Data for this study derive from secondary sources, including peer-reviewed journals (Q1–Q2), international legal conventions, and institutional reports. Analytical synthesis is used to connect technical findings, such as AI-based detection systems (Thombre et al., 2022), with governance concerns such as transparency and accountability (Grønsund & Aanestad, 2020). This method ensures a systematic interpretation of how AI influences legal recognition, policy coherence, and operational decision-making in maritime governance.

To ensure analytical validity, triangulation is applied by cross-verifying insights from legal, technical, and policy sources. The study uses interpretive reasoning to explain how AI challenges traditional surveillance paradigms and promotes adaptive policy mechanisms (Chen et al., 2023). Reflexivity is maintained throughout to ensure transparency and ethical integrity, particularly given the strategic sensitivity of maritime security issues.

Ultimately, the qualitative-analytical case study approach offers both methodological flexibility and policy relevance. It bridges theoretical and practical domains by revealing how AI transforms governance structures while demanding new legal, ethical, and institutional frameworks. In the context of the Natuna EEZ, this methodology provides a nuanced lens to understand AI not merely as a technological advancement but as a governance evolution that redefines maritime sovereignty, sustainability, and regional stability (Brennan & Germond, 2024).

GEOPOLITICAL CONTEXT OF NATUNA EEZ

The Natuna region occupies a unique position in the geopolitical architecture of Southeast Asia. Bordering the South China Sea, it not only serves as a gateway to international maritime trade but also exists within a contested space where multiple regional powers assert overlapping claims. This reality places Indonesia in a delicate situation—although it does not claim sovereignty



in the disputed islands of the South China Sea, its EEZ around Natuna intersects with China's so-called "nine-dash line." Consequently, foreign vessels frequently enter Natuna's waters, often engaging in illegal fishing activities that directly undermine Indonesia's sovereignty and resource sustainability.

AI becomes particularly valuable in this context because it offers a means to strengthen surveillance capacity without provoking escalation. Through the integration of thermal and polarimetric imagery, for instance, AI-based systems can identify vessels even under conditions of low visibility or extreme weather. Trongtirakul et al. (2023) demonstrated the effectiveness of AI in analyzing thermal imagery for detecting oil spills, highlighting that similar techniques can be repurposed to monitor unauthorized vessel activity. This suggests that AI is not only a technological asset but also a diplomatic tool—enabling Indonesia to assert its sovereignty without resorting to overt military measures.

Moreover, AI can address the problem of stateless vessels that exploit gaps in international maritime law. As Coventry (2023) argues, such vessels operate beyond effective jurisdiction by taking advantage of legal loopholes on the high seas. In Natuna, AI systems that integrate global vessel databases with real-time surveillance could provide critical information on vessel ownership, registration status, and operational patterns, thereby supporting lawful enforcement. This combination of technical detection and legal intelligence ensures that enforcement actions remain aligned with international norms, while also improving Indonesia's capacity to prosecute offenders.

THE ROLE OF ARTIFICIAL INTELLIGENCE IN THREAT DETECTION AND PREDICTION

Artificial intelligence provides a wide spectrum of capabilities that can significantly strengthen maritime governance in Natuna. One of its central advantages is its ability to process and synthesize complex datasets collected from diverse sources, including satellite imagery, sonar systems, drones, and the Automatic Identification System (AIS). In a region like Natuna, where the sheer size of the maritime domain makes continuous human surveillance nearly impossible, AI becomes an indispensable instrument for establishing early warning mechanisms.

A prominent function of AI is anomaly detection. By analyzing navigation data, AI systems can recognize vessels that deviate from established shipping lanes or those that intentionally switch off AIS transmitters. These "dark ships" are frequently associated with illegal fishing, smuggling, or piracy. Murray and Perera (2020) presented an advanced approach using a dual linear autoencoder to predict vessel trajectories. Their model demonstrates that deviations from



expected courses can be accurately detected, thereby providing an early indication of potential violations. In Natuna, this predictive capability is particularly valuable since foreign vessels often disguise their presence by modifying their navigation paths.

