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RESEARCH ON AIRCRAFT TRAJECTORY PREDICTION METHODS BASED ON DEEP LEARNING

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Abstract

Air transportation is essential for global social and economic development, yet a gap persists between air transport services and market needs. To address this, ICAO advocates trajectory-based operations (TBO), highlighting the importance of accurate four-dimensional (4D) trajectory prediction (TP) for improved airspace capacity, efficiency, and safety. Traditional physics-based TP methods face limitations due to complex parameter requirements and observability issues, while machine learning (ML) approaches, though promising, still lack a robust framework and sufficient accuracy for medium- and long-term predictions. Data imbalance, especially under severe weather conditions, further hinders TP performance. Overcoming these challenges is vital for reliable trajectory prediction in air traffic management (ATM).

This research focuses on three critical areas of aircraft TP: 1) developing a new TP technology framework based on deep learning, 2) improving medium- and long-term TP accuracy, and 3) enhancing TP ability under severe weather conditions. The main findings from this research are as follows:

In terms of overall technical framework, a typical TP system architecture is proposed, consisting of several information processing units such as data preprocessing, data updating, prediction output, TP models, and trajectory integration fusion. A basic evaluation index system is also introduced, comprising system functionality, TP accuracy, confidence in prediction results, response speed, stability, reliability, environmental adaptability, user experience, and system maintainability. Typical structural patterns of hybrid TP models are proposed, including the recurrent neural network (RNN) + convolutional neural network (CNN), Attention + RNN, generative adversarial network (GAN), and clustering algorithm-based models. Methods for determining and optimizing the parameters and hyperparameters of deep learning TP models are also outlined.

In this framework, a novel 4D TP method based on the conditional tabular generative adversarial network (CTGAN) model is proposed, which leverages automatic dependent surveillance-broadcast (ADS-B) data to achieve high accuracy and stability in predicting multi-dimensional parameters under complex airspace conditions. The improved CTGAN model outperforms conditional generative adversarial networks (CGAN) in terms of accuracy, adaptability, and resilience, particularly in handling small sample data. It also surpasses long short-term memory (LSTM) in medium- to long-term TP accuracy over extended time spans. The model was trained and tested using historical 4D trajectory data from Hong Kong International Airport, and its performance was evaluated using metrics such as Jensen-Shannon (JS) divergence, maximum mean discrepancy (MMD), mean Euclidean distance (MED), and average running time. The results show a high degree of similarity between the predicted and real 4D trajectories, even with reduced input data. Comparative experiments demonstrate that the improved CTGAN achieves 10% faster computational speed than CGAN, with a 20% reduction in MMD and an 81.55% decrease in MED. Additionally, it significantly reduces prediction errors compared to LSTM, with greater improvements as the prediction time span increases. These findings validate the feasibility and potential of CTGAN for practical 4D TP applications.

In terms of improving medium- and long-term TP

accuracy, based on the CTGAN architecture, the C-CTGAN model—combining K-medoids clustering with CTGAN—was developed. The model's accuracy was evaluated from the perspectives of data distribution and trajectory distance using MMD and MED metrics. Mean absolute error (MAE) was used to compare the C-CTGAN LSTM, CNN-LSTM, CNN-LSTM-Attention, CNN-BiLSTM, and the original CTGAN models. The proposed C-CTGAN model significantly outperformed LSTM-based models and the original CTGAN in predicting medium- and long-term trajectories. Clustering proved effective in enhancing TP precision. Experiments show the C-CTGAN model reduced MAE of core trajectory parameters (latitude, longitude, geometric altitude, and ground speed) by 69.89%, 15.00%, 74.07%, and 84.21%, respectively, compared to the CNN-LSTM model. When compared to the original CTGAN model, MAE reductions were 20.43% (latitude), 39.09% (longitude), 31.98% (geometric altitude), and 17.07% (ground speed).

Regarding TP under severe weather conditions, a solution to the data imbalance problem is proposed by combining a data enhancement network and a TP network. A hybrid model architecture of the CTGAN and TP network is designed, and the CTGAN network is optimized. After using the optimized CTGAN to enhance minority-class samples, the TP network (LSTM is selected as a case) is applied for TP, which can significantly improve TP accuracy. Experiments showed that increasing the proportion of minority-class data from 4.7% to 13% reduced the average root mean square error (RMSE) by 20.46%. Compared with the classic data enhancement method, synthetic minority oversampling technique (SMOTE), the improved CTGAN is more suitable. for aircraft TP. Research shows that the data enhancement method effectively solved the problem of data imbalance in TP and provides a new method for TP based on minority-class sample data.