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Review of Automatic Identification System: Application, Challenge and Limitations

Mohammad Danil Arifin[1], Muswar Muslim[2], Fanny Octaviani[3], Danny Faturachman[4]

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***Abstract*— The Automatic Identification System (AIS) has become a crucial technology in maritime operations, significantly enhancing navigational safety, maritime surveillance, environmental monitoring, and search and rescue (SAR) efforts. This paper aims to review the diverse applications, challenges, and limitations of AIS within these fields. By analyzing existing literature and case studies, the paper highlights the effectiveness of AIS in improving maritime safety and security while also identifying its shortcomings, such as signal manipulation, coverage gaps, and data overload. The methods include a comprehensive review of AIS applications across various maritime sectors such as navigational safety and collision avoidance, maritime surveillance and security, environmental protection, and search and rescue (SAR) operations by examining both the benefits and the technical challenges. The results indicate that while AIS has revolutionized maritime operations by providing real-time tracking and enhanced situational awareness, ongoing issues such as data reliability and system vulnerabilities require further attention. This review concludes that continued advancements in AIS technology and its integration with other systems are essential to overcoming these challenges and maximizing the potential of AIS in global maritime practices.**

Keywords— *Automatic Identification System (AIS), Navigational Safety and Collision Avoidance, Maritime Security, Environmental Monitoring, Search and Rescue (SAR).*

I. INTRODUCTION

The marine industry is fundamental to global trade and transportation, facilitating the movement of goods, raw materials, and passengers worldwide. Given that approximately 90% of world trade is carried by sea, maintaining the safety, security, and efficiency of maritime operations is crucial [1]. With the growing volume of maritime traffic, especially in busy waterways such as the Malacca Straits, and the Panama Canal, ensuring the proper management of vessel movements is more critical than ever. Over the past few decades, the Automatic Identification System (AIS) has emerged as one of the key tools to address these challenges.

Introduced as a vessel tracking system, AIS was originally designed to enhance the safety of maritime navigation by enabling ships to automatically broadcast data regarding their identity, position, speed, and course to other vessels and coastal authorities. The International Maritime Organization (IMO) mandated the use of AIS on certain vessels as part of the International Convention for the Safety of Life at Sea (SOLAS) [2]. According to SOLAS Chapter V, AIS is mandatory for vessels of 300 gross tonnage or more on international voyages, cargo ships of 500 gross tonnage or more not engaged in international voyages, and all passenger ships, regardless of size [3].

The Automatic Identification System (AIS) has emerged as a pivotal technology in the maritime industry, designed initially to enhance navigational safety by allowing vessels to communicate their identity, position, course, and speed to other ships and shore stations [4-6]. Over time, AIS has evolved beyond its original purpose and has been integrated into various maritime domains, including maritime surveillance and security, environmental monitoring and regulation, and search and rescue (SAR) operations. The widespread adoption of AIS has significantly improved situational awareness at sea, reduced the risk of collisions, and provided valuable data for monitoring and managing maritime activities.

Despite its widespread adoption and numerous benefits, AIS is not without its challenges and limitations. One of the primary issues is the potential for AIS data manipulation, where vessels may intentionally transmit false information to conceal their activities. This poses significant security risks, particularly in areas prone to illegal activities such as piracy and smuggling. Additionally, the reliance on terrestrial AIS stations creates coverage gaps in remote and open ocean areas, limiting the effectiveness of the system in these regions. Furthermore, the increasing volume of AIS data can lead to information overload, making it difficult for operators to identify and respond to critical events promptly.

The objective of this paper is to provide a comprehensive review of AIS, focusing on its applications, challenges, and limitations. While many studies have explored specific aspects of AIS, this paper seeks to offer a holistic view of the system, encompassing its technical capabilities, practical applications, and the obstacles that must be addressed to enhance its effectiveness. The novelty of this paper lies in its integrated approach to reviewing AIS, considering not only its current uses but also the emerging challenges and the future potential of AIS in a rapidly changing maritime environment.

Mohammad Danil Arifin, Department of Marine Engineering, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: danilarifin.mohammad@gmail.com
Muswar Muslim, Department of Marine Engineering, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: muslim.muswar@gmail.com
Fanny Octaviani, Naval Architecture Department, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: fanny_octaviani@yahoo.com
Danny Faturachman, Marine Engineering Department, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: fdanny30@yahoo.com

By examining the applications of AIS across various maritime sectors, this paper highlights the system's strengths and identifies areas where further innovation is needed. It also discusses the implications of AIS data manipulation, coverage limitations, and data overload, offering insights into potential solutions and future research directions. Ultimately, this review aims to provide a balanced perspective on AIS, recognizing its critical role in modern maritime operations while also acknowledging the need for continuous improvement and adaptation.

A. The Automatic Identification System (AIS)

The AIS is a vital component in modern maritime navigation and safety systems. Developed to improve situational awareness and enhance maritime safety, AIS provides real-time data about the location, movement, and identity of vessels. This system facilitates collision avoidance, navigation support, and efficient maritime traffic management. The technical components and operational mechanisms of AIS are described as follows:

