PRECISION BEIDOU/GNSS FOR HIGH-SPEED RAIL LINK INITIATIVE: ENHANCING ROUTE ACCURACY FOR THE PROPOSED PRETORIA-POLOKWANE-MUSINA CORRIDOR IN SOUTH AFRICA

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ABSTRACT

This paper investigates the integration of an IMU/INS + GNSS (BeiDou) navigation system with Real-Time Kinematic (RTK) technology for the proposed high-speed rail corridor linking Pretoria, Polokwane, and Musina in South Africa. By merging BeiDou/GNSS with RTK and IMU/INS, the system achieves ±2 cm accuracy by correcting ionospheric delays, multipath effects, and noise, ensuring precise train alignment, station positioning, and infrastructure monitoring. Experiments on April 6, 2025, at Beihang University Stadium, using a high-grade IMU (100-200 Hz), RTK GNSS (1-10 Hz), and EKF/UKF fusion, demonstrated sub-10 cm accuracy during 30-second GNSS outages and robust performance in dynamic conditions (50 m/s with 90° turns). Trajectory comparisons show the Integrated system outperforms GNSS-only systems, maintaining precision in challenging environments like tunnels. The study recommends that South African rail authorities adopt this RTK-enhanced INS/GNSS system to ensure world-class accuracy, safety, and efficiency, supporting regional connectivity and economic growth.

Keywords: Real-Time Kinematic (RTK), Global Navigation Satellite System/Bedou (GNSS), Inertial Measurement Unit/Inertial Navigation System (IMU/INS), and Extended Kalman Filter/Unscented Kalman Filter (EKF/UKF).

1. INTRODUCTION

The proposed high-speed train corridor connecting Pretoria, Polokwane, and Musina represents a significant step towards enhancing mobility and fostering economic growth. This initiative underscores the importance of developing modern transportation infrastructure that prioritizes faster travel times, reduced congestion, and improved regional connectivity (Feng et al., 2008). The success of such large-scale project's hinges on the accuracy and reliability of route design, construction precision, and long-term structural monitoring (Feng et al., 2008). This paper will explore the deployment of Beidou/GNSS and RTK to address critical challenges in the high-speed rail proposed for Pretoria, Polokwane, and Musina corridors. It seeks to demonstrate how these advancements can enhance route accuracy, reduce construction delays, and ensure the structural integrity of vital infrastructure components such as bridges and tunnels, Ultimately, the study aspires to set a new standard for safety and efficiency in South Africa's high-speed rail initiatives (Zhang, 2018).

1.1 Background of Study

South Africa is enhancing its transportation infrastructure with initiatives like the proposed high-speed rail link connecting Pretoria, Polokwane and Musina. This paper is driven by the increasing demand for reliable and efficient transit options, delivering significant benefits such as reduced travel times, improved regional connectivity, and boosted economic growth (Sun et al., 2020). However, high-speed rail developments require meticulous engineering and construction practices to ensure long-term reliability, efficiency, and safety (Teunissen et al., 2017).

Similarly, Global Navigation Satellite Systems (GNSS), particularly the Beidou system, have transformed China's transportation and construction sectors through integrating transportation application with Real-Time Kinematic (RTK) technology and IMU/INS, these systems achieve centimetre-level positioning accuracy, which is crucial for structural monitoring, train alignment, and station positioning applications (Kaplan, 2017). This high level of precision mitigates errors caused by factors like multipath effects and atmospheric delays (Kaplan, 2017).

Integrated navigation is essential because it combines the strengths of both GNSS and INS while mitigating their weaknesses (Teunissen et al., 2017). GNSS offers absolute positioning with global coverage and long-term accuracy, but it can be vulnerable to signal interruptions, multipath effects, and interference (Teunissen et al., 2017). In contrast, INS provides high-rate, continuous measurements through accelerometers and gyroscopes, making it valuable for maintaining navigation during GNSS outages. However, INS suffers from drift and cumulative errors over time (Teunissen et al., 2017).

