Real-Time Vessel Trajectory Mapping System Based on Automatic Identification System (AIS) Data

Depandi Enda[1], Noerdin Basir[2], Boby Rahman[3], I Made Surya Kumara[4]
[1]Informatics Department, Politeknik Negeri Bengkalis, Indonesia
[2,3]Civil Engineering Department, Politeknik Negeri Bengkalis, Indonesia
[4]Department of Computer Engineering, Politeknik Negeri Bengkalis, Indonesia
depandienda@polbeng.ac.id[1], noerdin@polbeng.ac.id[2], bobyrahman@polbeng.ac.id[3], suryakumara33@gmail.com[4]

Abstract

The utilization of AIS data has been increasing along with the growing number of studies and the needs of users such as academics, researchers, and maritime administrators. To support faster and more efficient understanding, AIS data should be presented in interactive formats such as real-time maps, charts, and tables. However, before it can be used, AIS data must undergo processes of extraction, translation, and processing to obtain meaningful insights. One of the processed outputs is vessel trajectory data, which is generally obtained from logging processes at Remote Base Stations (RBS) in CSV format and further processed using tools such as Python and QGIS. This process has limitations, as it is not performed in real time and requires additional effort each time the trajectory data is to be presented. This study develops a real-time vessel trajectory mapping system based on Automatic Identification System (AIS) data. The system is designed to dynamically visualize vessel movements on an interactive map and to provide automatic vessel tracking and trajectory reconstruction features by utilizing data received from the AIS-POLBENG Remote Base Station. The system is built using a three-tier architecture consisting of a Python-based backend for data processing and storage in a PostgreSQL database, an in-memory cache using Redis to accelerate real-time data access, and a Laravel and Leaflet JS–based frontend for displaying vessel trajectories on the map. The evaluation was conducted on a vessel with MMSI number 525003XXX operating along the Pakning–Bengkalis route, resulting in an average location update interval of 10.14 seconds, which aligns with the AIS Class A update standards. This system has strong potential for applications in maritime research, marine traffic monitoring, and enhancing navigational safety within the Malacca Strait waters.

Keywords : Real-Time, Vessel Trajectory, Mapping System, AIS Data

1. INTRODUCTION

The Automatic Identification System (AIS) is a navigational aid designed to enhance maritime safety by serving as an early vessel-detection mechanism to prevent collisions, particularly under adverse weather conditions. Its concept is straightforward: AIS devices installed on vessels continuously broadcast positional data to surrounding vessels and any reachable AIS Remote Base Stations. Consequently, each AIS-equipped vessel can identify the positions, headings, and speeds of nearby vessels, enabling captains to determine safe maneuvering actions to avoid potential collisions.

AIS messages are transmitted via Very High Frequency (VHF) radio signals on 161.975 MHz (Channel 87B), the primary communication channel used by Class A AIS devices, and 162.025 MHz (Channel 88B), the alternative channel used by Class B devices. Generally, AIS messages are categorized into two types: AIVDM and AIVDO. AIVDO refers to raw AIS data transmitted from the vessel itself (Own-ship Message) through VHF signals. These data are encoded using the National Marine Electronics Association (NMEA 0183) format before transmission and are used by AIS transponders to broadcast the vessel's own position to nearby vessels or AIS receivers. Meanwhile, AIVDM refers to raw AIS data received via VHF Data-link Messages from other vessels or shore-based AIS stations. These data are utilized by AIS receivers (Base Stations) for monitoring and logging purposes. To enable further visualization and interpretation, the raw AIS data received must be decoded into a readable and interactive format.

AIS data have been widely applied across diverse use cases and multidisciplinary fields, including vessel geospatial pattern analysis (Feng et al., 2022) (Wang et al., 2019), abnormal route behavior detection (Wijaya & Nakamura, 2023), illegal vessel transshipment monitoring, maritime spatial planning (Busaina et al., 2024), maritime boundary surveillance (Enda et al., 2024, 2025), and the extraction of vessel trajectory and density information. These applications integrate various domains such as maritime studies, Geographic Information Systems (GIS), big data, data science, and IoT, creating both collaborative opportunities and new challenges in cross-sector AIS data utilization.

As research involving AIS data continues to expand, the demand for accessible AIS information among academics, researchers, and maritime administrators also increases. Presenting AIS data in more interactive forms—such as real-time maps, charts, and analytical tables—greatly improves users' ability to interpret and explore AIS datasets efficiently. However, before AIS data can be utilized, they must first be extracted, parsed, processed, and refined to obtain meaningful insights. One of the key outputs of AIS data extraction is vessel trajectory data. Typically, trajectory data are obtained from AIS logging processes conducted at Remote Base Stations (RBS). Data collected over a specific duration are stored in CSV files and subsequently processed using tools such as Python and QGIS to visualize individual trajectory points. This workflow carries limitations, as trajectory extraction is not performed in real time and requires significant effort each time the data are processed and presented.