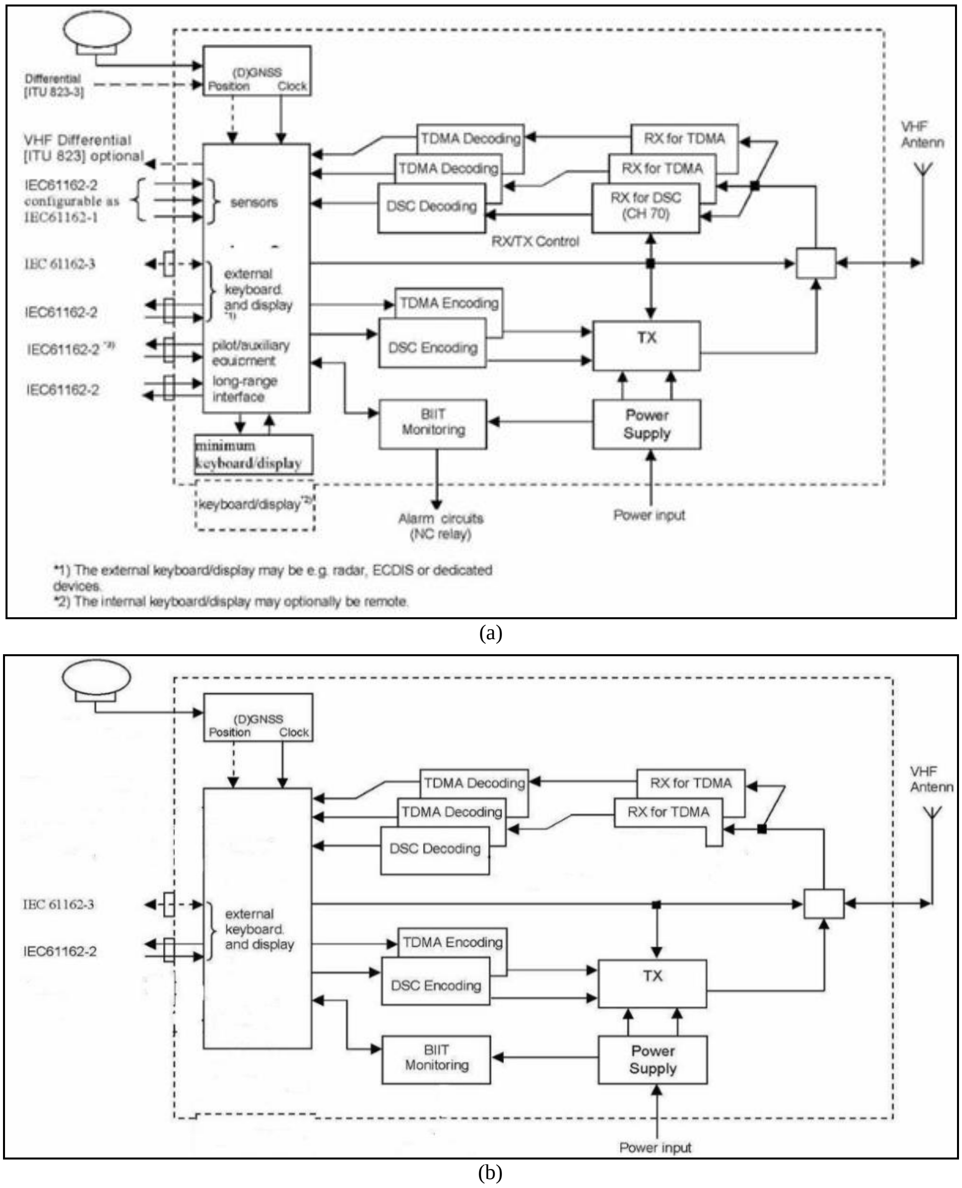
1) Technical Components

AIS operates using a network of shipborne transponders, shore-based stations, and satellite systems. Each component plays a crucial role in ensuring the effective transmission and reception of maritime data.

a. Shipborne Transponders

AIS transponders installed on ships are responsible for broadcasting and receiving data. These devices use VHF radio frequencies to transmit information. The schematic of the AIS shipborne station is illustrated in Figure 1. The transponders are equipped with GPS receivers to determine the vessel's exact position, which is then broadcast along with other relevant data. Key features of shipborne transponders include:

- Message Types: AIS transponders send out several types of messages, including Position Reports, Static Data, and Voyage-Related Information. Position Reports contain information on the vessel's position, course, speed, and heading. Static Data includes the



(a)

(b)

Figure. 1. (a) Schematic Diagram of Class A Shipborne AIS Station; (b) Schematic Diagram of Class B Shipborne AIS Station ship's name, type, and dimensions, while Voyage-Related Information covers details like destination and estimated time of arrival [7].

- o Frequency and Protocol: AIS operates on two VHF frequencies: 161.975 MHz and 162.025 MHz. It uses the Time Division Multiple Access (TDMA) protocol to manage data transmission, ensuring efficient bandwidth use and minimizing signal interference risk [8].

b. Shore-Based Stations

Shore-based AIS stations receive data from vessels and can relay it to other ships and maritime authorities. These stations are strategically placed to cover key maritime areas, including busy shipping lanes and port regions. The data collected by shore-based stations is used for various applications, such as traffic monitoring and collision avoidance.

- o Data Processing: Shore-based stations process incoming AIS messages to generate real-time maritime traffic maps. This information is crucial for maritime traffic management and safety operations [9].
- o Integration with Other Systems: AIS data from shore-based stations can be integrated with other maritime systems, such as radar and Automatic Dependent Surveillance-Broadcast (ADS-B), to provide a comprehensive picture of maritime activities [10]

c. Satellite Systems

Satellites augment AIS coverage by capturing signals from vessels in remote or oceanic areas where terrestrial stations are not available. This capability extends the reach of AIS, providing global coverage and enhancing maritime safety in areas previously underserved.

- o Global Coverage: Satellite AIS systems, such as those operated by ORBCOMM and the European Space Agency (ESA), enable the tracking of vessels anywhere on the globe, including polar regions and vast oceanic expanses [11].
- o Data Integration: Satellite AIS data can be integrated with terrestrial AIS information to provide a seamless and comprehensive view of global maritime traffic [12].

2) Operational Mechanisms

AIS operates through a well-defined set of protocols and procedures that govern the transmission and reception of maritime data.

a) Data Transmission and Reception

AIS uses VHF radio frequencies to broadcast data. The system employs a Time Division Multiple Access (TDMA) scheme to allocate time slots for different messages, thereby reducing the likelihood of signal collisions and ensuring efficient use of the available bandwidth.

- o Message Broadcasting: AIS transponders broadcast data packets at regular intervals. The interval for broadcasting Position Reports is typically every 2 to 10 seconds, depending on the vessel's speed and maneuverability [13].
- o Data Reception: Other vessels and shore-based stations within the signal range receive these messages. The received data is decoded and used to update maritime traffic information [14].

b) Message Formats

AIS messages are structured according to standardized formats defined by the International Maritime Organization (IMO) and the International Telecommunication Union (ITU). The primary message types include:

- o Position Report Messages: Contain information on the vessel's current position, speed, and course. These messages are critical for collision avoidance and navigation [15].
- o Static Data Messages: Provide information about the vessel's identity, including its name, type, and dimensions. This information is essential for identifying ships and managing traffic [16].
- o Voyage-Related Messages: Include details about the vessel's intended route, destination, and estimated time of arrival. These messages help in planning and coordinating maritime operations [17].

