From VesselAI to TwinShip: AI-Powered Maritime Analytics and Digital Twins

Loukas Ilias, Afroditi Blika, Ariadni Michalitsi-Psarrou, Theodoros Florakis, Giannis Xidias, Vassilis Michalakopoulos, Spiros Mouzakitis, Dimitris Askounis

DSS Lab, School of ECE, NTUA

15780 Athens, Greece

{lilias, ablika, amichal, tflorakis, gxidias, vmichalakopoulos, smouzakitis, askous}@epu.ntua.gr

I. Abstract

VesselAI Platform. This demo presents the VesselAI platform [1], [2], developed under the Horizon 2020 program, which delivers advanced maritime analytics through AI-based decision support, voyage optimization, and risk forecasting. The system ingests and harmonizes large-scale, heterogeneous big data sources - including Automatic Identification System (AIS) data, noon reports, oceanographic and meteorological data, and bathymetry - and processes them through machine learning and signal processing pipelines. Real-world use cases will be demonstrated, such as vessel route prediction, fuel consumption estimation, and automatic weather routing.

TwinShip Platform. The demo will also introduce the next phase of this work - the TwinShip [3] project (Horizon Europe) - which aims to extend VesselAI into a digital twin framework for real-time simulation. Early-stage User Interface (UI) prototypes and planned features from TwinShip will be shown alongside VesselAI's current capabilities.

Novelty. The novelty of this demo lies in the following:

- Integration of real-time signal and data processing, graph-based AI models, and predictive analytics into a fully operational, real-world system.
- Unlike many academic frameworks, VesselAI has been deployed and validated in actual maritime scenarios, delivering valuable advantages in terms of safety, fuel efficiency, and route optimization.
- In contrast to proprietary platforms, VesselAI is open-source, enabling transparency, reproducibility, and community-driven innovation.
- TwinShip aims to revolutionize the maritime domain through the development of digital twins, the use of real-time sensor data, and retrofitting options.

Overall, this integration of advanced data-driven methods into a deployed platform highlights the real-world potential of signal processing and machine learning (ML) in complex, safety-critical environments. The demo bridges theory and practice by showcasing how academic models become operational maritime tools.

II. Technical Details

Data Harmonization. The harmonization process integrates diverse datasets including AIS data, noon reports, oceanographic and meteorological data, and bathymetry. It leverages technologies such as a big data relational database (MonetDB), object storage and query engines (MinIO, Trino), and semantically enriched data representations.

Data Exploration Tool. An advanced query builder will be demonstrated though this demo, which has access to datasets stored in a datalake.

AI Services:

Vessel Route Forecasting. Vessel route forecasting (VRF) involves the task of predicting future routes and paths of vessels based on various factors such as historical navigation data, real-time conditions (fuel consumption, cost, and weather conditions). VRF ensures efficient navigation, planning, and decision-making in maritime operations.

Vessel Traffic Flow Forecasting. It is of paramount importance to secure efficient maritime navigation within the maritime domain. Vessel Traffic Flow Forecasting (VTFF), which assesses the quantitative activity level in a specific maritime area, plays a critical role in maritime navigation.

Vessel Collision Risk Assessment and Forecasting. Maritime traffic patterns are dynamic and influenced by numerous factors such as weather, vessel behavior, and navigational decisions. Accurately evaluating the potential for collisions among a group of monitored ships is a critical component of ensuring maritime safety.

Shore Control and Unmanned Vessels. This component predicts routes and detects unexpected behaviour of surrounding traffic, and finally utilizes the "Vessel Collision Risk Assessment and Forecasting" component.

Port Mooring Area Clustering. Port mooring area clustering helps optimize berth usage, reduce vessel waiting times, and improve overall operational efficiency. By identifying patterns in how different types of ships use mooring spots, port authorities can better allocate resources and plan infrastructure. It also enhances safety, supports environmental monitoring, and helps detect anomalies or unauthorized activities.

Fuel Consumption. Fuel consumption is monitored through the development of advanced ML algorithms utilizing multiple data sources. This component monitors the fuel consumption of both auxiliary and main engines.

CO_2 **Emissions.** These predictions help optimize routes and speeds, and are essential for meeting IMO regulations like EEXI and CII.

AI workflows - Airflow. VesselAI's Apache Airflow orchestrates AI model training and inference pipelines stored as Direct Acyclic Graphs (DAGs). As the orchestrator, Airflow executes the tasks of the pipelines in the correct order and ensures that the overall process is successful. The Airflow instance of VesselAI is equipped with all the necessary packages required to execute all the available model training and inference pipelines.