In addition to AIS-based surveillance, AI can also harness non-traditional data inputs. For example, Jang et al. (2022) introduced a vibration and motor noise analysis technique designed to detect anomalies in ship engines. Applied in a maritime security context, such acoustic and vibration data could serve as a vessel's unique mechanical "fingerprint." By incorporating this method, AI systems would be capable of identifying vessels even when they attempt to hide their identity by falsifying AIS information.

AI also excels in enhancing situational awareness under conditions that traditionally impair human observation. In the waters surrounding Natuna, weather conditions such as thick fog, tropical storms, and strong currents frequently hinder visibility. Thombre et al. (2022) emphasized that integrating sensors with AI algorithms creates an autonomous situational awareness framework capable of fusing data from multiple sources, including radar and sonar. Similarly, Zhao et al. (2023) demonstrated the application of SAR imagery processed through the LPDNet model, which can filter out oceanic noise and improve vessel detection during adverse weather. These innovations ensure that monitoring systems remain functional regardless of environmental conditions, thus bridging one of the major weaknesses of conventional patrol methods.

Another dimension is the prediction of ecological and resource-driven risks. Brennan and Germond (2024) illustrated how climate change contributes to the shifting migration of fish stocks, which in turn influences the occurrence of IUU fishing. In Natuna, AI systems could be designed to incorporate environmental variables such as sea surface temperature and chlorophyll concentrations, enabling predictions of fish movements. This would allow authorities to anticipate cross-boundary fishing pressures and potential disputes before they escalate.

Equally important is AI's role in detecting threats beyond fishing violations. Choi (2023) highlighted how sand mining activities in South Korea's EEZ created environmental degradation and security tensions. In the Natuna EEZ, AI systems could employ real-time bathymetric imaging to monitor seabed changes and identify illegal extraction activities. Escalle et al. (2023) and Moreno et al. (2023) also underscored the importance of monitoring fish aggregating devices (FADs). AI combined with satellite imagery could automatically detect the spread of unregistered FADs, many of which are environmentally destructive. Integrating such capabilities ensures that surveillance does not remain narrowly focused on sovereignty but also supports long-term marine ecosystem governance.



Finally, the integration of AI into risk prediction must also address human rights concerns. Selig et al. (2022) demonstrated that IUU fishing is often linked to exploitative labor practices, including forced labor and human trafficking. AI systems capable of analyzing vessel port calls, refueling patterns, and crew deployment cycles could provide indicators of exploitative practices hidden within maritime supply chains. Thus, AI contributes not only to securing marine resources but also to addressing broader governance issues related to human rights and international labor standards.

LEGAL AND POLICY DIMENSIONS OF AI INTEGRATION

While AI presents transformative opportunities, its successful adoption in maritime governance is heavily dependent on the legal and institutional environment. The use of AI-generated evidence, coordination among national agencies, and alignment with international law are pivotal for ensuring that technological innovation translates into enforceable outcomes.

First, the question of digital evidence recognition is fundamental. As Khobragade et al. (2021) noted in their analysis of anti-piracy laws in India and Malaysia, the admissibility of digital records is often contested in court due to gaps in legal frameworks. For Indonesia, similar challenges may arise if data collected from AI—such as radar images or sonar-based recordings—is not recognized as valid legal proof. Without legislative adaptation, the enforcement of maritime law in Natuna would remain incomplete despite sophisticated surveillance. This indicates the urgent need to revise national legislation such as the Fisheries Law and Information and Electronic Transactions Law to explicitly acknowledge the legitimacy of AI-derived digital evidence.