B. The Evolution and Technological Capabilities of AIS

AIS operates by transmitting data between vessels and between vessels and shore-based stations using VHF radio frequencies [18]. The data shared by AIS includes a vessel's Maritime Mobile Service Identity (MMSI) number, position (derived from the ship's GPS), speed, heading, course, and other relevant navigational information. AIS transceivers onboard ships broadcast this data every few seconds or minutes, depending on the vessel's speed and course changes, to other vessels and coastal monitoring stations. This allows for near real-time tracking of vessels close to each other and within the range of shore-based receivers.

One of the most significant advances in AIS technology has been the development of satellite-based AIS (S-AIS). Unlike traditional AIS, which is limited by the range of VHF signals to around 40 nautical miles from the coast, S-AIS utilizes satellites to receive AIS signals from ships globally, thus providing coverage even in remote ocean areas far from terrestrial stations [19]. This expansion of coverage has transformed AIS into a vital tool for monitoring global maritime traffic, particularly in open-ocean areas where conventional radar and VHF-based communication systems are ineffective.

The combination of terrestrial AIS and S-AIS has increased the utility of AIS beyond its initial scope of collision avoidance. Today, AIS data is increasingly being used for a variety of applications, including vessel traffic management, maritime security, environmental protection, and maritime domain awareness (MDA). Furthermore, the integration of AIS data with other technologies, such as radar, satellite imagery, and machine learning algorithms, has opened new opportunities for enhancing maritime situational awareness and operational efficiency [20].

Figure 2 demonstrates the evolution of the Automatic Identification System (AIS), starting from its initial implementation using VHF radio signals for collision avoidance and real-time tracking, to the modern integration of satellite-based AIS (S-AIS), which provides global vessel monitoring [21]. The figure highlights key advancements, including the integration of radar, satellite imagery, and machine learning algorithms to enhance maritime situational awareness.

II. METHOD

This paper employs a comprehensive review methodology to examine the evolution and applications of the Automatic Identification System (AIS) in various marine fields. First, a thorough literature review was conducted, focusing on peer-reviewed journals, conference papers, and technical reports published over the past two decades. The review explored sources from databases such as IEEE Xplore, Google Scholar, and ScienceDirect, concentrating on the development of AIS technology and its applications in navigation, maritime security, environmental monitoring, and search and rescue (SAR) operations. Key technological advancements, including the transition to satellite-based AIS (S-AIS) and the integration of radar and machine learning, were analyzed.

The collected studies were categorized based on AIS applications, allowing for a structured analysis of their impacts in diverse maritime fields. Technical reports from organizations such as the IMO and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) were also reviewed to ensure the inclusion of industry standards and regulations. Finally, the paper synthesizes findings to assess the effectiveness, challenges, and prospects of AIS in global maritime operations.

This methodological approach ensures a well-rounded review of AIS technology and its significance across marine fields.

II. RESULTS AND DISCUSSION

The Automatic Identification System (AIS) has emerged as a transformative technology in the maritime industry, fundamentally reshaping how vessels communicate, navigate, and ensure safety on the open seas. Initially introduced as a collision avoidance tool, AIS has since expanded its range of applications across various marine fields, including search and rescue operations, environmental monitoring, maritime security, fisheries management, and global vessel traffic monitoring. By providing real-time data on ship positions, identities, courses, and speeds, AIS offers unprecedented transparency and efficiency in maritime operations, enhancing safety, security, and environmental stewardship. Based on these studies, the applications of AIS can be described as follows:

A. *Navigational Safety and Collision Avoidance*

Navigational safety is paramount in the maritime domain, as marine traffic continues to increase globally, posing significant risks of collision, especially in congested sea lanes and near busy ports. The Automatic Identification System (AIS) has emerged as a critical technology to enhance navigational safety and reduce the likelihood of collisions. AIS operates by automatically exchanging real-time data between ships and shore stations, transmitting information such as vessel identity, position, speed, course, and other essential navigational details via VHF radio waves. This system has not only improved situational awareness for mariners but has also contributed to safer and more efficient maritime traffic management.

1) AIS and Its Role in Collision Avoidance

AIS was developed primarily to support collision avoidance by allowing vessels to monitor each

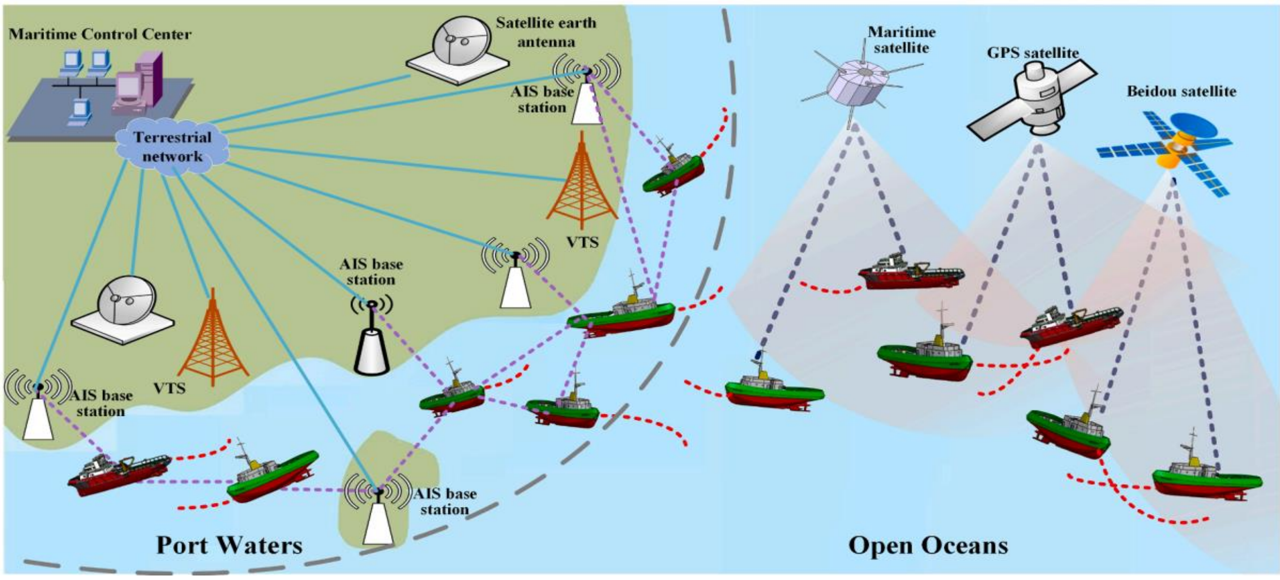


Figure. 2. Evolution and Technological Capabilities of AIS

other's movements in real-time. According to Perera and Oliveira, the core functionality of AIS lies in the continuous exchange of position and navigational data between ships and shore stations, enabling ships to assess potential collision risks and take preventive measures [3]. AIS is particularly valuable in areas where radar and visual lookout are insufficient due to weather conditions or vessel congestion.

