IMU-based Speed and Distance Estimation Analysis

1. Data Overview

Sampling Rate: 149.73 Hz
Total Duration: 423.18 seconds
Number of Samples: 63364
Nyquist Frequency: 74.87 Hz

2. Signal Processing Pipeline

2.1 Pre-processing:
• **Butterworth Low-pass Filter** (IMU data)
Removes high-frequency noise, preserves motion dynamics.
• **Nyquist Theorem:** Sampling rate must be at least twice the highest frequency of interest.

2.2 Orientation Estimation:
• **Gyroscope Integration (Euler angles):** Simple numerical integration to estimate roll, pitch, yaw.

2.3 Coordinate Transformation:
• **Body to World Frame:** 3D rotation matrix compensates for device orientation.

2.4 Acceleration Processing:
• **High-pass Filter:** Removes integration drift.

2.5 Visual: Raw and Filtered Accelerometer Magnitude

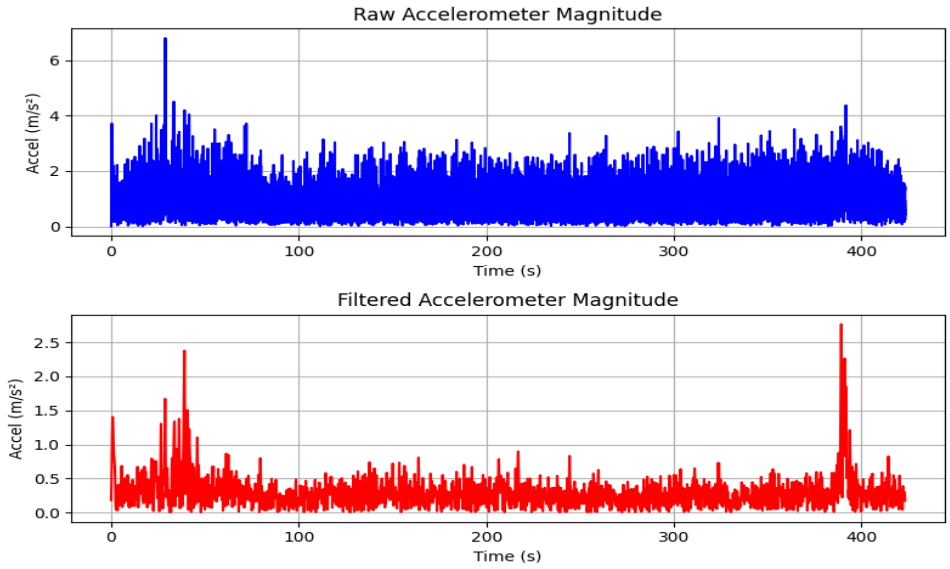

Figure: Shows the effect of low-pass filtering on the accelerometer signal. Filtering is crucial for removing noise before integration.

3. Machine Learning Analysis

3.1 Feature Extraction:
• Window Size: 1.0 seconds
• Features: Mean, Std, Max, Min, Peak-to-peak of IMU signals

3.2 Model: Random Forest Regressor
3.3 Performance: RMSE = 0.089 m/s

3.4 Visual: Speed Estimation Comparison

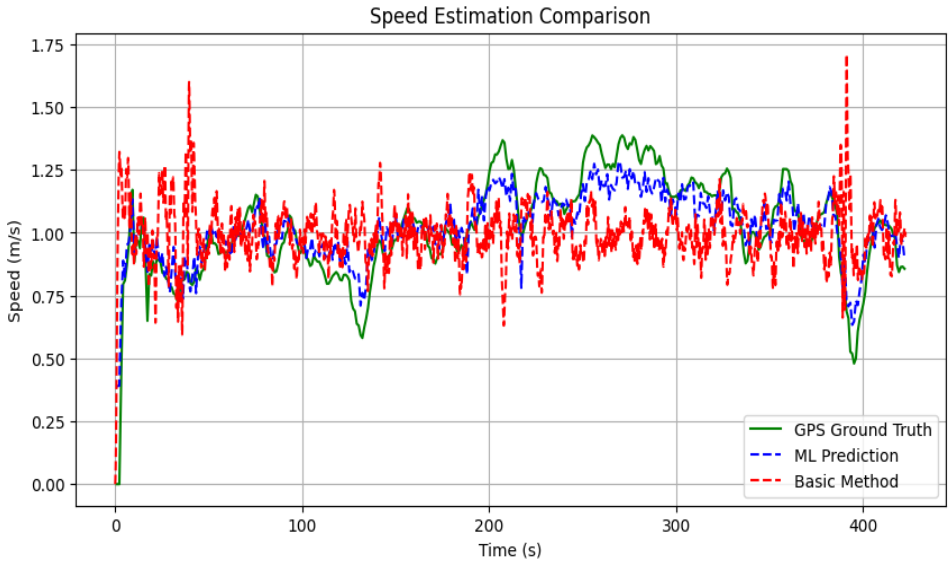

Figure: Comparison of speed estimated by GPS, ML, and basic integration. ML can learn to correct for drift and noise.