Second, governance of IUU fishing in disputed maritime spaces introduces an additional legal layer. Chen, Xu, and Li (2023) emphasized that maritime disputes do not exempt states from their international obligations to combat IUU fishing. This perspective reinforces the responsibility of Indonesia to deploy AI surveillance systems in Natuna even amid overlapping claims with China. By integrating vessel data with international databases like the FAO vessel registry or Interpol's Ocean Monitoring Network, Indonesia can ensure that its enforcement actions are legally defensible under international law.

Third, policy coherence across agencies is critical. Liu (2022), in his study of China's sulfur emission monitoring, highlighted the necessity of multi-sectoral oversight to support technological implementation. Applying this to Natuna, coordination between the Indonesian Navy, Bakamla, Ministry of Marine Affairs and Fisheries, and local authorities is essential to avoid fragmented surveillance. An integrated AI framework must therefore be embedded within an



institutional ecosystem that supports data sharing, collective accountability, and synchronized enforcement.

The legal and policy challenge is also intertwined with transparency in AI systems. Van de Merwe et al. (2024) argued that the effectiveness of autonomous systems depends on operator trust, which is strengthened through transparent and explainable decision-making models. In maritime governance, explainable AI is indispensable for ensuring that enforcement officers, courts, and policymakers understand the rationale behind system-generated alerts. Without transparency, AI risks being rejected as unreliable or even politically contentious, especially in disputed maritime zones.

Furthermore, policy innovation should be oriented towards preventive rather than reactive enforcement. Burmeister and Constapel (2021) stressed that autonomous collision avoidance systems must adhere to COLREGs, the international regulations for preventing collisions at sea. For Natuna, embedding such compliance into AI navigation systems ensures that Indonesian enforcement remains consistent with international maritime norms, thus avoiding unnecessary escalation with foreign vessels.

The importance of aligning AI policies with broader governance frameworks extends to sustainability as well. Oloruntobi et al. (2023) noted that the transition towards green shipping faces hurdles of policy harmonization and infrastructure readiness. For Indonesia, adopting AI for surveillance in Natuna must be integrated with sustainable practices to ensure that governance not only addresses illegal activity but also contributes to global maritime environmental standards.

ENVIRONMENTAL AND SUSTAINABILITY CONSIDERATIONS IN AI GOVERNANCE

Maritime governance in the Natuna EEZ cannot be separated from ecological concerns. IUU fishing not only undermines Indonesia's economic sovereignty but also intensifies ecological degradation by depleting fish stocks and disrupting marine habitats. An AI-based surveillance system, therefore, must not merely serve as a security instrument but also function as an ecological monitoring tool that supports sustainable governance.

The maritime environment poses unique challenges to digital surveillance. Siddiqua et al. (2022) demonstrated that environmental pollution, such as waste and chemical runoff, interferes with sensor accuracy and data collection. In Natuna, where industrial and fishing activities intersect with fragile ecosystems, AI systems must be resilient to such disturbances. Autocalibration mechanisms and adaptive algorithms are essential to filter out "noise" created by



marine debris or pollutants, ensuring that threat signals remain distinguishable. Perumal et al. (2021) further emphasized that debris distribution on coastlines and seabeds is uneven, complicating detection. AI trained on underwater imaging could classify and map debris patterns, thereby supporting both navigational safety and conservation efforts.

Sustainability also extends to monitoring destructive practices like sand mining. Choi (2023) highlighted how unregulated sand extraction in South Korea's EEZ caused both ecological harm and governance tensions. Similar activities in Natuna waters could erode seabed structures, destabilize ecosystems, and escalate into disputes. AI-enabled bathymetric monitoring systems can detect seabed morphology changes in real time, offering evidence-based governance tools. Another pressing ecological concern relates to the use of fish aggregating devices (FADs). Escalle et al. (2023) revealed that conventional drifting FADs, often constructed from non-biodegradable materials, are harmful to marine species and lead to entanglement of protected wildlife. Moreno et al. (2023) proposed biodegradable alternatives such as the Jelly-FAD, representing an ecological innovation that could be combined with AI tracking. By monitoring the presence and movement of FADs via satellite imagery, AI systems can assist authorities in ensuring compliance while also supporting international commitments to marine biodiversity.