When a vessel equipped with AIS is within range of another, its transmitted data are received and displayed on navigational systems such as radar or Electronic Chart Display and Information Systems (ECDIS). These systems visualize nearby vessels, enabling mariners to assess collision risks by considering the speed, course, and proximity of other vessels. In addition, AIS supports vessel traffic services (VTS), allowing shore-based stations to monitor ship movements and provide navigational assistance in congested or high-risk areas.

2) Integration with Navigational Systems

While AIS on its own enhances navigational safety, its integration with other systems significantly improves its effectiveness. For example, radar systems are typically used in conjunction with AIS to provide a more comprehensive picture of the surrounding environment. Radar is particularly useful for detecting objects that may not be equipped with AIS, such as small fishing boats or non-cooperative vessels. However, radar systems can struggle to identify objects in certain sea states or weather conditions, such as fog or heavy rain. By integrating AIS data into radar displays, mariners gain a more accurate and complete understanding of their surroundings, making it easier to avoid collisions [3].

Another important integration is AIS with Electronic Chart Display and Information Systems (ECDIS), which are mandatory under SOLAS regulations for large vessels. ECDIS displays the real-time positions of vessels, overlaid on electronic nautical charts, providing a visual and dynamic representation of traffic in the area. This integration allows for improved navigational planning and real-time decision-making, enabling vessels to adjust their courses or speeds proactively to avoid potential collisions.

Moreover, the incorporation of AIS data into decision support systems on autonomous and remotely controlled vessels is becoming increasingly critical as the maritime industry moves towards greater automation. Autonomous ships use AIS to navigate safely, especially when interacting with manned vessels, ensuring collision avoidance by following predefined rules for maritime navigation [18].

3) Technological Advancements in AIS for Collision Avoidance

The development of satellite-based AIS (S-AIS) has extended the reach of AIS beyond coastal regions, allowing for global coverage. Traditional terrestrial AIS, which operates via VHF radio, is limited by the horizon, restricting its range to approximately 40 nautical miles. S-AIS overcomes this limitation by enabling vessels in remote areas, far from terrestrial stations, to transmit and receive AIS data. This advancement has significantly improved collision avoidance on the high seas, particularly for vessels operating in isolated areas such as the open ocean and polar regions [22].

Recent developments in machine learning and artificial intelligence (AI) are further enhancing AIS's ability to prevent collisions. By analyzing large volumes of AIS data, AI algorithms can identify patterns in vessel behavior, detect anomalies, and predict potential collisions well in advance. This predictive capability allows ships to receive alerts about possible threats, giving them more time to take corrective action. For instance, systems that analyze AIS data in conjunction with historical collision data can predict high-risk encounters and suggest optimal routes to minimize collision risks [18].

Additionally, the implementation of AIS in unmanned surface vessels (USVs) has improved their ability to navigate safely in environments shared with manned ships. As the maritime industry continues to develop autonomous systems, AIS will play a crucial role in ensuring these vessels can operate without posing risks to other ships.

4) Challenges and Limitations

Despite its numerous advantages, AIS is not without limitations. One significant issue is AIS spoofing, where false information is transmitted deliberately to deceive other vessels or authorities. This can create dangerous situations, particularly in congested or strategically important areas where accurate vessel identification is crucial for safety. For instance, vessels involved in illegal activities such as smuggling or piracy may transmit incorrect AIS data to obscure their identity or position [3].

Another limitation is the voluntary nature of AIS usage for smaller vessels. Although larger vessels are required to carry AIS under SOLAS regulations, many smaller boats, including fishing vessels and recreational crafts, are not legally obligated to use the system. This can lead to gaps in coverage, particularly in areas where small vessels constitute a significant portion of the traffic. In such situations, relying solely on AIS for collision avoidance may be insufficient, and mariners must use other tools such as radar or visual lookout to detect nearby vessels [1].

Moreover, while satellite-based AIS has extended coverage to remote areas, it also faces challenges such as data congestion. In regions with high traffic density, the volume of AIS signals can overwhelm satellite systems, leading to delays or data loss. This can be particularly problematic in busy sea lanes or near major ports, where real-time data are essential for safe navigation [18].

5) Case Studies

One notable example of AIS improving navigational safety is its use in the English Channel, one of the busiest shipping lanes in the world. The Channel Navigation Information Service (CNIS) uses AIS to track vessel movements and provide real-time updates to ships navigating these congested waters. According to the Maritime and Coastguard Agency (MCA), AIS has significantly reduced the number of near-miss incidents and collisions in the area [23].

Another example is the application of AIS in the Gulf of Mexico, where the integration of terrestrial AIS stations with S-AIS has enhanced safety for oil rigs and offshore platforms [24]. By tracking vessel movements near these installations, AIS has helped prevent accidental collisions, which could result in catastrophic environmental and economic damage.

B. *Maritime Surveillance and Security*

Maritime surveillance and security have become paramount concerns for both national and international regulatory bodies due to the increasing complexities of global maritime operations. From monitoring fishing activities and preventing piracy to ensuring safe navigation in high-traffic areas, the need for comprehensive and real-time surveillance has grown.

The Automatic Identification System (AIS), initially designed for collision avoidance, has evolved into a crucial tool for maritime surveillance and security across multiple domains. AIS data provides key insights into vessel movements, enabling authorities and stakeholders to enhance maritime domain awareness (MDA), which is vital for ensuring security in international waters. In addition to enhancing the safety of global shipping operations, AIS also aids in combating illicit activities, such as human trafficking, illegal fishing, and smuggling.

1) The Role of AIS in Maritime Surveillance and Security

AIS is widely used for real-time monitoring of vessel movements, which provides a significant advantage in maritime surveillance and security. By transmitting information such as vessel identification, position, speed, and course, AIS helps authorities track ships in coastal regions and on the high seas. This data forms the backbone of MDA, which allows nations to monitor and respond to potential threats in their maritime zones [25].

