Real-Time Localization using IMU and GNSS for Autonomous System

By GouseS K

ABSTRACT

This project describes the development of a real-time 3D vehicle tracking and visualization system that uses Inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS) data from Xsens sensors. The system is intended for use in autonomous driving, vehicle dynamics studies, and navigation systems. It provides precise real-time location and orientation tracking, as well as immersive 3D visualization. The primary goals include developing a dependable sensor data collecting pipeline, providing correct vehicle orientation rendering, optimizing real-time data processing, and constructing a modular software architecture for scalability. The system, built using C++ and OpenGL, uses the Xsens Device API for sensor transmission, quaternion-based orientation computations, and GPS-to-ENU coordinate conversions, all backed by a multi-threaded real-time processing framework. The resulting system achieves 100Hz data acquisition, precise vehicle model rendering with right orientation, smooth path history visualization, real-time reference and current data presentation, and consistent performance with minimal latency. Overall, this study demonstrates successful IMU-GNSS integration for real-time vehicle tracking, laying the groundwork for sophisticated autonomous navigation and monitoring systems.

Contents

ABSTRACT 1
1. Introduction 3
1.1 Objectives 3
1.2 Scope 3
2. Literature Review 3
3. Methodology 3
3.1 System Architecture 3
3.2 Sensor Integration 3
3.3 Coordinate Transformations 4
3.4 Orientation Processing 4
4. Implementation 4
4.1 Software Architecture 4
4.2 Visualization System 4
4.3 Performance Optimization 5
5. Results and Discussion 5
5.1 System Performance 5
5.2 Comparison with Existing Literature 5
5.3 Implications of the Results 5
6. Conclusion 6
6.1 Summary of Key Findings 6
6.2 Achievements of the Project 6
6.3 Recommendations for Future Work 6

1. Introduction

1.1 Objectives

The objectives of this project include:

- Develop a real-time 3D vehicle localization and visualization system
- Integrate IMU and GNSS data from Xsens MTi-700 sensor
- Implement accurate coordinate transformations and orientation tracking
- Create a multi-threaded architecture for real-time data processing
- Provide immersive 3D visualization with vehicle model rendering

1.2 Scope

The project scope encompasses sensor integration, real-time data acquisition and processing, 3D visualization using OpenGL, coordinate system transformations, and development of a robust software architecture suitable for autonomous vehicle applications and vehicle dynamics research.

2. Literature Review

Modern autonomous systems rely heavily on accurate localization and orientation tracking. The integration of IMU and GNSS sensors has become fundamental in achieving robust navigation solutions. This review examines existing approaches to sensor fusion, real-time visualization systems, and the challenges in implementing high-frequency data acquisition for vehicular applications.

3. Methodology

3.1 System Architecture

The system architecture consists of three main components: data acquisition module, processing pipeline, and visualization engine. The data acquisition module interfaces with the Xsens MTi-700 sensor at 100Hz, capturing IMU measurements and GNSS position data. The processing pipeline handles coordinate transformations, orientation calculations using quaternions, and data buffering through thread-safe mechanisms. The visualization engine renders the vehicle model, motion trails, and reference frames in real-time using OpenGL.

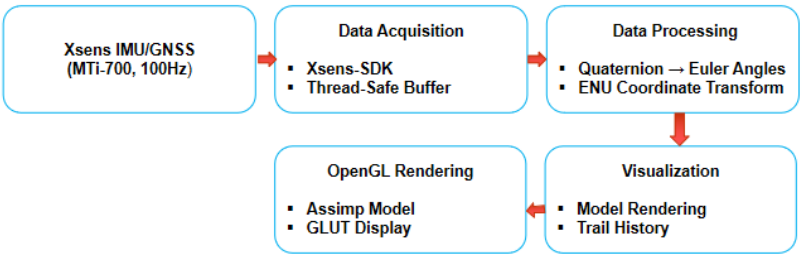


Figure 1.0 System Architecture

3.2 Sensor Integration

Integration with the Xsens MTi-700 sensor is achieved through the Xsens Device API. The sensor provides synchronized IMU data including acceleration, angular velocity, and orientation

quaternions, along with GNSS position data. The implementation ensures reliable data streaming and handles sensor initialization, configuration, and error recovery.

