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ALGORITHM AND SOFTWARE FRAMEWORK FOR SHIP MOTION RECONSTRUCTION FROM VDR DATA ON THE FULL MISSION BRIDGE SIMULATOR K-SIM

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Abstract

This paper presents a novel algorithm and software framework for reconstructing ship motions from Voyage Data Recorder (VDR) data on the Full Mission Bridge Simulator (K-Sim). VDR data are converted from different formats, then processed to generate control commands transmitted to the K-Sim system. The proposed algorithm interpolates time steps between consecutive VDR frames, ensuring smooth and accurate ship motion simulation. Compared to traditional approaches, the proposed method enables fast, precise, and realistic reproduction of ship trajectories. Furthermore, after simulation, ship motion data can be exported as tables, plots, or videos for replay and further analysis. Experiments with real VDR datasets confirm the feasibility and accuracy of the method, highlighting its potential in maritime accident investigation and training.

Keywords: *VDR, K-Sim, Full Mission Bridge Simulator, Maritime Accident Investigation.*

1. Introduction

Voyage Data Recorders (VDRs) are mandated onboard ships to record navigational, sensor, and audio data for accident investigation and safety analysis. The IMO performance standard A.861(20) specifies the minimum data items and recording requirements, positioning the VDR as the maritime equivalent of an aviation "black box" [1]. However, this standard focuses on data acquisition and storage rather than on methods for reconstructing a voyage in an operationally realistic environment. In practice, investigators still face challenges related to data integrity, synchronization, interpretation, and security of recorded data, which can affect the reliability of accident reconstruction based on VDR records [4], [10].

In parallel, Full Mission Bridge Simulators provide a high-fidelity environment for maritime training and evaluation. Kongsberg Digital's K-Sim Navigation simulator offers realistic bridge equipment and integrated systems (e.g., radar, ECDIS, conning, and environmental effects) comparable to those on real ships, enabling comprehensive scenario-based training and assessment [2]. Existing research using K-Sim and similar bridge simulators has mainly focused on training effectiveness, competence assessment, and human factors, rather than on automated replay of recorded voyages [8].

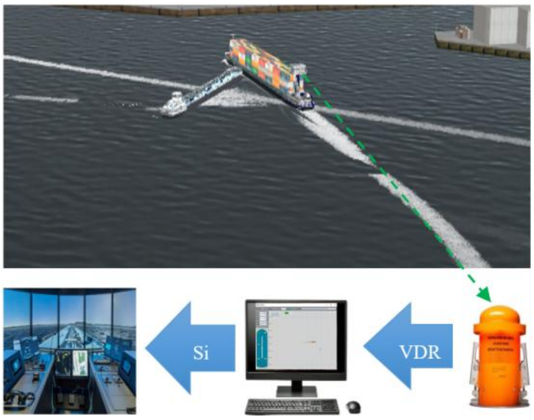

Figure 1. Overview of VDR data simulation solution

Previous studies have used recorded data to reconstruct events and vessel trajectories for accident analysis. For example, Piccinelli and Gubian analyzed the Costa Concordia accident from a digital forensics perspective using VDR data, providing insights into event sequences, but not reproducing the voyage in a synchronized full-mission bridge simulator [5]. Other works reconstructed ship trajectories using AIS data [6] or re-enacted accidents using AIS combined with virtual reality environments [9]. While these approaches support visualization and retrospective analysis, they are typically implemented in standalone/offline environments and do not reproduce a full-mission bridge setting synchronized to the original VDR timeline and bridge systems.

Data-driven ship motion simulation and forecasting methods have also been proposed. Yang et al. developed a dynamic data-driven ship motion simulation framework for visual-aided navigation [3], and Jiang et al. presented a data-driven method for ship motion forecasting [7]. These studies demonstrate the value of data-driven models for simulation and prediction, but they do not address the practical workflow of importing heterogeneous VDR data, interpolating the timeline, and controlling a full-mission bridge simulator to faithfully replay a recorded voyage.