This research proposes an automated, real-time vessel trajectory mapping system utilizing AIS data acquired from the AIS-POLBENG RBS. The system is web-based, emphasizing real-time vessel trajectory tracking and automated generation of historical trajectory data. The system is designed to provide a fast, responsive, and real-time interactive map visualization that adheres to operational standards. Accordingly, it offers improved accessibility for users in consuming AIS data, particularly for reconstructing and analyzing vessel routes based on AIS information.

2. REVIEW OF LITERATURE

Related Work

Several previous studies have investigated the utilization of AIS data for maritime spatial planning. AIS Data Visualization for Maritime Spatial Planning (MSP) (Le Tixerant et al., 2018), presented a comprehensive workflow pipeline for visualizing vessel trajectories from raw AIS data, which is a critical prerequisite for meaningful AIS-based trajectory analysis. The study also demonstrated a real-world case displaying 90 million AIS records—representing one month of global observations—visualized using open-source tools (Le Tixerant et al., 2018). Maritime tracking data analysis and integration with AISDB introduced an open-source platform designed to address challenges in AIS data processing and analysis, enabling integration with environmental datasets to enhance assessments of vessel movement and environmental impact (Spadon et al., 2024). Prototype trial of a traditional vessel tracking system with web-based visualization developed a tracking prototype using specialized telemetry for automatic vessel monitoring. The tool automatically recorded positions whenever activated, and demonstrated reliable accuracy and precision based on a 95% confidence interval when compared with a handheld GPS device (Nazzla et al., 2023). Information extraction from AIS data for identifying shipping lines based on Maritime Mobile Service Identity (MMSI) processed and analyzed AIS data to support maritime spatial planning by mapping maritime traffic density and constellation, navigational routes, hierarchical maritime networks, fishing zones, and spatial-temporal interactions of maritime activities (Ma'ruf et al., 2024).

Further studies have focused on analyzing and extracting vessel trajectory characteristics. A novel machine learning approach to analyzing geospatial vessel patterns using AIS data applied auto-regressive modeling and clustering analysis to explore vessel behavioral patterns (Ferreira et al., 2022). The use of Kalman Filter (KF) techniques for vessel track estimation investigated real-time tracking using GPS-based Kalman Filter techniques implemented in C++, demonstrating highly feasible and accurate tracking performance (Assaf et al., 2020). Construction of a real-time vessel trajectory prediction model based on automatic identification system data introduced a novel algorithm, Combination of DBSCAN and DTW (CDDTW), to identify navigational characteristics and proposed the Real-Time Ship Trajectory Prediction Model (RSTPM), achieving superior prediction accuracy—approximately 20 meters in inland waters—compared with conventional models (Xi et al., 2023).

3. METHOD

The research procedure consists of five stages: Planning, Analysis, System Design, Implementation, and Testing, as illustrated in **Figure 1**. The research procedure begins with planning the system to be developed, including identifying and gathering both user and system requirements. This is followed by a requirements analysis phase, prioritizing essential features, and designing the system architecture, including the database structure and the algorithm for the real-time vessel trajectory tracking system. The next phase is system implementation, which involves developing program code and performing comprehensive unit and system testing. The final phase evaluates the performance of the developed application by calculating the average vessel location update rate. The following procedure was employed to develop the real-time vessel trajectory mapping system based on AIS data.

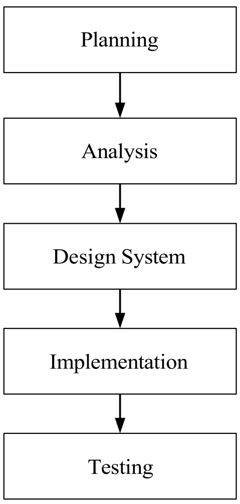

Fig. 1. Research procedure

The study was conducted in the Software Development Laboratory of the Informatics Engineering Department over a development period of two months. The required hardware and software components utilized in building the system are as follows:

Hardware Requirements

The hardware utilized in this study includes a laptop for local application development, a server for application deployment, and a LAN internet connection. The specifications of the hardware components used are presented in **Table 1**. These hardware resources ensure reliable performance to support real-time vessel trajectory processing and visualization.