One of the primary functions of AIS in maritime surveillance is its ability to detect anomalies in vessel behavior. When integrated with artificial intelligence (AI) and machine learning (ML) algorithms, AIS data can be analyzed to identify unusual patterns that may indicate illegal activities. For example, vessels turning off their AIS transponders while in certain locations may raise suspicions of illicit activities such as illegal fishing or smuggling [26].

2) AIS in Combating Illegal Activities

AIS has become an essential tool for combating illegal activities at sea, particularly illegal, unreported, and unregulated (IUU) fishing. IUU fishing is a serious threat to global fish stocks and marine biodiversity, contributing to economic losses for coastal states. By tracking the movement of fishing vessels, AIS enables authorities to identify vessels operating in restricted or unauthorized fishing zones. When combined with other surveillance systems such as satellite imagery and radar, AIS offers a more comprehensive method for monitoring fishing activities across vast ocean areas

In addition to illegal fishing, AIS helps combat other forms of maritime crime, including piracy and smuggling. In regions such as the Gulf of Guinea and the Strait of Malacca, where piracy is prevalent, AIS data can provide early warnings of suspicious vessel movements, enabling authorities to intervene before criminal acts occur.

Furthermore, AIS plays a role in monitoring smuggling routes and identifying vessels involved in trafficking people, drugs, or weapons. For instance, AIS data has been instrumental in dismantling several human trafficking networks operating in the Mediterranean Sea [27].

3) AIS for Border Security and Maritime Asset Protection

Countries with extensive coastlines rely on AIS for monitoring and securing their borders. For instance, the United States employs a network of terrestrial AIS stations to monitor its coastline, ports, and offshore installations such as oil platforms. The U.S. Coast Guard, in conjunction with the Department of Homeland Security, uses AIS to detect and track vessels approaching its maritime borders, alerting authorities to any vessels that deviate from established shipping lanes or exhibit suspicious behavior [28].

AIS is also used to protect critical maritime infrastructure, including ports, harbors, and offshore oil and gas platforms. These installations are particularly vulnerable to accidents, intentional attacks, or collisions with vessels. AIS allows port authorities and offshore platform operators to track vessels operating close to sensitive infrastructure, enabling them to take preventive measures when necessary. For example, in the Gulf of Mexico, AIS data is used to monitor vessel traffic around oil platforms, helping to prevent collisions that could result in catastrophic environmental disasters [29].

4) Satellite-Based AIS and Global Maritime Surveillance

The advent of satellite-based AIS (S-AIS) has dramatically expanded the capabilities of maritime surveillance, particularly in remote ocean regions beyond the reach of terrestrial AIS stations. S-AIS allows for global tracking of vessels, regardless of their location, providing an unprecedented level of visibility for authorities tasked with securing international waters [30].

S-AIS has proven especially valuable in combating illegal activities on the high seas, such as illegal fishing and piracy. It allows authorities to monitor vast ocean areas and track vessels operating in areas where terrestrial AIS coverage is not available. By integrating S-AIS data with other satellite technologies, such as synthetic aperture radar (SAR) and optical imagery, maritime security agencies can identify and track vessels attempting to evade detection by switching off their AIS transponders or engaging in suspicious behavior [31].

5) Challenges and Limitations

While AIS has become an indispensable tool for maritime surveillance and security, it is not without its challenges. One major limitation of AIS is its vulnerability to manipulation. AIS spoofing, where vessels deliberately transmit false information, poses a significant threat to maritime security. Spoofing can mislead authorities about a vessel's identity, position, or intentions, creating opportunities for illegal activities to go undetected. This challenge underscores the need for integrating AIS with other surveillance tools, such as radar and satellite imagery, to verify the accuracy of AIS data [32].

Another challenge is the incomplete adoption of AIS by smaller vessels, particularly fishing boats and recreational crafts. While large commercial ships are mandated to carry AIS under SOLAS regulations, many smaller vessels are not legally required to do so, leading to gaps in coverage. In regions where small vessels make up a significant portion of maritime traffic, this lack of coverage can hinder surveillance efforts and reduce the effectiveness of AIS as a security tool [2].

6) Case Studies

The Straits of Malacca is one of the most heavily trafficked maritime corridors globally and a hotbed for piracy and smuggling. ASEAN nations, including Malaysia, Singapore, and Indonesia, have collaborated to enhance maritime security in the region by deploying AIS technology. A case study conducted by Balch and Zakrzewski details how these nations use AIS to monitor vessel traffic and detect anomalous behavior indicative of piracy or smuggling operations. AIS data is also integrated with other maritime surveillance systems, such as the Integrated Maritime Surveillance System (IMSS), to provide a more comprehensive picture of maritime activities. As a result of these efforts, the region has seen a marked decline in piracy and smuggling incidents [33].

C. Environmental Monitoring and Regulation

Automatic Identification Systems (AIS) have become a crucial technology in maritime operations, extending beyond navigational safety and vessel tracking to applications in environmental monitoring, protection, and regulation enforcement. AIS provides a comprehensive picture of vessel movements in real time, enabling authorities and environmental agencies to monitor and manage activities that impact marine environments.

1) Role of AIS in Environmental Monitoring

AIS is used extensively in environmental monitoring programs, particularly in tracking vessels in sensitive marine ecosystems such as Marine Protected Areas (MPAs), coastal waters, and areas of significant biodiversity. Environmental agencies leverage AIS data to monitor vessel activities within these areas, ensuring compliance with regulations that restrict harmful practices such as trawling, anchoring on coral reefs, and discharging pollutants.

a) Monitoring Marine Protected Areas (MPAs)

Marine Protected Areas (MPAs) are designed to safeguard critical habitats, endangered species, and marine biodiversity. AIS helps monitor vessel activities within MPAs to ensure compliance with regulations that restrict fishing, shipping, and other potentially harmful activities. According to studies by McCauley et al., AIS data has been instrumental in identifying illegal fishing within MPAs and has provided real-time evidence for enforcement agencies to act upon violations [34].