Therefore, a gap remains in integrating real VDR recordings with Full Mission Bridge Simulators in an automated and reproducible manner. This paper addresses that gap by proposing an algorithm and software framework that converts VDR exports into a unified data structure, interpolates ship states between recorded frames, and transmits control commands to the K-Sim simulator for smooth and accurate voyage reconstruction in a realistic bridge environment.

2. Methodology

To reconstruct ship motions, the approach is to convert VDR data into JSON format, process it, and interpolate the time steps into sufficiently small intervals to feed into the K-Sim simulator, thereby achieving smooth motion reproduction consistent with the original data. The K-Sim Navigation simulator provides a full-mission bridge environment with integrated navigation systems and instructor control functionalities [2].

VDRs collect and store data from various onboard sensors and systems (AIS, GPS, gyro compass, radar, ECDIS, echo sounder, engine telegraph, VHF audio, etc.) [1]. Transmission formats generally follow IEC 61162/NMEA 0183 (ASCII sentences such as $GPGGA, $HDT) or IEC 61162-450 (Ethernet).

Internally, VDR data are often stored as proprietary binary files to ensure compression, synchronization, and security. Manufacturers (Kongsberg, Furuno, JRC, Danelec, etc.) each have specific formats. For data retrieval, utilities are usually provided to export into more common formats such as .DAT, .CSV, or .XLS/XLSX.

2.1. Data structure

In this study, the application converts various input formats into JSON. A ShipData class defines fields such as Time, Latitude, Longitude, Speed, Heading, Course, Rudder, and Propeller. A DataManager class reads the exported VDR files (Excel/XML), parses the content, and stores it as JSON for processing and time synchronization.

Table 1. List of main variables

No.	Parameters/Variables
1	Time
2	Latitude/Longitude
3	Speed
4	Heading
5	Course
6	Heel
7	Pitch
8	Propeller_Level
9	Rudder_Angle

2.2. Motion reconstruction algorithm (Motion class)

The algorithm reads JSON data and subdivides the time interval between consecutive VDR frames (usually 1 second) into multiple smaller steps (dt < 1). Linear interpolation is applied to calculate position, speed, and heading at each sub-step, ensuring smooth motion.

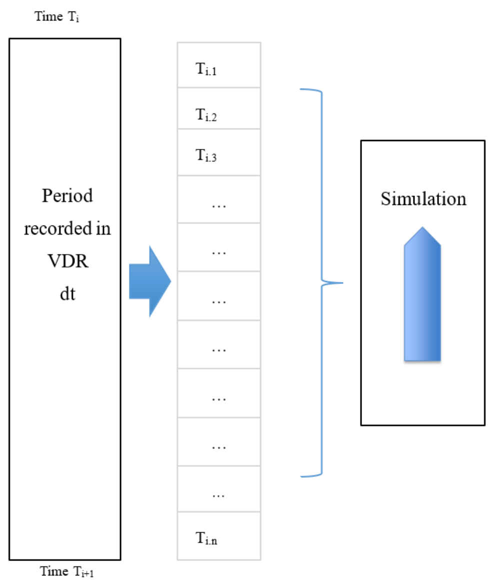

Figure 2. Diagram illustrating the principle of subdividing the time step to smooth ship motion

2.3. Ship control in K-Sim (KsimControl class)

The reconstructed ship states are transferred to the K-Sim simulator in three ways:

1. UDP/NMEA streaming: Interpolated VDR states are transmitted via UDP/NMEA at each sub-

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time ($T_{i,j}$) to update ship motion and redraw the 3D state.

2. Direct parameter update: Control variables can be directly updated in the simulation control panels depending on the ship model.

3. Autopilot input: Commands are sent to the autopilot system within K-Sim, which then manoeuvres the ship to the required states.