The significance of ecosystem monitoring is further reinforced by discoveries of vulnerable species in less observed waters. Harris et al. (2024) documented the presence of several rare *Mobula* ray species in the Chagos Archipelago, emphasizing that tropical ecosystems harbor uncharted biodiversity. Given Natuna's similar ecological conditions, AI systems could integrate environmental DNA (eDNA) inputs to identify and track species distribution. Such integration would allow Indonesia not only to monitor illegal fishing but also to protect habitats critical to global biodiversity, positioning Natuna as a center of conservation diplomacy.

Finally, AI applications must incorporate long-term sustainability into design and operation. Shadman et al. (2023), in their study of offshore renewable energy in South America, argued that the resilience of energy and monitoring systems depends on the integration of environmental, technological, and socio-economic planning. For Natuna, this means that AI should be embedded in a governance model that simultaneously addresses ecological resilience, maritime security, and sustainable economic development.

REGIONAL AND GLOBAL IMPLICATIONS

The governance of Natuna's EEZ through AI-based systems has implications that extend beyond Indonesia's borders. Situated in the Indo-Pacific, Natuna occupies a strategic space within



regional maritime politics. As Son (2023) observed, Vietnam has already adopted constabulary maritime strategies, including “paragunboat diplomacy,” to assert claims in contested waters without provoking military escalation. Indonesia, with its independent and active foreign policy, can adopt a similar strategy by enhancing Bakamla and coast guard capabilities through AI integration. This reinforces sovereignty while minimizing the risk of conflict escalation.

At the same time, piracy and transnational crime remain persistent challenges in Southeast Asian waters. He et al. (2023) demonstrated that piracy risk correlates strongly with traffic density and weak legal infrastructures. AI-enabled risk modeling in Natuna can help Indonesia anticipate piracy hotspots by analyzing not only traffic patterns but also socio-economic conditions that drive maritime crime. Such predictive governance would enable preventive diplomacy and coordinated law enforcement in the broader region.

Satellite technologies also play a critical role in regional security. Thangavel et al. (2023) introduced the concept of distributed satellite systems (DSS), which expand surveillance coverage by combining multiple orbital baselines. For Natuna, deploying DSS integrated with AI offers both technical superiority and diplomatic leverage, as Indonesia could share surveillance data with ASEAN partners, thereby strengthening collective security frameworks.

Furthermore, climate change and ecological concerns create new dimensions of governance diplomacy. Smeaton et al. (2021) pointed out that marine sedimentary carbon stocks are critical for global climate stability. Mapping and protecting carbon-rich seabeds in Natuna through AI could provide Indonesia with an additional tool for environmental diplomacy, aligning security governance with global sustainability goals.

Finally, global narratives around maritime threats must be approached critically. Yates and Brodie (2023) argued that exaggerated claims of illicit trade often obscure more pressing local challenges. For Natuna, the adoption of AI should focus on addressing real governance gaps rather than inflating threats. By grounding strategies in evidence-based analysis, Indonesia can strengthen its international credibility as a responsible maritime power.

CONCLUSION

The integration of artificial intelligence into maritime governance represents a transformative step for Indonesia in managing the complex security and ecological challenges of the Natuna EEZ. AI’s strengths in anomaly detection, predictive modeling, and multisensor integration provide capabilities that surpass conventional patrol systems, offering real-time surveillance and adaptive responses to illegal fishing and other maritime threats.



Yet, the adoption of AI is not merely a technical endeavor; it is a multidimensional governance challenge. Legal frameworks must be updated to recognize AI-derived evidence, institutional structures must coordinate across agencies, and human operators must be trained to interact effectively with intelligent systems. Environmental sustainability and community participation further underscore that governance cannot be separated from ecological and social realities.