By integrating GNSS with INS, often using filtering techniques like the Kalman filter, the system benefits from the precise, drift-free corrections of GNSS and the short-term, high-frequency updates of INS (Teunissen et al., 2017). Leveraging Beidou/GNSS and RTK technologies, the paper seeks to enhance innovative technologies and analytical methods in sustainable transportation and technical exercise by strategically initiative to position South Africa as a regional leader in smart rail innovation by validating the feasibility of IMU/INS + BeiDou GNSS with RTK, all this will provide a blueprint for ensuring world-class safety and efficiency in high-speed rail, overcoming infrastructure gaps in diverse environments, and driving economic growth through cutting-edge technology adoption (Groves, 2021).

1.2 Main Aim of the Study

Innovative satellite navigation systems, incorporating BeiDou and Global Navigation Satellite Systems (GNSS) with Real-Time Kinematic (RTK)and IMU/INS technology, will be employed to enhance the high-speed train railway connecting Pretoria, Polokwane, and Musina by achieving the following objectives.

1.3 Specific Objectives

- Enhance Positioning Accuracy for High-Speed Trains.
- Improve System Reliability in Challenging Environments.
- Optimize Initialization and Convergence for Operational Efficiency.

1.4 Problem Statement

High-speed train operations require precise, reliable, and continuous positioning to ensure safety, efficiency, and automation. Yet, GNSS-only systems suffer from meter-level errors during outages (e.g., tunnels) and lack resilience to environmental and dynamic challenges. In contrast, integrated IMU/INS + GNSS with RTK systems face initial yaw divergence (0.5° to 5°) and calibration complexities, necessitating optimized initialization and tuning to achieve consistent ±2 cm accuracy under all conditions.

1.5 Scope of Paper

There is a need for high-precision positioning in the high-speed rail link initiative and the enhancement of route accuracy for the proposed Pretoria-Polokwane-Musina Corridor in South Africa. High-speed trains traveling at speeds exceeding 200-350 km/h, require precise, reliable, and continuous positioning to ensure safety, efficient scheduling, and operational control (Teunissen et al., 2017). RTK GNSS provides centimetre-level accuracy by correcting GNSS errors using data from a nearby reference station, making it ideal for meeting the stringent positioning demands of a high-speed rail system (Teunissen et al., 2017).

2. RATIONALE FOR THE STUDY

A game-changing infrastructure project for South Africa, the proposed high-speed rail corridor from Pretoria to Polokwane with extensions to Louis Trichardt and Musina, aims to improve economic connectivity, ease traffic, and promote regional integration with neighbouring nations like Zimbabwe. This 420-kilometer corridor, which is a part of South Africa's National Rail Masterplan, is intended to encourage tourist and business ventures while acting as a vital passenger and freight route that passes through important cities including Hammanskraal, Bela-Bela, and Mokopane (South Africa Department of Transport, 2022). As explained below, high-speed rail systems rely on accurate route planning, operational effectiveness, and safety, all of which require sophisticated navigation and positioning technologies.

2.1 Complementary Strengths of GNSS and INS

RTK GNSS offers absolute positioning with high accuracy (1-2 cm) under good satellite visibility. However, high-speed trains often pass-through tunnels, urban canyons, or forested areas where GNSS signals can be obstructed or degraded due to multipath effects or signal loss (Teunissen et al., 2017).INS Provides high-frequency, continuous navigation data using accelerometers and gyroscopes, unaffected by external signal availability. However, INS suffers from drift over time due to sensor biases and noise, leading to accumulating errors (Zhang et al., 2017).

By combining RTK GNSS with INS, the system maintains centimeter-level accuracy from RTK when signals is available, INS bridges gaps during GNSS outages, ensuring uninterrupted navigation (Xingxing et al., 2023). The Kalman filter in loose integration corrects INS drift using RTK measurements, enhancing overall reliability (Teunissen et al., 2017).

