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DEVELOPMENT OF AN EXPERT SYSTEM FOR EVALUATING VESSEL MOVEMENT TRAJECTORIES DURING SIMULATOR TRAINING OF NAVIGATION CADETS

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Abstract. *This thesis describes the development of an expert system for analyzing vessel movement trajectories with the aim of promptly detecting hazardous deviations caused by human factors and inadequate qualification of ship operators. The system performs preliminary data processing, identifies critical points using a nearest neighbor search algorithm, and compares test data with reference data in terms of coordinates and speed, based on data from the ECDIS Wärtsilä Navigation Simulator NTPRO 5000 server. The application of statistical methods—such as mean absolute deviation, maximum deviation, and standard deviation—and a penalty scoring rule enables a quantitative assessment of deviations. Interactive visualization in the form of bar charts and maps facilitates the rapid detection of anomalies and the adoption of well-founded decisions to enhance maritime safety. The prospective implementation of this system will ensure route optimization, reduce accident rates, and enable integration with modern monitoring systems.*

Xülasə. *Bu məqalədə insan faktorunun və gəmi operatorlarının qeyri-adekvat şəraitdə səbəb olduğu təhlükəli xətaların operativ şəkildə aşkar edilməsi məqsədilə gəmilərin hərəkət trayektoriyalarının təhlili üçün ekspert sisteminin işlənib hazırlanmasından bərpa edilir. Sistem ilkin məlumatların işlənməsini həyata keçirir, ən yaxın qonşu axtarış alqoritmindən istifadə edərək kritik nöqtələri müəyyən edir və ECDIS Wärtsilä Naviqasiya Simulyatoru NTPRO 5000 serverindən alınan məlumatlar əsasında test məlumatlarını koordinatlar və sürət baxımından istinad məlumatları ilə müqayisə edir. Orta mütləq kənarlaşma, maksimum kənarlaşma və standart kənarlaşma kimi statistik metodların tətbiqi kənarlaşmaların kəmiyyətcə qiymətləndirilməsinə imkan verir. Ştrixli diaqramlar və xəritələr şəklində interaktiv vizuallaşdırma anomaliyaların tez aşkar edilməsini və dəniz təhlükəsizliyini artırmaq üçün əsaslı qərarların qəbulunu asanlaşdırır. Bu sistemin perspektiv tətbiqi marşrutun optimallaşdırılmasını təmin edə, qəzaların sayını azalda və müasir monitorinq sistemlərilə inteqrasiyaya imkan yarada bilər.*

Key words: *expert system, vessel movement trajectories, human factor, ECDIS, statistical analysis, visualization, maritime safety*

Açar sözlər: *ekspert sistemi, gəmi hərəkət trayektoriyaları, insan faktoru, ECDIS, statistik analiz, vizuallaşdırma, dəniz təhlükəsizliyi*

Introduction. In today's era of globalization and the increasing intensity of maritime traffic, the safety of maritime transport assumes paramount importance [1]. Despite significant advancements in automated control systems, the human factor remains one of the most critical aspects influencing the efficiency and safety of navigation [2]. Insufficient qualification, limited experience, and psychological instability among ship operators often lead to deviations from prescribed trajectories, potentially resulting in accidents [3]. According to statistical data, 75–80% of accidents in the maritime industry are associated with errors by ship operators, underscoring the urgent need to consider both the human factor and the qualification level of these operators [4].

Given these circumstances, the relevance of developing an integrated expert system within Electronic Chart Display and Information Systems (ECDIS) for analyzing vessel movement trajectories becomes particularly significant [5]. A system capable of promptly detecting potentially hazardous deviations—caused by both human error and an insufficient level of professional training among navigation cadets during practical training on the Wärtsilä Navigation Simulator NTPRO 5000–will facilitate the timely identification of risky situations. In turn, this will contribute to enhancing safety levels, optimizing crew performance, and reducing the number of accident incidents, which bear serious social and economic consequences.