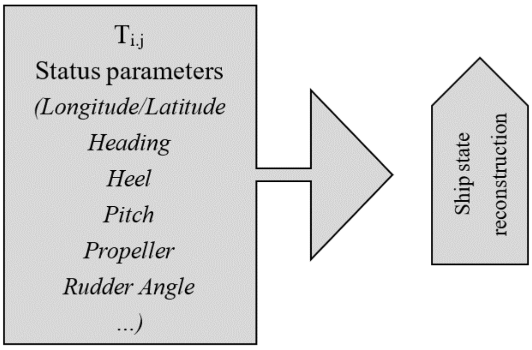

Figure 3. Data transmission method for reconstructing ship states (1, 2)

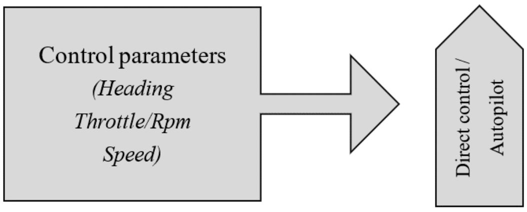

Figure 4. Direct ship control method using the autopilot system

A hybrid method combining state updates and autopilot commands is used to ensure accurate heading, speed, and realistic environmental effects.

2.4. API application development

As described in the previous section, the API application was developed based on the main code classes. Figure 5 illustrates the detailed communication flow between modules, including JSON data conversion, motion interpolation, and real-time UDP/NMEA transmission from VDR processing to simulator control through the API interface.

- DataManager: Converts VDR data from various formats into JSON.

- Motion Algorithm: An algorithm that subdivides the VDR data over defined time intervals into smaller time steps to ensure smooth ship motion. It reconstructs the motion within the application window.

- K-Sim Control: The main API code responsible for communicating with and transmitting data to the K-Sim simulation to reproduce ship motion. A UDP/NMEA communication method is used, compatible with K-Sim. This code block also sends control signals based on VDR data to K-Sim and operates the ship via the integrated autopilot system in the simulation.

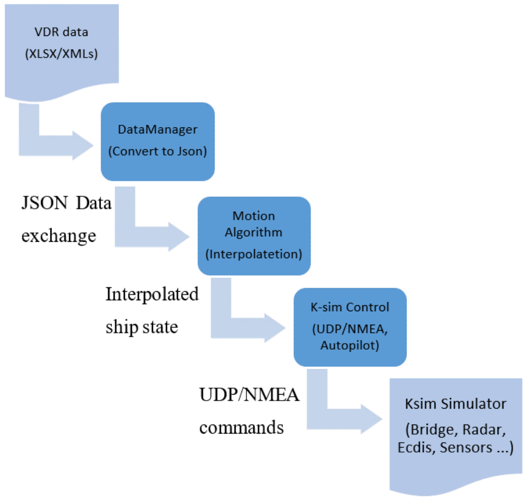

Figure 5. Diagram illustrating the principle of ship motion reconstruction on the K-Sim simulation based on VDR data

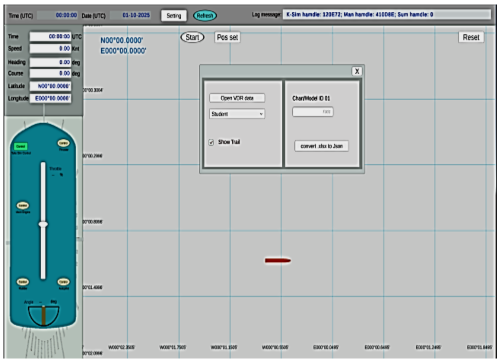

Figure 6. Main interface of the application

- K-Sim Simulator: A bridge simulation system in which the initial scenario is set according to the initial time of the VDR data. The ship models are selected to match the vessel being simulated, and meteorological and environmental conditions are configured to reflect real situations (wind, waves, currents, tides, and weather conditions). During the replay in the simulation, ships move accurately according to the VDR data. When 3D data is available, the system also integrates it for visualization. Since the replay runs directly on the simulated bridge, navigational equipment such as Radar, ECDIS, speed log, GPS, gyrocompass, echo sounder, etc., are displayed in sync with the simulation timeline, enabling comprehensive and realistic simulation of scenarios based on VDR data.