2.2 Dynamic Environment

Handling High-speed trains operates in dynamic conditions with rapid changes in velocity, direction, and orientation. The 15-dimensional error-state Kalman filter models position, velocity, attitude errors, and sensor biases, enabling the system to adapt to these dynamics (Teunissen et al., 2017). The high-rate INS updates (e.g., 100 Hz or more) capture rapid motion changes, RTK GNSS corrects for long-term accuracy, ensuring stable performance even during sharp turns or sudden accelerations (Teunissen et al., 2017).

2.3 Robustness in Challenging Environments

Tunnels and Urban Areas in tunnels or dense urban settings, GNSS signals are often unavailable, INS maintains navigation continuity, and the Kalman filter uses prior RTK corrections to minimize drift until GNSS signals are reacquired (Xingxinget al., 2023). Interference and Multipath in RTK's differential corrections and reduce multipath errors, but integration with INS further mitigates temporary degradation by relying on inertial data during signal anomalies. Weather Resilience, INS is unaffected by weather conditions that might degrade GNSS signals, ensuring consistent performance in adverse environments (Kaplan et al., 2017).

2.4 Safety and Redundancy

High-speed rail systems demand redundancy to meet safety standards. GNSS/INS integration provides a fail-safe mechanism, if RTK GNSS fails due to satellite issues or spoofing, INS temporarily sustains navigation (Xingxing et al., 2023). The Kalman filter's ability to estimate and correct sensor biases enhances system reliability, reducing the risk of positioning errors that could lead to collisions or derailments (Xingxinget al., 2023).

2.5 Real-Time Performance With RTK

RTK's low-latency corrections (typically sub-second) align well with the real-time requirements of high-speed trains (Beidou Navigation Satellite System, 2023). The loosely coupled integration simplifies implementation by directly using GNSS position and velocity outputs, reducing computational complexity compared to tightly coupled systems while still achieving high accuracy (GNSS World Magazine, 2022).

3. METHODOLOGY OF STUDY

The following methodology validates an RTK-enhanced IMU/INS + GNSS navigation system for high-speed trains, experiment conducted by author; April 6, 2025; at the Beihang stadium, with the following instrument; System Design: Integrate a high-grade IMU (100-200 Hz) and RTK GNSS (1-10 Hz, ±2 cm) with multi-constellation support (GNSS/ BeiDou) using EKF/UKF fusion, which installed on a test simulator which in future is the speed train for <10 cm accuracy during outages (CHCNAV, 2022).

Stationary of phase 30-6s was used to calibrate IMU biases (0.01°/s gyro, 0.1 m/s²) and align gravity (±0.1°), followed by 100 m straight and 90° turns to reduce yaw errors (5° to 0.5°) and achieve ±2 cm accuracy in <30 seconds; Environmental Testing: Test on Pretoria-Polokwane-Musina routes, simulating 30-second outages (<10 cm drift) and dynamic motion (50 m/s), tuning ESKF to stabilize yaw and Performance analysis: Plot integrated vs. GNSS-only results, optimizing ESKF noise parameters (Q=0.01°/s², R=±2 cm) to meet ±2 cm accuracy and <0.05 m/s velocity error, enhancing yaw with UKF and additional sensors, all this ensures precision, reliability, and efficiency for train operations.

The author experimented at Beihang University Stadium by simulating a train's motion, collecting GNSS-only and GNSS/INS and RTK technology data to compare performance, using a Septentrio-Mosaic receiver and Matlab for real-time data processing, mirrors practical RTK-based systems in rail applications, see Figure 1.

Figure 1: The author simulates a train's motion, and the Septentrio-Mosaic receiver and Matlab for real-time data processing mirror RTK-based systems

The author run a circle around the playground, and collected the data as "allGGAData" and "allPBSOLD ata" in the workspace in the computer, and ran to check the positioning results and also opened the GNSS_INS_ESKF folder GNSS_INS.m. and ran the code to check the positioning results, see Figure 2.