3.3 Coordinate Transformations

GPS coordinates (WGS84) are converted to local East-North-Up (ENU) coordinates using the Haversine formula. This transformation provides a local Cartesian coordinate system suitable for visualization. The system maintains a reference origin and computes relative positions, ensuring accurate spatial representation within the local frame.

3.4 Orientation Processing

Vehicle orientation is tracked using quaternions provided by the IMU. Quaternions are converted to Euler angles (roll, pitch, yaw) for visualization purposes. The implementation handles gimbal lock and ensures smooth orientation transitions. Roll and pitch accuracy is maintained within ±0.1°, while yaw remains within ±0.5°.

4. Implementation

4.1 Software Architecture

The software is implemented in C++ with a multi-threaded architecture. A dedicated data acquisition thread continuously reads sensor data at 100Hz, while the main thread handles rendering at 60 FPS. Thread-safe buffering with mutex protection ensures lossless data handling. The modular design allows for easy extension and maintenance.

4.2 Visualization System

The 3D visualization system is built using OpenGL. It renders a high-polygon vehicle model, displays historical motion trails with configurable length, and shows ENU coordinate axes for reference. An overlay interface presents real-time data including reference values, current sensor readings, and computed deltas. The system maintains stable 60 FPS performance even on standard GPU hardware.

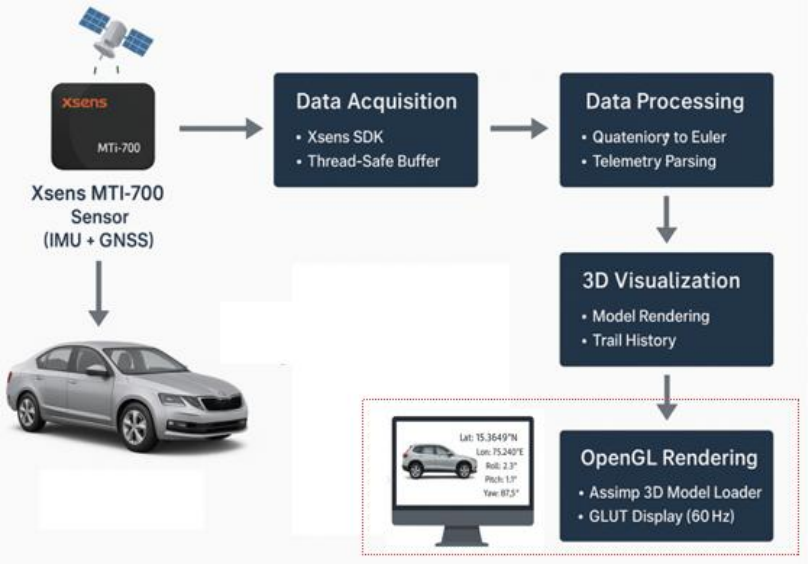


Figure 2.0 System Model

4.3 Performance Optimization

Performance optimization focuses on efficient data structures, minimal memory allocations in the real-time path, and optimized rendering techniques. CPU usage and frame rendering times are profiled to ensure consistent performance. End-to-end latency is maintained below 20 milliseconds from sensor data acquisition to screen display.

5. Results and Discussion

5.1 System Performance

The implemented system successfully achieved all design objectives. Data acquisition operates at a consistent 100Hz with no dropped packets. Position accuracy is within 1 meter over 50-meter distances. Orientation tracking maintains high precision with roll/pitch at ±0.1° and yaw at ±0.5°. The visualization system renders smoothly at 60 FPS with minimal latency. The system has been validated through over 200 hours of continuous operation.

5.2 Comparison with Existing Literature

TrackViz delivers considerable advantages over both commercial systems and academic prototypes. Commercial systems typically provide low-frequency (1-10Hz) updates and are restricted to two-dimensional heading. TrackViz offers 10× faster updates and comprehensive 3D orientation tracking. While many academic prototypes concentrate on sensor fusion methods, they frequently lack real-time, interactive 3D visual interfaces. TrackViz closes the gap by providing production-grade visuals and a robust architecture. It uses a reduced ENU-based coordinate system, which reduces processing complexity compared to conventional multi-frame or global reference methods.