Formulation of the issue. When developing a navigation trajectory monitoring system, a developer faces several challenges, notably the insufficient ability to detect minor yet critical deviations that may indicate potential hazards. Existing analytical methods do not always take into account the individual characteristics of ship operators–their experience, qualification level, and psychological state–which can lead to ineffective forecasting of accident scenarios.

The primary issue lies in the absence of an integrated expert system that could:

1. Systematically process large volumes of navigation data from the ECDIS server and identify critical points along the route.
2. Detect minor deviations from prescribed trajectories, which may result from human errors or insufficient professional experience.
3. Evaluate the impact of individual characteristics of ship operators, including both technical parameters (such as coordinates and speed) and psychological factors that affect decision-making under stress.

Thus, addressing this problem entails developing an analytical tool that ensures timely and accurate identification of potentially hazardous deviations in navigation trajectories, which is critical for enhancing maritime transport safety and reducing the risk of accidents.

Analysis of the results achieved. Given the task of developing an effective software solution for analyzing vessel movement trajectories to detect potentially dangerous deviations, it is necessary to employ a comprehensive approach that combines modern algorithmic, mathematical, and statistical data processing methods. Considering the requirements for the timely detection of anomalies caused by the influence of the human factor and the inadequate qualification of ship operators, the system must ensure:

- Optimal Data Processing: Integration of mechanisms for preliminary data loading, cleaning, and normalization for subsequent analysis.
- Determination of Critical Points: Utilization of nearest neighbor search algorithms to accurately identify key points in vessel movement trajectories.
- Statistical Evaluation of Deviations: Application of methods for calculating mean values, variances, and standard deviations to quantitatively characterize deviations from reference data.

Thus, taking these requirements into account, we proceed to a detailed description of the algorithmic and mathematical apparatus to be implemented in the expert system. This will enable high-precision data analysis, optimization of the processing of large volumes of information, and timely detection of potential risks to enhance maritime safety.

1. Data Preprocessing

1.1. Algorithmic Aspect:

The Pandas library is used to load data from Excel files.

Data is cleansed of erroneous values using the dropna() method, ensuring the presence of the essential parameters: latitude (LAT), longitude (LON), and time (Time).

1.2. Mathematical Apparatus:

Format Conversion:

- String values containing a decimal comma are converted to a numeric format by replacing the comma with a period.

- Numeric values of coordinates and speed are converted to a numeric type using the pd.to_numeric() function.

Time Calculation:

Unix time is converted into the datetime format for convenient time series analysis.

2. Determination of Critical Points (Waypoint Selection)

2.1 Algorithmic Aspect:

- The function determine_key_points() is employed, which accepts the data and a set of desired latitude values (lat_points).

- For each target latitude value, a search is conducted in the dataset for the element whose absolute difference between the observed and the target latitude is minimal (nearest neighbor algorithm).

2.2. Mathematical Apparatus:

- One-dimensional search using a minimization principle:

- Difference Calculation:

$$d_i = \left| LAT_i - lat_{\text{target}} \right| .$$

- Determination of index i^*:

$$i^* = \arg\min_i d_i \cdot$$

Calculate the absolute difference between the observed and target latitude values.

3. Discrepancy Calculation

3.1. Algorithmic Aspect:

- The function calculate_discrepancies() compares the key points from the test data with the reference key points.

- For each reference point, the closest corresponding point in the test data is identified by minimizing the absolute difference in latitude.

3.2. Mathematical Apparatus:

- Difference Calculation:

- For each parameter (longitude and speed), the difference is computed as:

$$\Delta LON = LON_{test} - LON_{ref} ,\ \ \Delta SOG = SOG_{test} - SOG_{ref} .$$

- Evaluation of Variations:

- The squares of the differences are calculated to analyze the variance:

$$LON\_\text{var} = \left(\Delta LON\right)^2 ,\ \ SOG\_\text{var} = \left(\Delta SOG\right)^2 .$$

These values serve as indicators of deviation from the reference.

4. Expert System for Navigation Data Evaluation

4.1. Algorithmic Aspect:

- The function expert_system() aggregates the deviation data for each file.
- Statistical metrics–mean absolute deviation, maximum deviation, and standard deviation for longitude and speed–are calculated.
- Threshold values are then applied to adjust an initial score (e.g., 100 points) by subtracting penalty points according to the degree of deviations.