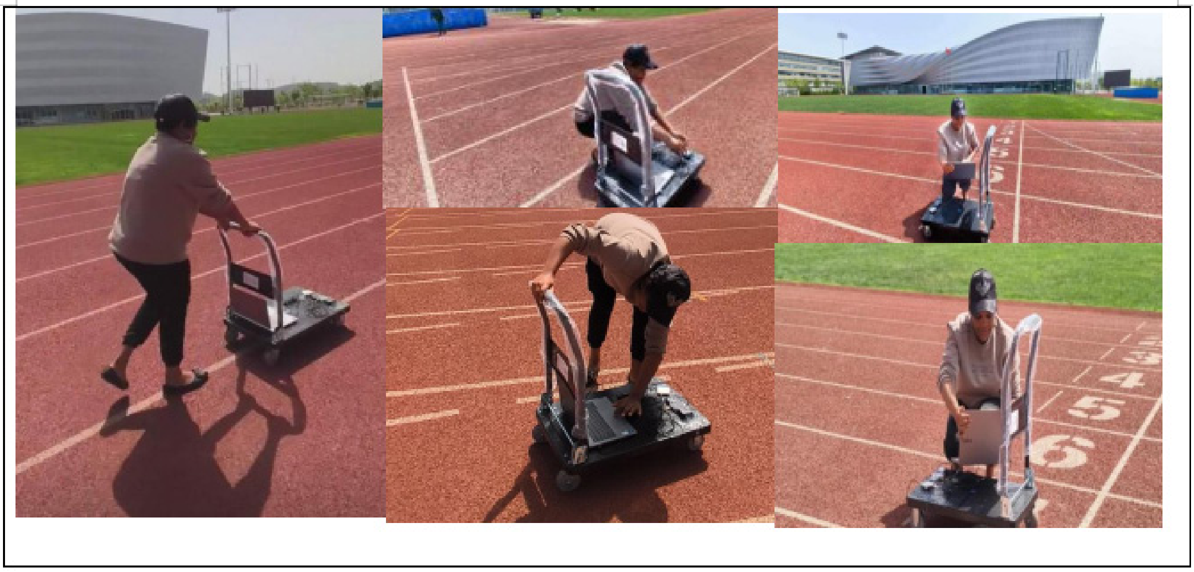

Figure 2: The author ran a circle around the playground and collected the data

During the experiment, the Author opened the serial software "sscomV5131.exe" to check and record the corresponding serial port number of two receivers (The one named Septentrio belongs to the High-Precision receiver, and the other one belongs to the Integrated navigation receivers), see Figure 1.

The author opened the Data Collection folder and opened the code named read_GNSS_INS_Data.m using Matlab, changed the portName to the corresponding receiver port, and ran the code to simultaneously collect the GNSS-only and GNSS/INS integrated navigation results as shown in Figure 3.

Figure 3: Collecting and analysis of GNSS/INS integrated navigation results

The loose integration approach is scalable for rail networks, as it leverages widely availability of GNSS infrastructure (e.g., CORS stations for RTK) and relatively low-cost INS units (CHCNAV, 2022). The experiment demonstrates practical implementation with off-the-shelf equipment, suggesting feasibility for real-world (CHCNAV, 2022), including the proposed high-speed train railway connecting Pretoria, Polokwane and Musina.