Regionally, AI strengthens Indonesia's capacity to safeguard sovereignty without escalating conflict, aligning with the broader Indo-Pacific security architecture. Globally, AI-supported governance enables Indonesia to contribute to climate resilience, biodiversity protection, and sustainable maritime development.

Ultimately, the novelty of this study lies in positioning AI not simply as a surveillance technology but as a governance innovation that bridges law, policy, ecology, and diplomacy. For Indonesia, particularly in the Natuna EEZ, AI offers not only a defensive shield against IUU fishing but also a strategic tool for asserting sovereignty, enhancing legitimacy, and building sustainable maritime resilience in an era of increasing uncertainty.

FUTURE DIRECTIONS

The future of maritime governance in the Natuna Exclusive Economic Zone (EEZ) will depend on Indonesia's ability to transform artificial intelligence (AI) from a technological tool into a core element of national policy architecture. In the coming decade, AI is expected to evolve from a detection system into an integrated decision-making partner, capable of shaping adaptive maritime governance that simultaneously addresses security, sustainability, and sovereignty. As maritime threats become increasingly hybrid—combining illegal fishing, environmental exploitation, and cyber intrusion—Indonesia must transition toward a governance model that positions AI at the intersection of defense strategy, ecological protection, and diplomatic engagement.

The next phase of AI development should focus on establishing a fully networked surveillance ecosystem that connects satellites, autonomous surface vehicles, underwater drones, and coastal sensors into a single data fusion network. Such an approach would create what can be called an *intelligent maritime domain awareness (iMDA)* framework, where AI continuously learns from operational patterns and predicts risks across environmental, legal, and behavioral dimensions. By embedding learning loops into this network, AI will not only respond to illegal activity but also refine national decision-making regarding maritime zoning, fishing quotas, and



patrol scheduling.

Future research must also address the governance of AI ethics and accountability. As the technology becomes more autonomous, the potential for algorithmic bias or operational errors will require transparent auditing mechanisms. Indonesia's policymakers must consider establishing an *AI Oversight Council for Maritime Affairs*, which would be responsible for validating algorithms, ensuring data integrity, and enforcing human rights compliance in the use of digital surveillance. This aligns with global trends calling for responsible AI that upholds international law and environmental justice.

Equally important is the regional integration of AI-driven systems within ASEAN and the Indo-Pacific frameworks. Data-sharing agreements, joint maritime patrols, and collaborative innovation hubs can transform AI from a national project into a regional public good. Indonesia's leadership in this sphere would not only enhance maritime governance at home but also position it as a technological and diplomatic leader in Southeast Asia's evolving security architecture. Long-term sustainability should also be embedded in AI system design. Future systems must prioritize energy efficiency, low-carbon operations, and environmentally adaptive technologies such as biodegradable sensors and green data centers. Integrating AI into Indonesia's blue economy strategy would enable sustainable fisheries management, minimize ecological footprints, and support the global transition toward carbon-neutral maritime operations.

Education and human capital development remain foundational for this transition. Training programs that combine marine science, data analytics, and ethics of AI governance will be essential to prepare Indonesia's next generation of maritime leaders. Collaboration with universities and defense institutions can accelerate knowledge transfer and ensure that AI governance reflects both technological competence and cultural understanding of Indonesia's maritime identity.

Finally, future maritime governance must recognize AI as a diplomatic instrument as much as a security tool. By promoting AI-enabled transparency and cooperative monitoring, Indonesia can contribute to reducing tensions in the South China Sea and advance international norms for the sustainable management of shared maritime spaces. The future of AI in Natuna, therefore, is not only about building smarter machines but about shaping wiser governance — one that balances sovereignty, legality, and stewardship of the sea.



