Master Thesis Proposal

Air Traffic Control Primary Surveillance Radar Signal Processing Using Machine Learning

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1 Introduction

The use of radar technology for air traffic surveillance plays a critical role in ensuring safe, efficient, and effective air traffic control (ATC). Traditional radar signal processing methods can struggle with challenges such as noise, interference, or clutter, and the vast amounts of data generated by modern air traffic systems. Recent advancements in machine learning (ML) have opened up new opportunities to enhance the capabilities of radar systems, providing more accurate, efficient, and adaptive methods for detecting, tracking, and identifying aircraft. This thesis will explore the application of machine learning techniques to improve primary surveillance radar (PSR) signal processing. It will address both the theoretical and practical aspects of integrating these techniques into radar systems.

1.1 Research Problem Statement

The main problem this thesis will aim to investigate is: *to what extent can machine learning methods improve the efficiency, accuracy, and robustness of primary radar signal processing systems?* The primary research question therefore is:

> **Can machine learning models reliably fully replace traditional signal processing methods on a primary surveillance radar for better target detection, extraction, tracking, and classification in real-time air traffic monitoring?**

2 Objectives

- **Main Objective**: To explore, evaluate, and implement machine learning models in a primary surveillance radar signal processing system.
- **Specific Objectives**:
  - To understand the different stages involved in radar signal processing and tracking.
  - To understand the challenges in current air traffic surveillance systems.

- To investigate and understand radar signal preprocessing techniques for noise reduction, clutter removal, and feature extraction.
- To evaluate and select appropriate machine learning models (supervised, unsupervised, and reinforcement learning) for radar data processing and tracking.
- To develop, train, and integrate machine learning models for aircraft detection, extraction, tracking, and classification.
- To assess the machine learning-based model performance against currently used traditional methods with respect to real-time processing, accuracy, and robustness.
- To explore the potential integration of the developed machine learning models into existing air traffic control systems.

3 Literature Review

The literature review will focus on existing radar signal processing methods, including both traditional and machine learning-based techniques. Key areas to cover:

- **Traditional Radar Signal Processing**: Current radar signal processing methods such as filtering, Doppler analysis, constant false alarm rate (CFAR) methods, and clutter suppression.
- **Machine Learning for Radar Data**: Review of the application of supervised, unsupervised, and reinforcement learning models to radar data processing, including classification, tracking, time-series analysis and anomaly detection in radar systems.
- **Radar Data Challenges**: A review of noise, clutter, interference, and other environmental factors that impact radar data quality, along with how machine learning techniques can mitigate these issues.

4 Research Methodology

The methodology will be structured in several phases to ensure a systematic exploration of machine learning applications in radar signal processing. Training and reference data will be provided; therefore, data collection is not part of this project.

4.1 Data Preparation

- **Dimensionality Reduction**: Apply techniques such as principal component analysis (PCA) and autoencoders (AE) to reduce the feature space while retaining key information, ensuring efficient processing and reducing the risk of overfitting.
- **Feature Extraction, Selection, and Engineering**: Utilize feature selection methods to identify the most informative features, ensuring model robustness and reducing computational complexity.
- **Data Normalization and Scaling**: Apply normalization and scaling techniques to normalize radar data, ensuring all features are on a comparable scale and preventing any single feature from disproportionately affecting model performance.

4.2 Machine Learning Model Development

- **Model Selection**: Evaluate a range of machine learning models:
  - **Supervised Learning**: Use classification (e.g., aircraft classes vs. non-aircraft) and regression techniques for detecting and tracking aircraft.
  - **Unsupervised Learning**: Explore clustering algorithms and anomaly detection for identifying unknown objects.
  - **Deep Learning**: Test convolutional neural networks (CNNs) for feature extraction and recurrent neural networks (RNNs) or Long Short Term Memory (LSTMs) for time-series tracking.
  - **Reinforcement Learning**: Investigate reinforcement models for adaptive tracking in dynamic air traffic scenarios.
- **Model Training**: Split the data into training and test sets, applying cross-validation techniques to ensure the models generalize well.

4.3 Model Evaluation

- **Performance Metrics**: Evaluate models using accuracy, precision, recall, F1-score (for classification), and mean squared error (for regression). For tracking, evaluate position error, track continuity, and false alarm rates.
- **Real-Time Processing**: Analyze the feasibility of real-time processing by measuring inference time, system latency, and throughput.
- **Robustness Testing**: Evaluate how models handle noisy, cluttered, and low-resolution radar data, as well as dynamic environmental conditions (e.g., weather or interference).

5 Expected Results and Impact

5.1 Expected Outcomes

- **Enhanced Radar Signal Processing**: Machine learning models will provide more accurate detection, classification, and tracking of aircraft, even in the presence of noise and clutter.
- **Improved Real-Time Processing**: The models will be designed to operate in real-time, offering faster processing times without sacrificing accuracy, making them suitable for live air traffic monitoring.
- **Adaptability**: The use of reinforcement learning or deep learning approaches will allow the radar system to adapt to dynamic changes in the environment, such as new types of aircraft or interference patterns, as well as deployment on different sites.

5.2 Impact

- **Air Traffic Control Efficiency**: This research could lead to more efficient air traffic management by improving the ability to track aircraft in crowded airspaces and mitigating human error.
- **Safety**: Improved accuracy in detection and tracking could reduce the likelihood of collisions and enhance overall aviation safety.
- **Technological Innovation**: This thesis will contribute to the integration of machine learning technologies into critical infrastructure, showcasing how modern techniques can revolutionize traditional systems.

6 Timeline

Phase	Timeline	Deliverables
Phase 1: Literature Review	Month 1-2	Comprehensive review of existing research
Phase 2: Data Preparation	Month 3-6	Cleaned and preprocessed radar data
Phase 3: Model Development	Month 4-7	Trained machine learning models
Phase 4: Model Evaluation	Month 5-8	Performance metrics and evaluation report
Phase 5: Thesis Writing	Month 7-9	Final thesis draft
Phase 6: Final Review & Submission	Month 10	Completed thesis ready for submission

7 Resources

- **Datasets**: Access to radar signal datasets (e.g., radar simulators, air traffic datasets).
- **Hardware**: High-performance computing infrastructure for model training.
- **Software**: Software tools for machine learning (e.g., Python, TensorFlow/PyTorch, MATLAB, C/C++).

8 Conclusion

This research aims to bridge the gap between machine learning and traditional radar signal processing in air traffic surveillance. By evaluating and applying modern machine learning models, the thesis will contribute to improving radar-based tracking and detection systems, potentially enhancing safety and efficiency in air traffic control.