Data Visualization - Creation of Reports. The Visualization and Reporting Engine service provides User Interfaces with visualization, dashboarding, and reporting functionalities. This component has utilized established visualization technologies, such as Apache Superset. Apart from Apache Superset, this component has also been enhanced with the necessary visualization and reporting mechanisms and strategies, so as to ensure that it is aligned with the needs and objectives of VesselAI stakeholders.

From VesselAI to TwinShip - TwinShip's Vision. TwinShip project introduces a Digital Twin (DT) enabled Decision Support System (DSS) into the VesselAI digital platform. Leveraging both operational pilot vessels and a visionary concept for unmanned ships, the project aims to cut greenhouse gas emissions by 30-40% by 2030, 80-90% by 2040, and ultimately reach net-zero emissions by 2045, using 2008 as the baseline. Voyage optimization, retrofitting options, machinery performance and control, engine-propeller combinator diagram, lifecycle cost analysis, and so on, will be some of the use cases of the TwinShip platform. To facilitate the development of the use cases, large language models (LLMs) and AI agents will be used.

Demo Content.

- Pre-recorded video demonstrations of VesselAI platform's capabilities and use cases (trajectory prediction, route optimization, fuel estimation, data exploration tool, visualization engine, etc.).
- A locally hosted dashboard running in Docker for walkthrough of selected features.
- Integrated UI prototypes and early-stage interface components from the upcoming TwinShip project, illustrating planned features such as digital twin visualization.

Software Requirements. A software stack has been put in place built upon the RedHat Linux. Several components are included: (i) Batch Manager (Slurm), (ii) Message Passing Interface (MPI) stack using Open MPI, (ii) Performance toolkit (an extension version of HPC Toolkit, PAPI, and third-party products), (iii) Acceleration Environment (specific packaged drivers and compilation tools respectively for accelerators such as NVIDIA/GPUs, ALTERA/FPGAs), (iv) Maintenance Manager, (v) parallel file system based on the Intel® Enterprise Edition of Lustre (IEEL) core.

Hardware Requirements. (i) CPU: Intel's homogeneous Numa, (ii) GPU: Nvidia V100(5120 cores/32GB), (iii) FPGA: Intel /Stratix 10 GX2800, (iv) Interconnection Fabric: InfiniBand FDR (56 Gb/s) and Ethernet (10GB/s) will be the corresponding protocols, (v) Memory Storage Hierarchy: HPL/HPCG benchmarks, 300TB storage capacity.

III. Relevance

The demonstration addresses key challenges in applied signal processing and AI integration within the maritime domain, leveraging complex, heterogeneous big data sources such as AIS data, oceanographic measurements, meteorological forecasts, and bathymetry. This data is harmonized and enriched semantically to support real-time analytics and predictive modeling, which are central themes in signal processing research. Some of the signal processing and AI-driven services, which are implemented by the platform and are aligned with the EUSIPCO topics are:

- Vessel Route Forecasting, combining neural networks and graph-based clustering to predict vessel trajectories from time-series data.
- Vessel Traffic Flow Forecasting and Collision Risk Assessment, which rely on spatiotemporal modeling and sensor fusion.
- Voyage Optimization via automatic weather routing, an optimization problem informed by dynamic environmental signals.
- Fuel Consumption Estimation, where data-driven modeling integrates weather, speed, and engine signals.
- Port Clustering, which uses pattern recognition and unsupervised learning on spatial and signal-based features.

These applications demonstrate how modern signal processing methods - such as trajectory analysis, time-series prediction, sensor fusion, and clustering - can be deployed in a real-world, operational AI system. The extension into the TwinShip project introduces the digital twin paradigm, integrating live sensor data and real-time simulation for predictive monitoring and operational optimization.

By bridging theory and implementation across multiple projects (Horizon 2020 and Horizon Europe), this demo is highly relevant to the EUSIPCO community's mission to advance signal processing through big data addressing key societal and industrial challenges.

IV. Logistics

Setup. The demo will run on a standard laptop.

Requirements. Power outlet; internet connectivity; small table space.

Format. Combination of video demonstration, live UI navigation, and poster presentation describing system architecture and use cases.

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References

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[3] Twinship: Integrated digital twin framework to enable green ship operations towards zero emission vessels. https://twin-ship.eu/.