REFERENCES

- Brennan, J., & Germond, B. (2024). A methodology for analyzing the impacts of climate change on maritime security. *Climatic Change*, 177, Article 15. <https://doi.org/10.1007/s10584-023-03676-0>
- Burmeister, H.-C., & Constapel, M. (2021). Autonomous collision avoidance at sea: A survey. *Frontiers in Robotics and AI*, 8, 739013. <https://doi.org/10.3389/frobt.2021.739013>
- Chen, X., Xu, Q., & Li, L. (2023). Illegal, unreported, and unregulated fishing governance in disputed maritime areas: Reflections on the international legal obligations of states. *Fishes*, 8(1), 36. <https://doi.org/10.3390/fishes8010036>
- Choi, E. C. (2023). Investigating the management of marine sand mining: A case of West Sea Exclusive Economic Zone in South Korea. *Regional Studies in Marine Science*, 66, 103109. <https://doi.org/10.1016/j.rsma.2023.103109>
- Coventry, T. (2023). Seizing stateless smuggling vessels on the Mediterranean High Seas. *Leiden Journal of International Law*, 36(4), 925–946. <https://doi.org/10.1017/S092215652300016X>
- Escalle, L., Mourot, J., Hamer, P., Hare, S. R., Phillip Jr., N. B., & Pilling, G. M. (2023). Towards non-entangling and biodegradable drifting fish aggregating devices – Baselines and transition in the world's largest tuna purse seine fishery. *Marine Policy*, 149, 105500. <https://doi.org/10.1016/j.marpol.2023.105500>
- Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., Hamza, E. H., Rooney, D. W., & Yap, P.-S. (2023). Artificial intelligence for waste management in smart cities: A review. *Environmental Chemistry Letters*, 21, 1959–1989. <https://doi.org/10.1007/s10311-023-01604-3>
- Goodman, A. J., Walker, T. R., Brown, C. J., Wilson, B. R., Gazzola, V., & Sameoto, J. A. (2020). Benthic marine debris in the Bay of Fundy, eastern Canada: Spatial distribution and categorization using seafloor video footage. *Marine Pollution Bulletin*, 150, 110722. <https://doi.org/10.1016/j.marpolbul.2019.110722>
- Grønsund, T., & Aanestad, M. (2020). Augmenting the algorithm: Emerging human-in-the-loop work configurations. *Journal of Strategic Information Systems*, 29(3), 101614. <https://doi.org/10.1016/j.jsis.2020.101614>
- Harris, J. L., Collins, C., Spalding, M., & Stevens, G. M. W. (2024). First records of the sicklefin (*Mobula tarapacana*), bentfin (*Mobula thurstoni*), and spinetail (*Mobula mobular*) devil rays in the Chagos Archipelago. *Journal of Fish Biology*, 104(6), 1628–1632. <https://doi.org/10.1111/jfb.15678>