Table 1. Hardware specifications

No	Hardware and Usage Description	Specifications
1	Laptop for local application development	• CPU: Intel Core i5 8th Gen • RAM: 16 GB • Display: Full HD 1920×1080p • SSD: 1 TB
2	Server for application deployment	• CPU: 2× CLX 4210, 10 Cores / 20 Threads (2.20 GHz) • Chipset: Intel C621 • RAM: 64 GB • SSD: 2× Samsung PM883 3.84 TB
3	LAN Internet Connection	• Speed: 30 Mb/s

Software Requirements

The software utilized in this study comprises an operating system, Linux panel, webserver, web programming language, database, JavaScript library, and map library, with their specifications summarized in **Table 2**. Collectively, these software components support the development, deployment, and operation of the real-time ship trajectory mapping system.

Table 2. Software specifications

No	Software	Specifications
1	Operating System	• Linux Ubuntu 20.04 LTS
2	Linux Panel	• AAPanel version 7.0.24
3	Webserver	• NGinx version 1.24.0
4	Web Programming Language	• PHP version 8.3 • Laravel Framework version 11
5	Database	• PosgreSQL version 13 • Redis in memory database cache version 7.2.10
6	JavaScript Library	• jQuery JavaScript Library v3.6.0 • jQuery Validation Plugin - v1.19.3
7	Map Library	• Leaflet version 1.94 • Leaflets ajax, draw, fullscreen, panel layers, rotatedMarker

4. RESULT & DISCUSSION

User and System Requirements

The results of the functional requirements collection and the prioritization of system features **(Table 3)** indicate that there are six user requirements and five system requirements. The priorities for both user and system requirements are categorized into three levels: (1) must, indicating high-priority features that must be addressed first, (2) moderate, representing medium-priority features, and (3) low, for system features scheduled for implementation in the final development phase.

Tabel 3. User and system requirements with priority levels

No	Functional Requirements	Priority Levels
1	Users can track vessel trajectories in real time on a map display	Must
2	Users can generate historical vessel trajectory data within a specific time range	Must
3	Users can log in to the application	Moderate
4	Users can log out from the current session	Moderate
5	Users can configure the data update interval for real-time vessel trajectory tracking	Low
6	Users can reset vessel trajectory history data	Low
7	The system provides vessel selection and search functionality for trajectory tracking	Must
8	The system displays loading indicators on the map while retrieving historical trajectory data	Must

9	The system supports zoom-in and zoom-out map interactions	Moderate
10	The system provides a full-screen map display mode	Low
11	The system offers multiple map layers, including OpenStreetMap, CyclOSM, Esri World Imagery, and OpenSeaMap	Low

System Design

The next design stage involves structuring the database, specifically defining the data schema for the vessel position table, as presented below:

Table 4. Vessel position table structure

No	Field	Data Type	Description
1	timestamp	datetime	Timestamp value
2	mmsi	integer	Length 9-digit number
3	lat	float	Precision 6 decimal places
4	lon	float	Precision 6 decimal places
5	shipname	varchar	Length 50 dynamic character
6	ship_type	varchar	Length 50 dynamic character
7	destination	varchar	Length 50 dynamic character
8	flag_name	varchar	Length 30 dynamic character
9	heading	integer	Length 11-digit number
10	speed	float	Precision 2 decimal places
12	turn	float	Precision 2 decimal places
13	maneuver	varchar	Length 20 dynamic character
14	course	float	Precision 2 decimal places
15	navigation_status	varchar	Length 30 dynamic character

The vessel position table structure in **Table 4** indicates that there are 15 columns storing decoded AIS raw data, which are saved in the Redis cache database via the backend application (Enda et al., 2021). This data is consumed by the vessel trajectory tracking map in real time and subsequently used as marker data to be displayed as moving markers forming the vessel's trajectory pattern.

System Implementation

The real-time vessel trajectory tracking shown in **Figure 2** displays a vessel with MMSI 525003XXX, classified as a passenger and observation vessel, equipped with a Class A AIS transponder and traveling at a temporary speed of 4.6 knots, with its destination set to Air Putih Port, Bengkalis.

Fig. 2. Real-time vessel trajectory tracking

Based on **Figure 3**, the trajectory of the selected vessel with MMSI 525003XXX presents data generated over one day on October 23, 2025. The trajectory illustrates a short-route voyage between Sumatra Island and Bengkalis, Riau. During the monitoring period, a total of 20 vessel trajectories were recorded.