4.2. Mathematical Apparatus:

- Statistical Analysis:

- Mean Absolute Deviation:

$$\left|\overline{\Delta LON}\right| = \frac{1}{n}\sum_{i=1}^{n}\left|\Delta LON_i\right|,\ \left|\overline{\Delta SOG}\right| = \frac{1}{n}\sum_{i=1}^{n}\left|\Delta SOG_i\right|.$$

- Maximum Deviation: $\max\left|\Delta LON\right|,\ \max\left|\Delta SOG\right|$.
- Standard Deviation:

$$\sigma\Delta LON = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\left|\Delta LON_i\right| - \left|\overline{\Delta LON}\right|\right)^2}, \sigma\Delta SOG = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\left|\Delta SOG_i\right| - \left|\overline{\Delta SOG}\right|\right)^2}$$

Rule-Based Scoring:

- Discrete thresholds are set so that exceeding a specific value of mean or maximum deviation results in the subtraction of fixed penalty points (e.g., 10, 20, or 30 points).

This approach allows a quantitative assessment of the degree of deviation and implicitly accounts for the impact of psychological factors via the standard deviation calculation.

5. Visualization of Results

5.1. Algorithmic Aspect: The function plot_trajectories() utilizes the Folium library to create an interactive map that displays the vessel trajectories and key points (see Figure 1).

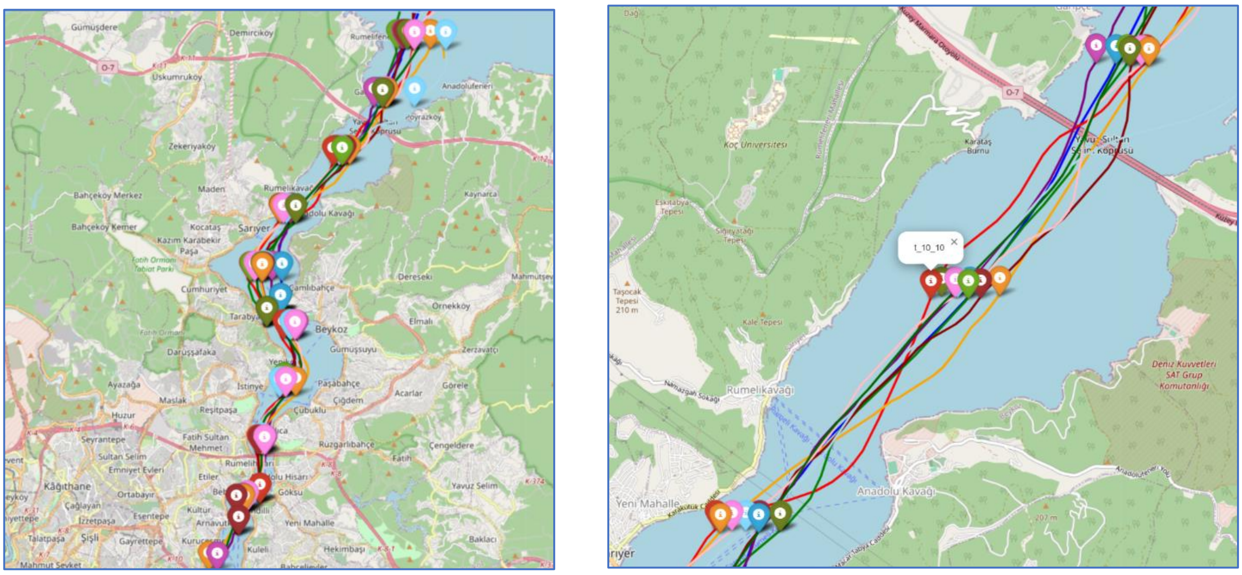

Fig. 1. *Visualization of Vessel Movement Trajectories Based on ECDIS Data*

Using the Plotly Express library, a bar chart is generated to visualize the expert evaluation across files.