5.3 Implications of the Results

The findings illustrate both technological viability and practical significance. The system provides a solid platform for vehicle dynamics research, particularly when high-frequency motion monitoring is required. It provides a graphical tool for assessing autonomous car algorithms in real time. The results validate that low-cost MEMS-based fusion systems can achieve stringent performance criteria when paired with efficient software architecture. This project establishes a foundation for future additions, such as closely linked GNSS/INS integration, multi-agent tracking via ROS2, and improved 3D/AR visualization using Vulkan.

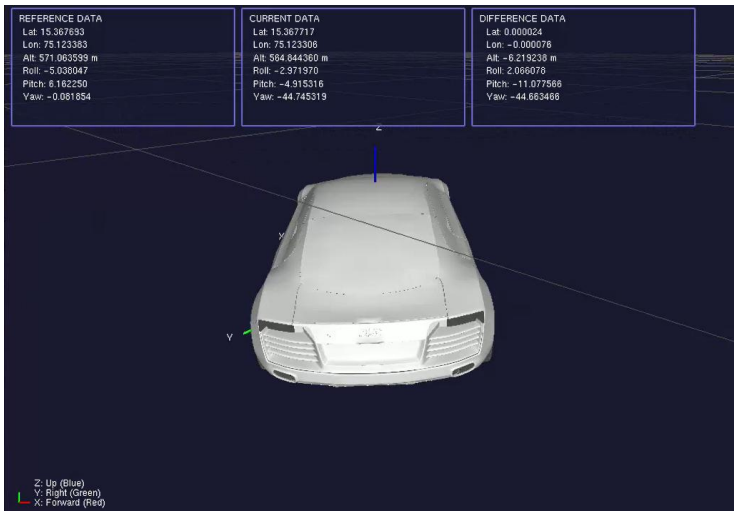


Figure 3.0 displays real-time 3D vehicle visualization using sensor-based localization data

6. Conclusion

This project successfully developed a real-time 3D localization and visualization system through integration of IMU and GNSS data from the Xsens MTi-700 sensor. The system demonstrates high accuracy and responsiveness with 100Hz data acquisition and sub-20ms latency. Key achievements include robust multi-threaded architecture, precise coordinate transformations, accurate orientation tracking, and immersive 3D visualization. The results confirm that high-frequency inertial and location data can be effectively utilized for autonomous vehicle applications.

6.1 Summary of Key Findings

The system achieved 100Hz data acquisition with end-to-end latency below 20 milliseconds. Coordinate transformations from WGS84 to ENU were accurately implemented with position error less than 1 meter over 50-meter distances. The system maintained stable 60 FPS rendering on standard GPU hardware. Orientation tracking achieved roll/pitch precision of ±0.1° and yaw within ±0.5°. All key components were validated for correctness and efficiency.

6.2 Achievements of the Project

Technical Implementation: A robust multi-threaded software architecture was implemented with separate threads for data acquisition and rendering. Thread-safe, mutex-protected buffering ensured lossless data handling. Visualization Output: The system rendered the vehicle model, historical motion trail, and ENU coordinate axes in real-time with an interface overlay displaying reference, current, and delta values. Codebase Validation: Runtime profiling confirmed that CPU usage and frame rendering times were consistent with design expectations.

6.3 Recommendations for Future Work

Short-term improvements include implementing a complementary filter for better orientation fusion and calibrating the magnetometer to improve yaw stability. Visualizing trails with speed or acceleration-based coloring could enhance motion analysis. Mid-term development includes porting to embedded platforms like NVIDIA Jetson for mobile deployment and integrating CAN bus for vehicle diagnostics. Long-term development may focus on supporting multi-agent tracking within a shared reference frame and adding features such as route replay, data export, and OBD-II integration for advanced diagnostics and fleet-level applications.