

Post-Event Sensor Fusion of IMU & GPS Data in the Context of Avalanche Research

Calibration and two-stage EKF fusion of IMU and GPS data for post-event 3D trajectory reconstruction

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Introduction: Snow is a highly complex material. Its density, layering, and water content vary continuously with weather and terrain, making avalanches difficult to capture with models alone. Field measurements are therefore essential. The AvaNode, developed by OST with SLF, ETH Zürich, and the University of Innsbruck, addresses this need. Probes are deployed in the snowpack to record motion during avalanche events. Each probe carries an IMU sensor and GPS to capture accelerations, angular velocities, and positions.

Approach / Technology: Reconstructing motion from raw IMU and GPS data is challenging: IMUs accumulate drift when integrated, while GPS provides low-rate and often distorted updates during tumbling. To address this, the project began with sensor validation and calibration. The ICM-20948 IMU was characterized and corrected for systematic errors, reducing accelerometer variance by over 90% and bringing gyroscope bias close to zero. Accelerometer and magnetometer calibration was performed with the Magneto tool, which applies ellipsoid fitting to transform distorted distributions into spheres. This compensates for bias, scale deviations, and axis misalignment, ensuring reliable gravity and magnetic references.

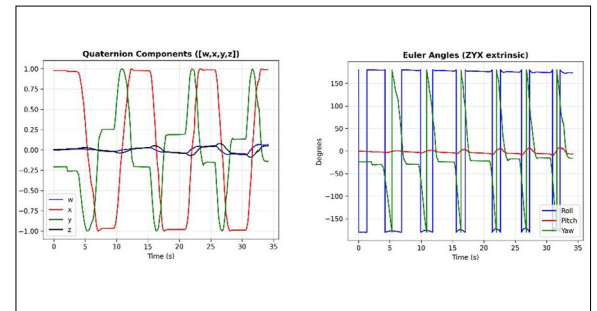
On this basis, a two-stage Extended Kalman Filter (EKF) was implemented. The first stage estimates orientation with a quaternion-based filter fusing gyroscope, accelerometer, and magnetometer data, adapting its trust to motion conditions. In static phases it relies on gravity for roll and pitch, while in dynamic phases it emphasizes gyroscope integration with magnetometer heading correction. The second stage transforms accelerations into global coordinates, integrates them to position, and constrains drift with periodic GPS updates. Validation covered conditions from controlled rotations to bicycle rides and projectile throws, spanning stable to avalanche-like motion.

Result: The pipeline reconstructed probe motion accurately under moderate dynamics. In a bicycle test, the trajectory length differed by only 4.3% from a reference, while accelerometer-only integration produced errors over an order of magnitude larger. Orientation tracking remained stable and drift-free across repeated rotations, demonstrating the robustness of quaternion-based fusion.

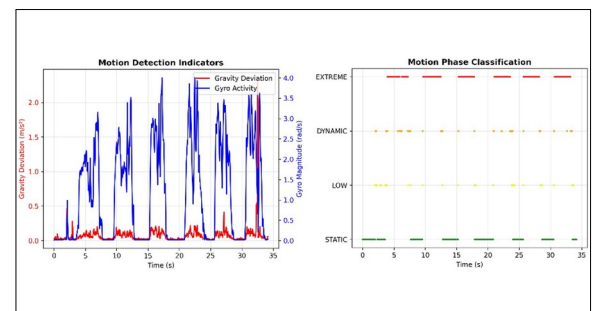
Under extreme dynamics, limitations became clear. During downhill throws, accelerometer and gyroscope readings saturated. GPS accuracy degraded during tumbling due to the phase wind-up effect, producing zigzag trajectories and unreliable positions. Even in more controlled angled throws, GPS introduced curved paths and limited vertical resolution, masking the expected parabolic altitude profile.

The system provides a reliable method for post-event trajectory and orientation reconstruction of AvaNode probes. It enables motion analysis not possible from IMU or GPS alone. Future work should focus on higher-dynamic-range sensors, improved GPS modules for rapid multi-axis motion, and validation in real avalanche conditions.

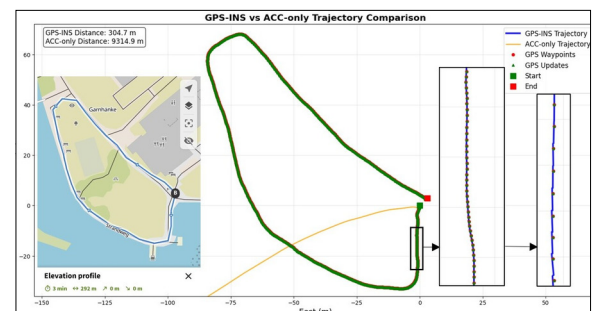
Orientation tracking over time during repeated table-top rotations, shown in quaternion and Euler form.
Own presentation



EKF classification of motion phases (static to extreme) with dynamic adjustment of accelerometer and gyroscope noise.
Own presentation



Two-stage EKF trajectory reconstruction during outdoor bicycle test with GPS correction
Own presentation



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Subject Area
Information Technology for Engineering, Sensorics