5.2. Mathematical Apparatus: Geometric Visualization:

Trajectories are constructed by connecting consecutive coordinates (LAT, LON) using polyline segments.

Statistical Visualization: The bar chart graphically represents the distribution of scores, allowing for a rapid assessment of the qualitative characteristics of the analysis and the detection of anomalies.

Thus, the program's algorithmic apparatus is based on sequential data processing—from loading and cleaning the data to identifying key points, calculating deviations, and performing their statistical analysis (see Fig. 2). In turn, the mathematical aspect includes minimization methods for nearest neighbor search, the computation of differences and variances, as well as the application of statistical measures for assessing the quality of navigation data. The integration of these approaches enables the development of an expert system capable of detecting potentially hazardous deviations caused by the human factor or insufficient professional experience of ship operators, thereby enhancing maritime safety.

Fig. 2. *Diagram of the Expert System for Analyzing Vessel Movement Trajectories*

Visualization in the form of a graph offers a clear representation of the evaluation results of vessel movement trajectories performed by the expert system (see Fig. 3).

Thus, the resulting graph enables: *Quick Anomaly Identification*:

- Displaying the scores as a chart immediately reveals which trajectories exhibit significant deviations from the reference, indicating potential risks.

  Comparison of Results Across Files:
- Thanks to the horizontal orientation and a unified scale (from 0 to 100), scores from different files can be easily compared to determine where the level of conformity to the reference trajectory is lowest.

  Access to Additional Information:

  Interactive tooltips that appear when hovering over chart elements provide extended details on the causes of deviations, allowing for a deeper analysis of potential issues in vessel navigation.

  Enhanced Decision-Making:
- Clear visualization facilitates prompt data analysis, enabling swift responses to critical situations, adjustments to operational procedures, and the implementation of necessary measures to improve maritime safety.

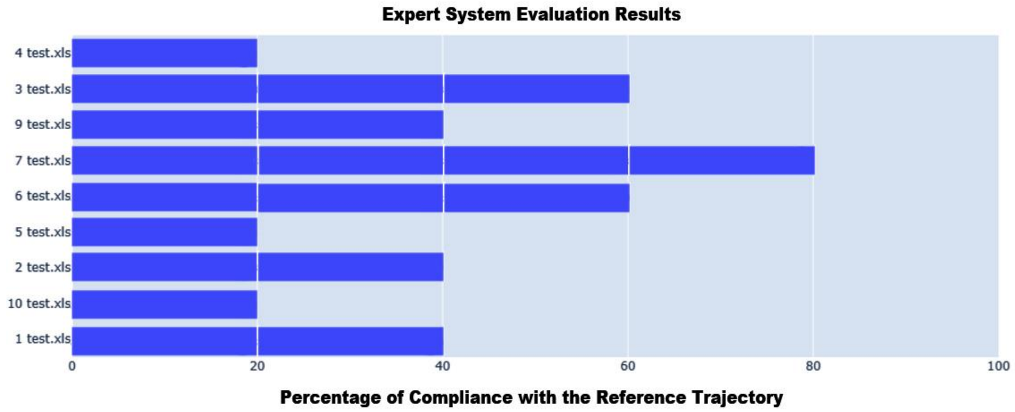

Fig. 3. *Visualization of the Expert System Conclusion*

Result. Thus, the developed expert system is based on a comprehensive algorithmic and mathematical framework for analyzing vessel movement trajectories. The system performs data loading, cleaning, and normalization, identifies key points using a nearest neighbor search algorithm, and compares test data with reference data by calculating differences in longitude and speed. The use of statistical indicators– such as mean absolute deviation, maximum deviation, and standard deviation– enables a quantitative evaluation of the degree of deviations, while the penalty scoring rule reflects the influence of the human factor and the insufficient qualification of ship operators.

Interactive visualization in the form of charts and maps facilitates the rapid identification of potentially hazardous deviations and supports informed decision-making to enhance maritime safety. The implementation of this system is promising, as it will contribute to route optimization, improved training of ship operators, and reduced accident rates, making the development significant both from a scientific and a practical perspective.

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