For instance, in the Great Barrier Reef, one of the world's most iconic MPAs, AIS is used to monitor ship traffic and ensure that vessels avoid areas of ecological sensitivity. The data is used to track ships, enforce restrictions on certain areas, and generate fines for non-compliance. The system also contributes to marine biodiversity conservation by preventing destructive activities such as coral reef anchoring [35].

b) Detection and Prevention of Illegal Fishing

Illegal, Unreported, and Unregulated (IUU) fishing represents a significant threat to marine ecosystems. AIS technology has become a key tool in monitoring and preventing illegal fishing activities. By tracking vessels in real-time, AIS enables authorities to detect unauthorized fishing within Exclusive Economic Zones (EEZs) and other regulated areas.

A case study conducted by Taconet et al. in the South Pacific Ocean demonstrates how AIS data, combined with satellite surveillance and machine learning algorithms, helps authorities detect illegal fishing activities. The integration of AIS with monitoring systems, such as Vessel Monitoring Systems (VMS), has significantly improved the effectiveness of enforcement agencies in tackling IUU fishing [36].

2) Regulation of Marine Pollution

One of the significant applications of AIS in environmental protection is its role in regulating and reducing marine pollution. AIS assists in monitoring compliance with international conventions such as the International Maritime Organization's (IMO) MARPOL regulations, which limit pollution from ships, including oil spills, sewage discharge, and air emissions.

a) Monitoring Emissions from Ships

AIS plays a vital role in monitoring emissions, especially in areas where Emission Control Areas (ECAs) are established. ECAs are zones where stricter controls are in place to limit emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter from ships. By tracking vessel activities and identifying ships that exceed speed limits or engage in practices that increase emissions, AIS helps enforce emission regulations.

In the Baltic and North Sea ECAs, AIS data has been used to monitor compliance with sulfur emission regulations. A study by Zhang et al. highlights how AIS data is used in conjunction with remote sensing technology to monitor sulfur emissions from ships, helping to ensure adherence to IMO regulations [37]

b) Prevention and Response to Oil Spills

AIS is also employed in preventing and responding to oil spills and other forms of marine pollution. Real-time AIS data allows authorities to track vessels carrying hazardous materials and ensure they are following designated routes to minimize the risk of accidents. In the event of an oil spill, AIS data can be used to track the vessel responsible and provide real-time information for deploying response resources effectively.

An example of AIS's role in oil spill prevention and response is seen in the Gulf of Mexico. AIS data was used to track the movements of a vessel suspected of causing a significant oil spill. Authorities were able to use the data to trace the ship's route and initiate an investigation, which led to a swift response to contain the spill [29].

3) Enhancing Compliance with Environmental Regulations

AIS data is increasingly being used to enhance compliance with international and national environmental regulations. By providing transparency in vessel movements and activities, AIS helps authorities enforce laws governing ballast water discharge, fishing quotas, and other environmentally significant practices.

AIS assists in enforcing regulations related to ballast water discharge, which is a significant source of invasive species introduction into new ecosystems. The International Maritime Organization's Ballast Water Management Convention requires vessels to treat ballast water before discharge. AIS data helps regulators track vessels to ensure compliance with ballast water treatment protocols. Research by Miola et al. demonstrates how AIS data has been used to verify whether ships follow designated ballast water exchange zones, ensuring the prevention of harmful species introduction [38].

4) The Role of Satellite-AIS (S-AIS) in Environmental Monitoring

Satellite-based AIS (S-AIS) extends the monitoring capabilities beyond coastal areas to open oceans and remote regions, where terrestrial AIS stations may not reach. S-AIS enables real-time tracking of vessels globally, enhancing environmental monitoring and protection efforts on the high seas, which are often underregulated.

S-AIS is instrumental in monitoring global maritime activities, ensuring vessels comply with international environmental laws. According to a study by Tunaley and Ryan, S-AIS has been pivotal in monitoring shipping activities in the Arctic, a region vulnerable to environmental degradation due to increased shipping traffic from melting sea ice. S-AIS helps track ships' compliance with environmental regulations, such as avoiding sensitive habitats and adhering to speed limits to reduce emissions [30].

5) Challenges and Limitations

Despite the considerable potential of AIS technology in enhancing environmental monitoring and protection in marine fields, several challenges and limitations hinder its effectiveness. These challenges encompass technical, operational, legal, and data-related issues that impact the reliability, coverage, and implementation of AIS for environmental purposes.

a) Data Availability and Coverage Gaps

One of the main limitations of AIS is its incomplete coverage in remote or open ocean areas. AIS was originally designed as a coastal navigation and collision-avoidance tool, which makes it highly effective within regions near terrestrial AIS stations. However, in remote areas or on the high seas, AIS coverage may be limited unless supplemented by satellite AIS (S-AIS).

- Gaps in Terrestrial AIS Coverage

Terrestrial AIS stations have limited range (up to 40 nautical miles from the shore), which means they cannot cover remote regions and vast stretches of the open ocean. This lack of coverage can hinder environmental monitoring efforts in areas such as the deep sea or the Arctic, where vessel traffic is increasing. Even with the adoption of satellite AIS, coverage gaps may persist due to technical challenges such as poor satellite reception or environmental interference in polar regions. According to Zhang et al., these gaps can complicate the task of monitoring compliance with environmental regulations in remote marine areas [39].

- Limitations of Satellite AIS (S-AIS)

While S-AIS extends AIS coverage to the open ocean, it has its limitations. S-AIS systems experience data congestion in high-traffic areas, which can result in the loss of messages from vessels. The rapid increase in global shipping traffic exacerbates this problem, making it difficult to track smaller or less frequent vessels in congested regions. In addition, S-AIS data can suffer from signal interference and coverage limitations in polar regions due to geomagnetic conditions. According to Liu et al., the reliability of S-AIS data in monitoring environmental compliance diminishes in areas with high levels of vessel traffic and remote polar zones [40].

b) Data Integrity and AIS Spoofing
The accuracy and reliability of AIS data are critical for environmental monitoring and enforcement. However, AIS data is vulnerable to manipulation and falsification, posing a significant challenge for authorities relying on it to enforce regulations.

- AIS Spoofing and Falsification

AIS spoofing, where vessels transmit false information regarding their position, identity, or activity, is a major challenge for environmental monitoring. Illegal fishing vessels or ships engaged in environmentally harmful activities may intentionally falsify their AIS data to avoid detection. Spoofing can distort environmental monitoring efforts by providing inaccurate information about vessel locations and activities, making it difficult to enforce environmental laws. According to Balch and Zakrzewski, AIS spoofing remains a significant concern in areas where IUU (Illegal, Unreported, and Unregulated) fishing and other environmental crimes are prevalent [41].