3. Results

A simulation case was conducted using VDR data generated from a simulated collision scenario between a tanker and a container vessel on the New Maas River in Rotterdam. The application output is also demonstrated in a supplementary video (see Appendix).

Table 2. Main particulars of used ship models

Ship model	Tanker	Container
LoA	110 m	135 m
B	11.44 m	14.2 m
T	2.25 m	2.6 m
Propulsion	1 x 1520 HP	2 x 1278 HP
Propellers	1	2
Rudders	1	2

Table 3. Extract of the Tanker VDR data

Time	Latitude [º]	Longitude [º]	Speed [kn]	Heading [º]	Course [º]
00:00	51.901684	4.425282	7.2014	88.8411	88.8411
00:08	51.901687	4.426623	6.9107	88.8312	88.8312
00:18	51.901694	4.427123	6.4699	88.7090	88.7091
00:28	51.901700	4.427594	6.1093	88.4481	88.4480
00:38	51.901706	4.428039	5.7998	88.1005	88.1007
00:48	51.901714	4.428460	5.5030	87.6548	87.6549
00:58	51.901722	4.428861	5.2341	87.1118	87.1116
01:08	51.901731	4.429243	4.9893	86.4620	86.4622
01:10	51.901733	4.429317	4.9631	86.3252	86.3251
01:28	51.901756	4.429956	4.5819	85.0038	85.0039
01:38	51.901771	4.430289	4.3836	84.2039	84.2037
01:48	51.901787	4.430609	4.1963	83.3559	83.3560
01:58	51.901806	4.430916	4.0444	82.4703	82.4704
02:08	51.901825	4.431211	3.9120	81.5358	81.5358
02:18	51.901847	4.431494	3.7536	80.5053	80.5052
02:28	51.901871	4.431767	3.6129	79.4045	79.4047
02:38	51.901896	4.432030	3.4905	78.2631	78.2629
02:48	51.901923	4.432283	3.3879	77.0858	77.0856
02:58	51.901949	4.432528	3.2671	75.6488	75.6490
03:08	51.901981	4.432767	3.3127	73.9472	73.9471

The main particulars of the ship models are presented in Table 2, and the VDR data of the tanker model are shown in Table 3.

The main interface of the VDR application is presented in Figure 6, and an overall view of the simulation controlled by the API application is illustrated in Figures 7-10.

To validate the reconstruction accuracy, the extracted VDR data (Table 3) and the simulator outputs (Table 4) were compared. In addition, a detailed graphical comparison between the VDR input data and the maneuvering results from the simulation is presented in Figures 11-14.

Table 4. Maneuvering data of the ship (Tanker) exported from simulation

Time	Latitude [º]	Longitude [º]	Speed [kn]	Heading [º]	Course [º]
00:00	51.901.681	4.426.201	7.2014	888.411	888.411
00:08	51.901.686	4.426.623	6.8972	887.789	887.791
00:18	51.901.692	4.427.123	6.4941	885.387	885.387
00:28	51.901.698	4.427.594	6.1262	881.327	881.326
00:38	51.901.705	4.428.039	5.7955	876.189	876.190
00:48	51.901.714	4.428.461	5.5105	870.356	870.356
00:58	51.901.724	4.428.861	5.2272	863.669	863.668
01:08	51.901.737	4.429.242	4.9616	855.829	855.827
01:10	51.901.751	4.429.606	4.7583	847.169	847.166
01:28	51.901.768	4.429.953	4.5593	837.775	837.777
01:38	51.901.787	4.430.285	4.3702	828.017	828.015
01:48	51.901.808	4.430.603	4.1860	818.067	818.067
01:58	51.901.832	4.430.907	4.0161	808.088	808.091
02:08	51.901.857	4.431.200	3.8741	797.440	797.441
02:18	51.901.884	4.431.480	3.7273	786.502	786.501
02:28	51.901.913	4.431.750	3.5943	775.775	775.775
02:38	51.901.943	4.432.009	3.5001	764.896	764.896
02:48	51.901.975	4.432.257	3.2604	754.756	754.758
02:58	51.902.003	4.432.490	3.1333	741.855	741.854
03:08	51.902.033	4.432.723	3.2833	720.596	720.596