- He, Z., Wang, C., Gao, J., & Xie, Y. (2023). Assessment of global shipping risk caused by maritime piracy. *Heliyon*, 9, e20988. <https://doi.org/10.1016/j.heliyon.2023.e20988>
- Ichimura, Y., Dalaklis, D., Kitada, M., & Christodoulou, A. (2022). Shipping in the era of digitalization: Mapping the future strategic plans of major maritime commercial actors. *Digital Business*, 2, 100022. <https://doi.org/10.1016/j.digbus.2022.100022>
- Jang, J.-G., Noh, C.-M., Kim, S.-S., Shin, S.-C., Lee, S.-S., & Lee, J.-C. (2022). Vibration data feature extraction and deep learning-based preprocessing method for highly accurate motor fault diagnosis. *Journal of Computational Design and Engineering*, 10(1), 204–220. <https://doi.org/10.1093/icde/qwac128>
- Khobragade, J. W., Kumar, A., Abd Aziz, S. N. B., & Maurya, D. (2021). The anti-maritime piracy law in India and Malaysia: An analytical study. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 5(4), 208–219. <https://doi.org/10.1080/25725084.2021.2006462>
- Liu, X. (2022). The supervision and multi-sectoral guarantee mechanism of the global marine sulfur limit—Assessment from Chinese shipping industry. *Frontiers in Marine Science*, 9, 1028388. <https://doi.org/10.3389/fmars.2022.1028388>
- Moreno, G., Salvador, J., Zudaire, I., Murua, J., Pelegrí, J. L., Uranga, J., Murua, H., Grande, M., Santiago, J., & Restrepo, V. (2023). The Jelly-FAD: A paradigm shift in the design of biodegradable fish aggregating devices. *Marine Policy*, 147, 105352. <https://doi.org/10.1016/j.marpol.2022.105352>
- Munim, Z. H., Dushenko, M., Jimenez, V. J., Shakil, M. H., & Imset, M. (2020). Big data and artificial intelligence in the maritime industry: A bibliometric review and future research directions. *Maritime Policy & Management*, 47(5), 577–597. <https://doi.org/10.1080/03088839.2020.1788731>
- Murray, B., & Perera, L. P. (2020). A dual linear autoencoder approach for vessel trajectory prediction using historical AIS data. *Ocean Engineering*, 209, 107478. <https://doi.org/10.1016/j.oceaneng.2020.107478>
- Nisa, K. S., Suendo, V., Sophiana, I. C., Susanto, H., Kusumaatmaja, A., Nishiyama, N., & Budhi, Y. W. (2022). Effect of base promoter on activity of MCM-41-supported nickel catalyst for hydrogen production via dry reforming of methane. *International Journal of Hydrogen Energy*, 47(47), 23201–23212. <https://doi.org/10.1016/j.ijhydene.2022.05.081>
- Oloruntobi, O., Mokhtar, K., Gohari, A., Asif, S., & Chuah, L. F. (2023). Sustainable transition towards greener and cleaner seaborne shipping industry: Challenges and opportunities.



- Cleaner Engineering and Technology, 13, 100628.
<https://doi.org/10.1016/j.clet.2023.100628>
- Ourdas, C., & Ponis, S. (2023). Evaluating the effects of gamification in behavioral change: A proposed SEM-based approach. Sustainability, 15, 5442. <https://doi.org/10.3390/su15065442>
- Perumal, K., Boopathi, V., Chellaiyan, S., Muthuramalingam, S., & Raja, P. (2021). Sources, spatial distribution, and abundance of marine debris on Thondi coast, Palk Bay, Southeast coast of India. Environmental Sciences Europe, 33, Article 136. <https://doi.org/10.1186/s12302-021-00576-x>
- Qiao, D., Liu, G., Lv, T., Li, W., & Zhang, J. (2021). Marine vision-based situational awareness using discriminative deep learning: A survey. Journal of Marine Science and Engineering, 9(4), 397. <https://doi.org/10.3390/jmse9040397>
- Ranyal, E., Sadhu, A., & Jain, K. (2022). Road condition monitoring using smartsensing and artificial intelligence: A review. Sensors, 22(8), 3044. <https://doi.org/10.3390/s22083044>
- Sánchez-González, P.-L., Díaz-Gutiérrez, D., Leo, T. J., & Núñez-Rivas, L. R. (2019). Toward digitalization of maritime transport? Sensors, 19(4), 926. <https://doi.org/10.3390/s19040926>
- Selig, E. R., Nakayama, S., Wabnitz, C. C. C., Österblom, H., Spijkers, J., Miller, N. A., Bebbington, J., & Decker Sparks, J. L. (2022). Revealing global risks of labor abuse and illegal, unreported, and unregulated fishing. Nature Communications, 13, 1612. <https://doi.org/10.1038/s41467-022-28916-2>
- Shadman, M., Roldan-Carvajal, M., Pierart, F. G., Haim, P. A., Alonso, R., Silva, C., Osorio, A. F., Almonacid, N., Carreras, G., Maali Amiri, M., Arango-Aramburo, S., Rosas, M. A., Pelissero, M., Tula, R., Estefen, S. F., Pastor, M. L., & Saavedra, O. R. (2023). A review of offshore renewable energy in South America: Current status and future perspectives. Sustainability, 15, 1740. <https://doi.org/10.3390/su15021740>
- Siddiqua, A., Hahladakis, J. N., & AlAttia, W. A. K. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. Environmental Science and Pollution Research, 29(43), 58514–58536. <https://doi.org/10.1007/s11356-022-21578-z>
- Smeaton, C., Hunt, C. A., Turrell, W. R., & Austin, W. E. N. (2021). Marine sedimentary carbon stocks of the United Kingdom's Exclusive Economic Zone. Frontiers in Earth Science, 9, 593324. <https://doi.org/10.3389/feart.2021.593324>