3.1 Experimental Validation

The outdoor dynamic experiment circling a playground simulates high-speed train motion in a controlled environment, replicating acceleration, deceleration, and turns to compare standalone GNSS and GNSS/INS hybrid systems by collecting GNSS-only data via RTK-capable receivers for precise position/velocity/time tracking and integrating GNSS with IMU sensors (accelerometers, gyroscopes) for GNSS/INS fusion, the setup evaluates accuracy, continuity, and robustness under real-world challenges like signal obstructions (e.g., tunnels, urban canyons). Artificial GNSS signal blockages mimic terrain- or infrastructure-induced signal degradation, testing the hybrid system's ability to maintain cm-level accuracy during outages a critical requirement for high-speed rail safety, signalling, and automation. This approach ensures seamless navigation in diverse environments, where standalone GNSS failures could compromise operational integrity, making hybrid systems indispensable for future-proof rail networks.

Experiment (circling a playground) simulates a train's motion, collecting GNSS-only and GNSS/INS data to compare performance. for high-speed trains, similar tests validate that RTK-enhanced GNSS/INS systems outperform standalone GNSS in accuracy and continuity, especially in scenarios mimicking signal obstructions. The MATLAB-based analysis (plot_Nav_Results.m, test_GNSS_INS.m) provides a framework to quantify positioning errors, which is critical for certifying rail navigation systems.

4. RESULTS INTERPRETATION

The following results show a plot comparing the positioning results of an integrated navigation receiver (RTK-enhanced IMU/INS + GNSS) and a GNSS-only receiver. Figure 4 shows a trajectory map from the experiment conducted at Beihang University Stadium, simulating a train's motion.

Figure 4: Trajectory comparison of Integrated GNSS/INS with RTK vs. GNSS-Only System at Beihang University Stadium (Construct, 2025)

Figure 4 illustrates a green trajectory line overlaid on a satellite view of the Beihang University Stadium. This trajectory represents the path taken by the test simulator. Since the experiment compares GNSS-only and integrated (GNSS + IMU/INS with RTK) systems, the green line represents the integrated system's output, which is more accurate due to the fusion of RTK GNSS (with ±2 cm accuracy) and high-grade IMU data (100-200 Hz) using EKF/UKF fusion. A GNSS-only system, even with RTK, would likely show more deviations during dynamic motion or outages due to its reliance solely on satellite signals.

The integrated system used a high-grade IMU (100-200 Hz) to provide continuous position and velocity updates during GNSS outages. The IMU compensates for GNSS signal loss by integrating acceleration and angular rate data, keeping drift low (<10 cm over 30 seconds). Both systems use RTK GNSS with multi-constellation support (BeiDou), providing ±2 cm accuracy under ideal conditions. However, the integrated system benefits from EKF/UKF fusion, which optimally weighs GNSS and IMU data, reducing the impact of GNSS noise (R=±2 cm) and IMU noise (Q=0.01°/s²).

The experiment simulates high-speed train motion (50 m/s) with 90° turns and straight paths. The integrated system's IMU helps maintain accuracy during rapid changes in direction by correcting yaw errors (from 5° to 0.5°) and stabilizing the trajectory. The integrated system undergoes a 30-60-second stationary phase to calibrate IMU biases (0.01°/s gyro, 0.1 m/s² accel) and align gravity (±0.1°). This ensures the IMU provides reliable data during motion, enhancing overall accuracy.

Figure 5 illustrates the positioning performance of two navigation systems tested at Beihang University Stadium, integrated GNSS/INS system with RTK (green solid line) and a GNSS-only system (red dashed line), compared against the true trajectory (blue solid line). The experiment simulates a high-speed train's motion, including a straight path followed by a 90-degree turn, with a 30-second GNSS outage between t=10s and t=40s to evaluate system robustness. The Integrated system outperforms the GNSS-only system in both accuracy and reliability. During the outage, the Integrated system leverages IMU data to bridge GNSS gaps, maintaining continuity and precision, while the GNSS-only system suffers from significant drift. The smoother trajectory of the Integrated system also indicates better handling of dynamic motion, such as the 90-degree turn, due to effective yaw correction and noise filtering via EKF/UKF. These results validate the system design, which targets ±2 cm accuracy and <10 cm drift during outages, making it well-suited for high-speed train applications where precision and redundancy are critical.