4. Methods Comparison

Method	Total Distance (m)	Relative Error (%)
GPS (Ground Truth)	432.13	0.00
ML Method	431.20	0.22
Basic Method	421.14	2.54

4.1 Visual: 2D Path Comparison (GPS, Basic, ML)

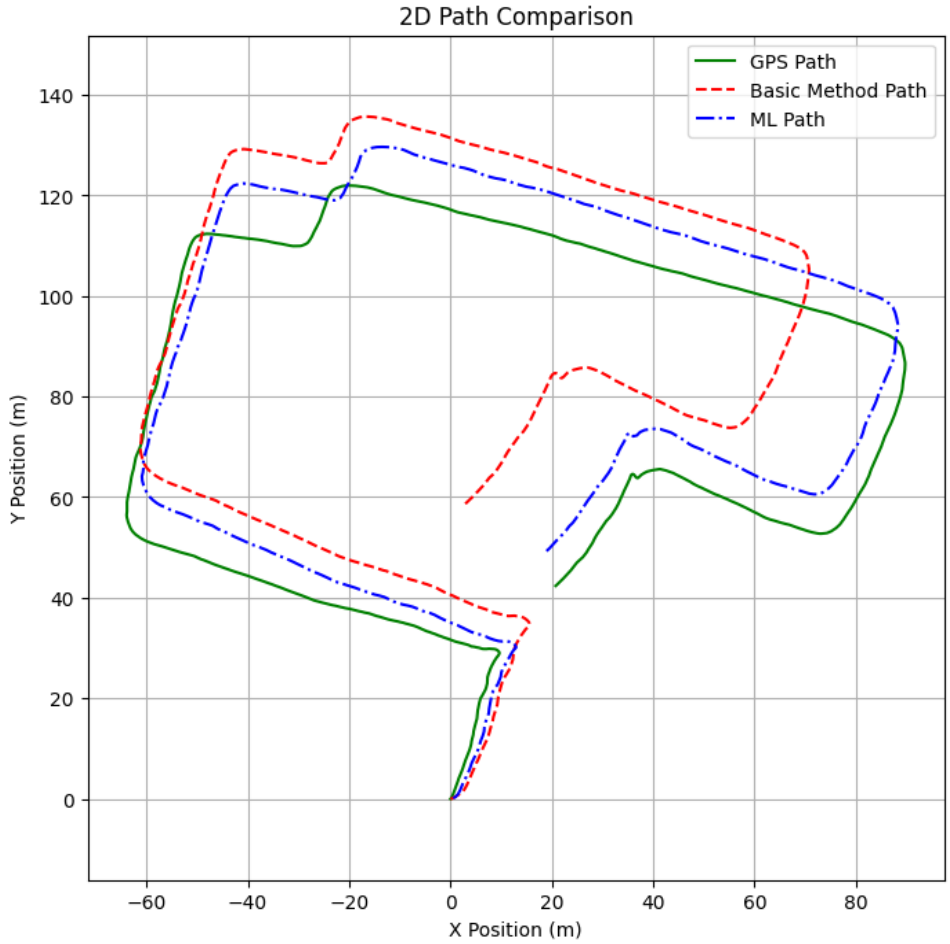

Figure: Comparison of reconstructed paths using GPS, basic integration, and ML-predicted velocities. ML can reduce drift and error compared to basic integration.

5. Error Analysis & Signal Processing Concepts

5.1 Sources of Error:
• **Integration Drift:** Small errors in acceleration accumulate over time.
• **Sensor Noise:** IMU noise is filtered using Butterworth filters.
• **Orientation Errors:** Gyroscope drift affects coordinate transformation.

5.2 Signal Processing Concepts:
• **Filtering:** Butterworth filters are used for both low-pass (noise removal) and high-pass (drift removal).
• **Sampling Theorem:** Ensures no aliasing in digital signals.
• **Numerical Integration:** Trapezoidal rule is used for velocity and position estimation.
• **Feature Engineering:** Statistical features from IMU signals are used for ML.