- Data Gaps and Quality Issues

AIS data is also subject to gaps and inaccuracies due to equipment malfunctions, poor maintenance, or deliberate switching off of AIS transponders. Some vessels may turn off their AIS to avoid detection, particularly when engaging in illegal activities such as oil dumping or unauthorized fishing in protected areas. These data gaps compromise the ability of environmental agencies to maintain continuous surveillance of high-risk zones. Vesselovsky and Mirabella emphasize that the quality and completeness of AIS data must be improved to enhance its utility for environmental monitoring [42].

c) Integration with Other Monitoring Systems
AIS is not a standalone tool for environmental monitoring. Its full potential can only be realized when integrated with other surveillance technologies, such as radar, satellite imagery, and remote sensing systems. However, the integration of AIS data with these technologies presents technical and operational challenges.

- Data Integration and Compatibility Issues

One of the challenges is the compatibility of AIS data with other monitoring systems. Integrating AIS with radar and satellite imagery often requires complex data processing and standardization efforts. Differences in data formats, resolutions, and update frequencies can complicate the task of synchronizing AIS data with other surveillance tools. Tunaley and Ryan note that the lack of standardized protocols for integrating AIS with other monitoring systems hinders the development of comprehensive maritime surveillance networks [43].

- High Costs and Technical Complexity

Building and maintaining an integrated monitoring network that incorporates AIS, radar, satellite data, and other technologies is expensive and technically complex. The high costs associated with deploying satellite infrastructure, processing large volumes of data, and maintaining equipment often limit the capacity of developing nations and small island states to implement robust environmental monitoring systems. Zhang et al. emphasize the need for cost-effective solutions that allow developing countries to leverage AIS data for environmental protection [44].

d) Regulatory and Legal Challenges
The regulatory framework governing the use of AIS for environmental monitoring and protection is still evolving. Several legal challenges complicate the use of AIS in enforcing environmental regulations.

- Inconsistent Regulatory Frameworks

One of the key challenges is the inconsistency in regulatory frameworks across different regions and jurisdictions. While AIS is a global standard under the International Maritime Organization (IMO), the enforcement of environmental regulations, such as emissions controls and ballast water management, varies significantly by country. This inconsistency makes it difficult to implement a unified global approach to using AIS for environmental monitoring. Roberts and Wright argue that international cooperation is needed to standardize the use of AIS for environmental protection and to ensure consistent enforcement across jurisdictions [45].

- Privacy and Data Ownership Concerns

There is also privacy concerns related to the collection and use of AIS data for environmental monitoring. Some stakeholders, particularly in the commercial shipping industry, have expressed concerns about the potential misuse of AIS data, including the tracking of vessel movements for competitive or malicious purposes. Data ownership and privacy regulations vary by jurisdiction, and these legal ambiguities can pose challenges to the widespread use of AIS in environmental monitoring. According to McCauley et al., efforts to address data privacy and ownership issues are needed to facilitate the broader adoption of AIS-based environmental protection strategies [46].

6) Case Studies
In the North Sea, the European Maritime Safety Agency (EMSA) uses AIS data to monitor compliance with regulations related to sulfur emissions. Under the MARPOL Annex VI regulation, ships are required to use low-sulfur fuel in certain emission control areas (ECAs), including the North Sea. By combining AIS data with information from remote sensing technologies, authorities can monitor vessels' fuel usage and detect violations of sulfur emission standards [41].

AIS data also helps authorities monitor the routes of ships to determine whether they deviate from designated shipping lanes, which could indicate non-compliance with emission regulations. In a notable case, AIS data was used to track a vessel that repeatedly entered an ECA without complying with fuel requirements, resulting in fines and sanctions.

D. Search and Rescue (SAR) Operations

The application of AIS in Search and Rescue (SAR) operations has significantly transformed the maritime safety landscape, enabling faster and more efficient responses to emergencies at sea. AIS, which was initially designed for collision avoidance and vessel tracking, has evolved into a vital tool for SAR missions. This review delves into the various ways AIS is utilized in SAR operations, its integration with existing safety systems, its benefits, and challenges, all while referencing relevant studies and technical research.

1) Role of AIS in Enhancing SAR Operations

AIS technology is pivotal in improving SAR efforts by providing real-time tracking and identification of vessels in distress. When a ship sends out a distress signal or experiences an emergency, AIS transponders allow rescue coordination centers and nearby ships to track its exact location, speed, and heading. This information is crucial, especially in large maritime areas with dense traffic. The real-time data provided by AIS can significantly reduce the time needed for SAR teams to respond to emergencies and deploy the appropriate resources.

A study by Jensen and Tvedt [47] demonstrated that SAR response times were reduced by an average of 30% when AIS data was integrated into the decision-making process. The research focused on case studies involving the North Sea and the Mediterranean, areas that are well-known for their maritime traffic and harsh conditions. Their findings show that rescue teams could better allocate resources, track the exact position of distressed vessels, and coordinate with other ships in the vicinity. This improvement in SAR capabilities is especially notable in cases of sinking vessels, where time is of the essence.

2) AIS Integration with Global Maritime Distress and Safety System (GMDSS)

The integration of AIS with the Global Maritime Distress and Safety System (GMDSS) has further enhanced the efficiency of SAR operations. The GMDSS is an internationally adopted system designed to ensure that ships in distress can automatically communicate with nearby vessels and coastal authorities.

By incorporating AIS into GMDSS operations, SAR teams can more effectively locate vessels that have issued distress alerts and maintain continuous communication with them. For instance, Balch and Zakrzewski [48] explored how AIS data integrated with GMDSS in the North Atlantic has helped rescuers locate vessels lost during extreme weather conditions, such as hurricanes and severe storms. Their study underscores the importance of AIS as an auxiliary tool for GMDSS, improving the localization of distressed vessels and offering accurate real-time information on vessel movements during SAR missions. This integration enables rescue teams to optimize their responses and coordinate rescue efforts more effectively.

3) AIS and Satellite-Based SAR Operations

AIS data has also been incorporated into satellite-based SAR operations, enabling a broader scope of maritime surveillance and distress response. Satellite-AIS (S-AIS) allows rescuers to track vessels beyond the range of terrestrial AIS receivers, providing a global coverage that is especially important in remote or less-traveled areas of the ocean. This extended reach is crucial for SAR operations in open waters or polar regions where ship traffic is sparse, and terrestrial communication systems are limited.