- Son, B. A. (2023). Rise of constabulary maritime agencies in Southeast Asia: Vietnam's paragonboat diplomacy in the North Natuna Seas. *Social Sciences*, 12(4), 241. <https://doi.org/10.3390/socsci12040241>
- Sui, B., Zhang, J., & Liu, Z. (2023). A real-time ship encounter collision risk detection approach in close-quarters situation. *Measurement and Control*, 56(9–10), 1613–1625. <https://doi.org/10.1177/00202940231175086>
- Thangavel, K., Servidia, P., Sabatini, R., Marzocca, P., Fayek, H., Cerruti, S. H., España, M., & Spiller, D. (2023). A distributed satellite system for multibaseline AT-InSAR: Constellation of formations for maritime domain awareness using autonomous orbit control. *Aerospace*, 10(2), 176. <https://doi.org/10.3390/aerospace10020176>
- Thombre, S., Zhao, Z., Ramm-Schmidt, H., Vallet García, J. M., Malkamäki, T., Nikolskiy, S., Hammarberg, T., Nuortie, H., Bhuiyan, M. Z. H., Särkkä, S., & Lehtola, V. V. (2022). Sensors and AI techniques for situational awareness in autonomous ships: A review. *IEEE Transactions on Intelligent Transportation Systems*, 23(1), 64–79. <https://doi.org/10.1109/TITS.2020.3023957>
- Trongtirakul, T., Agaian, S., Oulefki, A., & Panetta, K. (2023). Method for remote sensing oil spill applications over thermal and polarimetric imagery. *IEEE Journal of Oceanic Engineering*, 48(3), 973–987. <https://doi.org/10.1109/JOE.2023.3245759>
- Vairo, T., Cademartori, D., Clematis, D., Carpanese, M. P., & Fabiano, B. (2023). Solid oxide fuel cells for shipping: A machine learning model for early detection of hazardous system deviations. *Process Safety and Environmental Protection*, 172, 184–194. <https://doi.org/10.1016/j.psep.2023.02.022>
- Van de Merwe, K., Mallam, S., Nazir, S., & Engelhardtson, Ø. (2024). Supporting human supervision in autonomous collision avoidance through agent transparency. *Safety Science*, 169, 106329. <https://doi.org/10.1016/j.ssci.2023.106329>
- Veitch, E., & Alsos, O. A. (2022). A systematic review of human-AI interaction in autonomous ship systems. *Safety Science*, 152, 105778. <https://doi.org/10.1016/j.ssci.2022.105778>
- Venskus, J., Treigys, P., & Markevičiūtė, J. (2021). Unsupervised marine vessel trajectory prediction using LSTM network and wild bootstrapping techniques. *Nonlinear Analysis: Modeling and Control*, 26(4), 718–737. <https://doi.org/10.15388/namc.2021.26.23056>
- Yates, D., & Brodie, N. (2023). The illicit trade in antiquities is not the world's third-largest illicit trade: A critical evaluation of a factoid. *Antiquity*, 97(394), 991–1003. <https://doi.org/10.15184/aqy.2023.90>



Zhao, C., Fu, X., Dong, J., Feng, C., & Chang, H. (2023). LPDNet: A lightweight network for SAR ship detection based on multi-level Laplacian denoising. *Sensors*, 23(13), 6084. <https://doi.org/10.3390/s23136084>