The deviations between the two datasets are summarized in Table 5, and the maximum, minimum, and average values of these errors are reported in Table 6. As no international standard currently specifies acceptable error thresholds specifically for VDR-to-full-mission-simulator trajectory reconstruction, the deviations in Table 6 are evaluated by benchmarking them against the established IMO/IEC performance

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Table 5. Deviations between the reconstructed simulation data and the original VDR measurements

Time	Latitude Diff [m]	Longitude Diff [m]	Speed [kn]	Heading [°]	Course [°]
00:00	-0.005	0.000	0.00	0.00	0.00
00:08	-0.003	0.000	-0.01	-0.05	-0.05
00:18	-0.005	0.001	0.02	-0.17	-0.17
00:28	-0.004	0.001	0.02	-0.32	-0.32
00:38	-0.003	0.001	0.00	-0.48	-0.48
00:48	0.001	0.000	0.01	-0.62	-0.62
00:58	0.005	-0.001	-0.01	-0.74	-0.74
01:08	0.010	-0.001	-0.03	-0.88	-0.88
01:10	0.034	-0.005	-0.20	-1.61	-1.61
01:28	0.022	-0.008	-0.02	-1.23	-1.23
01:38	0.031	-0.011	-0.01	-1.40	-1.40
01:48	0.039	-0.015	-0.01	-1.55	-1.55
01:58	0.049	-0.020	-0.03	-1.66	-1.66
02:08	0.058	-0.025	-0.04	-1.79	-1.79
02:18	0.067	-0.032	-0.03	-1.86	-1.86
02:28	0.077	-0.038	-0.02	-1.83	-1.83
02:38	0.087	-0.049	0.01	-1.77	-1.77
02:48	0.097	-0.070	-0.13	-1.61	-1.61
02:58	0.100	-0.083	-0.13	-1.46	-1.46
03:08	0.097	0.000	-0.03	-1.89	-1.89

Table 6. Statistical summary of deviations between simulation data and VDR measurements

Value	Latitude Diff [m]	Longitude diff [m]	Speed [kn]	Heading [°]	Course [°]
Max	0.01	0.09	0.02	0.00	0.00
Min	0.00	0.00	-0.20	-1.89	-1.89
Mean	0.00	0.01	-0.03	-1.15	-1.15

standards of the source shipborne sensors typically recorded by the VDR, including GNSS position, speed and distance measuring equipment, and transmitting heading devices [11]-[14].

As summarized in Table 7, the maximum position deviation (0.09m) is far below the IMO shipborne GNSS accuracy requirement [14], the speed

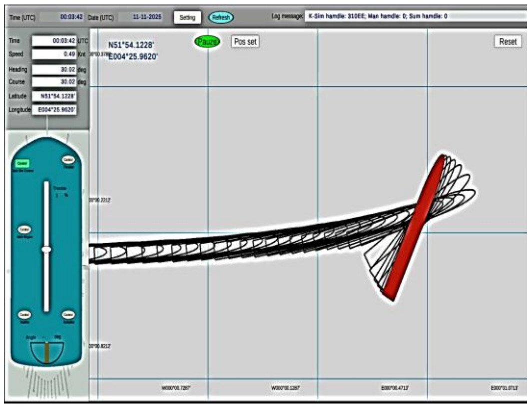

Figure 7. Tanker ship track reconstructed in the application

Figure 8. Ship track map based on VDR data on the K-Sim simulation

Figure 9. 3D scene reconstructed in the simulation

deviation is within the IMO speed and distance accuracy limits [12], and the mean heading/course discrepancy (−1.15°) is comparable to the IMO transmitting heading device accuracy under dynamic conditions [13].