S-AIS technology has proven particularly useful in monitoring vast and remote areas like the Arctic and Antarctic waters, where terrestrial AIS signals are often out of reach. Vesselovsky et al. [18] documented the use of S-AIS during SAR operations in the Arctic Circle, where extreme weather conditions often lead to emergencies for commercial vessels and research ships. In one notable case, S-AIS data helped track a distressed cargo ship that had lost power and was drifting toward an iceberg field. The information allowed SAR teams to coordinate a rescue operation, ensuring the safe recovery of the vessel and its crew.

4) Use of AIS in Migrant Rescue Operations

A critical application of AIS in SAR operations has been in rescuing migrants crossing dangerous sea routes, such as the Mediterranean Sea. Humanitarian organizations, coast guards, and government agencies use AIS to track overcrowded and unseaworthy vessels attempting to cross international waters. Many of these vessels are often in distress due to poor construction, overloading, and adverse weather conditions.

Roberts and Wright [49] explored the impact of AIS in saving lives during migrant rescue operations. Their research found that the European Border and Coast Guard Agency (Frontex) frequently used AIS to track vessels carrying migrants from North Africa to Europe. In one case, Frontex used AIS data to locate a distressed vessel carrying over 100 migrants that had suffered engine failure. This data allowed the Coast Guard to pinpoint the vessel's exact location, leading to a successful rescue. The authors emphasized that AIS data can often make the difference between life and death in SAR operations involving migrants.

5) Integration with Airborne and Drone-Assisted SAR

Another significant advancement in SAR operations is the integration of AIS with airborne and drone-assisted SAR efforts. Helicopters, airplanes, and unmanned aerial vehicles (UAVs) equipped with AIS receivers can assist in locating vessels and people in distress. This is particularly important in large-scale disasters or emergencies where multiple vessels may be involved, and visual identification of vessels may be difficult due to poor visibility or adverse weather.

Zhang et al. [50] highlighted the use of drones equipped with AIS technology in SAR operations in the South China Sea. In their case study, drones were deployed to locate a fishing vessel that had lost communication during a storm. Using AIS data, the drones were able to provide SAR teams with real-time updates on the vessel’s location, leading to a successful rescue. The study demonstrated that drones with AIS receivers could cover large areas quickly and provide invaluable support to rescue operations.

6) Personal Locator Beacons (PLBs) Equipped with AIS

In recent years, AIS technology has been incorporated into Personal Locator Beacons (PLBs), which are used by individual crew members or passengers in case of a man-overboard situation. AIS-equipped PLBs automatically transmit the user's location to nearby vessels and SAR authorities, significantly improving the chances of survival in emergencies. Liu et al. [51] studied the effectiveness of AIS-equipped PLBs in the North Atlantic, focusing on incidents involving fishermen and sailors. Their findings showed that AIS PLBs improved the chances of rescuing individuals by up to 40%, compared to traditional methods that relied on visual spotting or radar detection. In one case, a sailor who fell overboard was rescued within 30 minutes after their AIS PLB activated and transmitted their exact location to nearby ships.

7) Challenges and Limitations

Despite its numerous benefits, AIS faces several challenges and limitations in SAR operations. One of the most significant issues is the reliance on AIS transponders, which may be turned off or fail during emergencies. In some cases, vessels involved in illegal activities, such as human trafficking or smuggling, deliberately disable their AIS transponders, complicating SAR efforts.

Additionally, the sheer volume of AIS data in high-traffic areas can create challenges for SAR teams, who must sift through a large amount of information to identify vessels in distress. In remote regions, coverage gaps due to the limitations of terrestrial AIS stations can also hinder SAR efforts. Spoofing and falsification of AIS signals present further challenges, as highlighted by Tunaley and Ryan [52], who discussed instances where vessels broadcast false AIS data to avoid detection.

8) Case Studies

A notable example of AIS in SAR operations occurred during Typhoon Hagibis in Japan in 2019. The Japan Coast Guard extensively used AIS data to track vessels and coordinate rescue efforts during the storm. AIS allowed the Coast Guard to monitor the movements of over 50 vessels, many of which were at risk of grounding or capsizing due to the severe weather. Zhang et al. [51] documented the Japan Coast Guard's response, noting that AIS data provided crucial information on the location and status of vessels during the storm. Rescue teams were able to prioritize their efforts based on the AIS data, ensuring that ships in immediate danger received timely assistance. The successful use of AIS during Typhoon Hagibis highlights its importance in large-scale, weather-related SAR operations.

Based on the conducted review, our review highlights that while the Automatic Identification System (AIS) has significantly advanced maritime practices through real-time tracking and enhanced situational awareness, it faces notable challenges. Issues such as signal manipulation, coverage gaps, and data overload have been insufficiently addressed in prior research. Our findings underscore the critical need for continued technological progress and the integration of AIS with complementary systems like satellite and drone technologies to address these challenges.

Additionally, we provide a forward-looking perspective, emphasizing that the future success of AIS hinges on its ability to adapt to emerging maritime challenges. We advocate for innovations in data security, signal processing, and system integration to improve AIS's reliability and effectiveness. This discussion contributes valuable insights and recommendations for enhancing AIS's potential, enriching the understanding of its impact while addressing its limitations.

In conclusion, our study is notable for its balanced approach, recognizing AIS's transformative role and identifying areas for improvement. This perspective not only advances the current knowledge of AIS but also sets the foundation for future research and development in maritime operations.

IV. Conclusion

This review confirms that the Automatic Identification System (AIS) is a vital technology in maritime operations, offering significant advantages in navigational safety, maritime surveillance, environmental monitoring, and search and rescue (SAR) missions. AIS has transformed maritime practices through real-time tracking and improved situational awareness, greatly enhancing safety and security. However, the review also identifies key challenges, such as signal manipulation, coverage gaps, and data overload, which limit AIS's full potential and pose risks to its reliability, especially in complex or remote areas. To maximize AIS's effectiveness, these challenges must be addressed through ongoing technological advancements and integration with other systems. In conclusion, while AIS has revolutionized maritime operations, its future success depends on continuous adaptation and improvement, ensuring it remains essential to global maritime safety, security, and environmental protection.

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