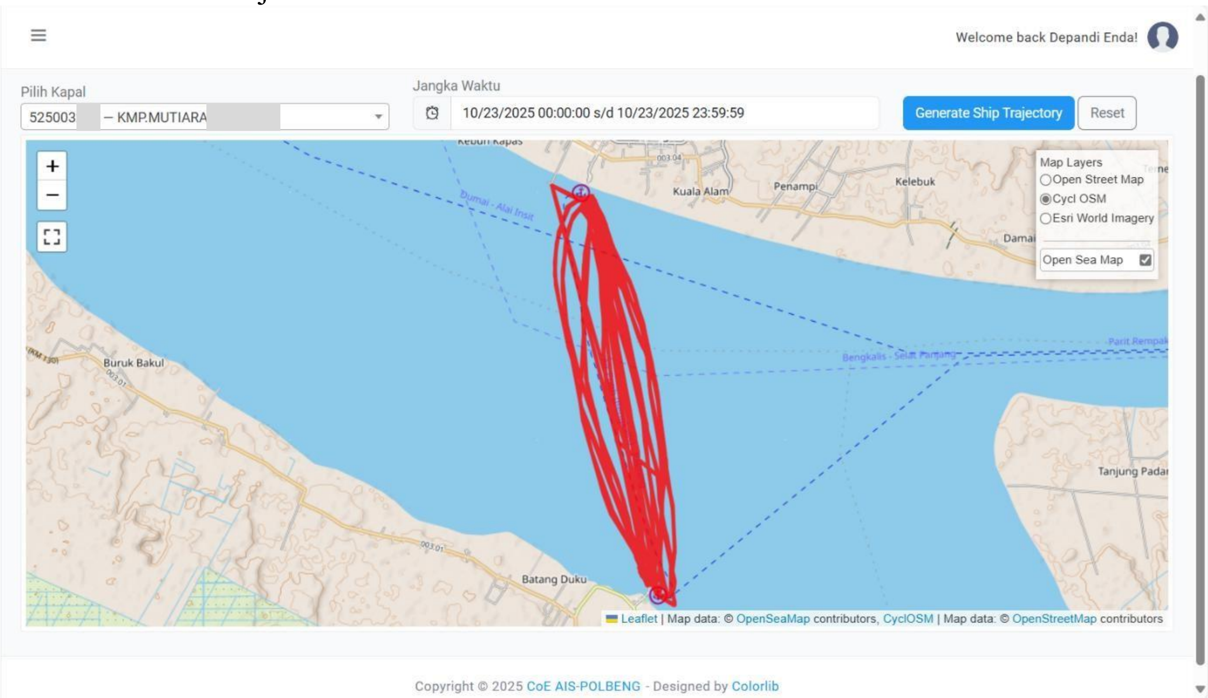

Fig. 3. Generate vessel trajectory history

System Testing

The average update rate evaluation for vessel position data was conducted using a short-range vessel trajectory on the Pakning–Bengkalis route. The testing period lasted for 1 hour and 10 minutes, starting when the initial departure point detected at 08:25 (Western Indonesia Time (WIB) and ending at the arrival point at 09:35 WIB. The results of the vessel trajectory tracking for the vessel with MMSI 525003XXX are presented in **Figure 4**.

Fig. 4. Result of trajectory tracking for vessel MMSI 525003XXX

The red line displayed on the map **(Figure 4),** represents the vessel's sailing route from the departure point at Roro Sungai Selari Port (Pakning) to the arrival point at Roro Air Putih Port (Bengkalis). The initial vessel position at 08:25 WIB was recorded at coordinates (Latitude: 1.378647; Longitude: 102.150032), while the final position at 09:34 WIB was recorded at coordinates (Latitude: 1.44932; Longitude: 102.138495). To facilitate the data analysis process, the distance calculation was performed using Jupyter Notebook. The next step was to compute the average update interval of the vessel position data.

```
[15]: #Make sure the timestamp is in datetime format
      position_df['timestamp'] = pd.to_datetime(position_df['timestamp'])
      #Calculate the time difference between points (seconds)
      position_df = position_df.sort_values('timestamp')
      position_df['time_diff'] = position_df['timestamp'].diff().dt.total_seconds()
      #Calculate the average update time
      average_update_time = position_df['time_diff'].mean()
      print(f"Average update time between points: {average_update_time:.2f} seconds")

      Average update time between points: 10.14 seconds
```

Fig. 5. Average update interval of coordinate data points

Based on **Figure 5**, the average data update interval for coordinate points was 10.14 seconds, indicating that the developed system can receive AIS data in compliance with the standards set by the IMO AIS Class A guidelines.

5. CONCLUSION

This study successfully developed a real-time vessel trajectory mapping system leveraging Automatic Identification System (AIS) data received from the AIS Remote Base Station at POLBENG. The system dynamically visualizes vessel movement on an interactive map built using Leaflet JS, supported by a Python-based backend, PostgreSQL, and Redis cache for temporary data storage. The implementation results demonstrate that the system can provide stable and consistent trajectory visualization with an average data update interval of 10.14 seconds, complying with standards for AIS Class A. Therefore, this system can serve as a decision-support tool for real-time AIS data analysis and visualization to enhance maritime research, vessel traffic monitoring, and navigational safety in waterways such as the Malacca Strait.

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