These results indicate that the reconstructed trajectory in K-Sim is consistent with the nominal accuracy of standard shipborne instrumentation recorded by the VDR.

Table 7. Benchmarking deviations in Table 6 against IMO/ IEC performance standards

Metric	Table 6 deviation	Standard	Limit (per standard)	Result
Position	Max 0.09 m (Lon)	MSC.112(73); IEC 61108-1	GNSS accuracy (95%)	Within
Speed	Mean −0.03 kn	A.824(19)	≤ 2% or 0.2 kn	Within
Heading/ Course	Mean −1.15°	MSC.116(73)	±1.0° (static), ±1.5° (dynamic)	Within

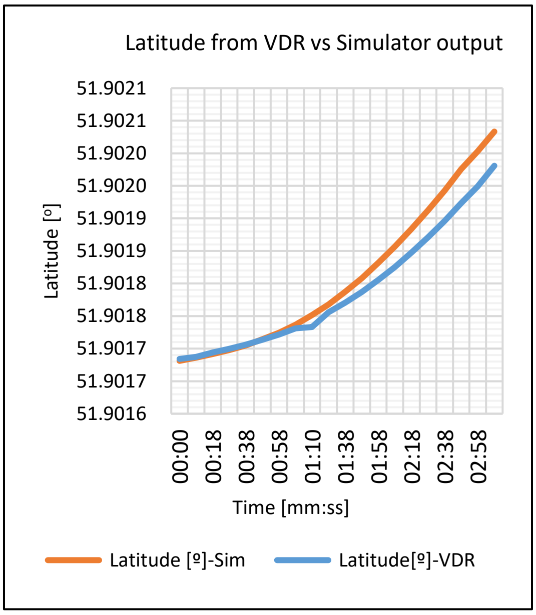

Figure 11. Latitude of the tanker ship from simulation versus VDR data

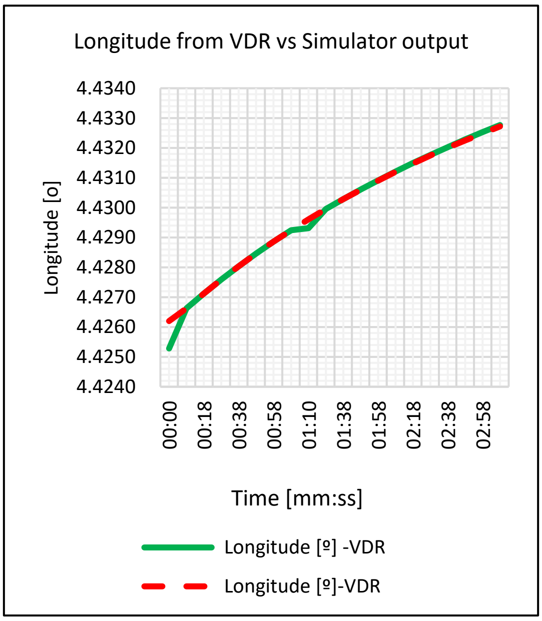

Figure 12. Longitude of the tanker ship from simulation versus VDR data

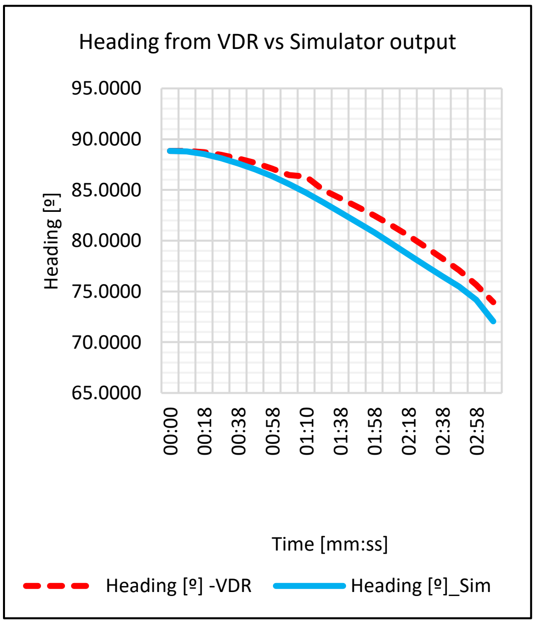

Figure 13. Heading of the tanker ship from simulation versus VDR data

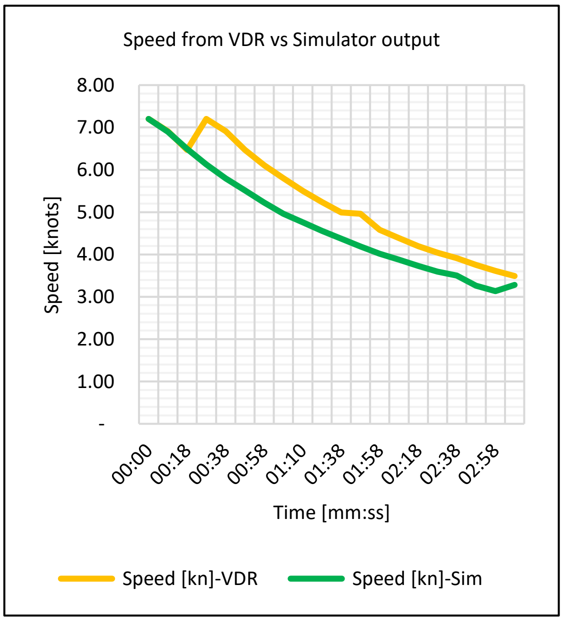

Figure 14. Speed of the tanker ship from simulation versus VDR data

associated IEC testing standard IEC 61108-1, specifies shipborne GNSS position accuracy of 100 m (95% probability) under specified test conditions [14], [11].

IMO Resolution A.824(19) defines speed and distance measuring accuracy not exceeding 2% of the vessel speed or 0.2kn, whichever is greater [12].

IMO MSC.116(73) specifies transmitting heading device accuracy within ±1.0° under static conditions and ±1.5° under dynamic ship motions [13].

The API operates seamlessly on the K-Sim instructor PC without additional hardware and achieves real-time performance. With this integrated capability, simulation data can be exported as tables, time-series graphs (e.g., heading, speed), or video replays to support accident investigation and training. The application was validated using real VDR data, and K-Sim successfully reproduced the ship's trajectory on ENC, radar, and ECDIS under realistic environmental conditions. The reconstructed motion and 3D visualization of the vessel were accurate and continuous, meeting the requirements for detailed maneuvering and navigation scenario simulations based on real VDR recordings.

4. Conclusion

This paper has introduced a new algorithm and software application for converting VDR data into simulations within K-Sim. The proposed solution overcomes the limitations of traditional methods, providing improved accuracy, visualization, and time efficiency.

The experimental results demonstrate its feasibility and potential for wide application in accident investigation, training, and maritime safety research.

Future developments may include simultaneous multi-ship simulations, integration of AIS data, radar overlay, real-time environmental conditions, and enhanced preprocessing techniques for handling incomplete or noisy VDR data.

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Appendix

Video demonstration:

A demonstration video of the developed API application is available at: https://www.youtube.com/watch?v=6yg9Tvjctj0

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