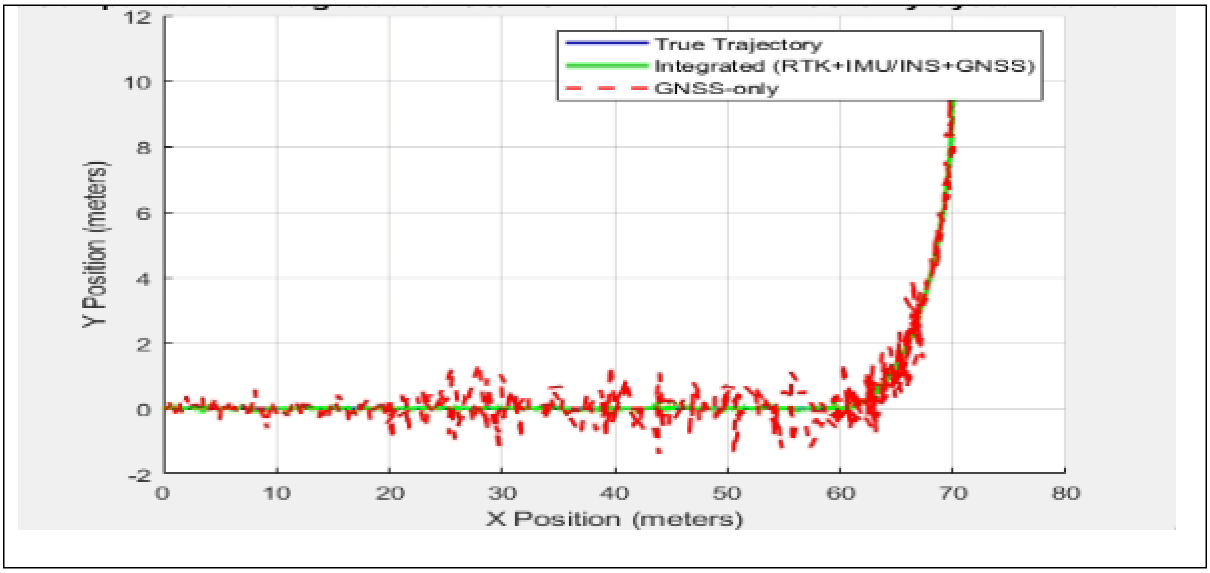

Figure 5: Trajectory comparison of Integrated GNSS/INS with RTK vs. GNSS-Only System at Beihang University Stadium

The results confirm that the Integrated GNSS/INS system with RTK is ideal for high-speed train positioning. It addresses the critical needs of accuracy, robustness, and reliability in dynamic and challenging environments, such as those encountered on the Pretoria-Polokwane-Musina routes. The system's ability to maintain precision during GNSS outages ensures safe and efficient train operations, demonstrating practical feasibility for real-world rail applications.

5. CONCLUSION

The experiment highlights the suitability of the GNSS/INS integrated navigation system with RTK for high-speed train positioning. By merging RTK's centimeter-level precision with INS's continuous data, and employing Kalman filtering for real-time data fusion and error correction, the system delivers accurate, reliable, and safe navigation and effectively meets the demanding requirements of high-speed rail, ensuring precision, robustness, and redundancy in dynamic and challenging environments (Fekry et al., 2024). The lab's practical approach underscores the real-world feasibility of this technology for such applications.

This study demonstrates that South Africa can confidently adopt RTK-enhanced INS/GNSS fusion technology for its proposed Pretoria-Polokwane-Musina high-speed rail link. The system delivers 10 cm positioning accuracy, even during GNSS outages, fast and reliable initialization, ensuring operational readiness and robust performance in dynamic conditions, critical for high-speed rail safety (Liu et al., 2023).

By integrating multi-constellation GNSS(BeiDou) with high-grade IMU and advanced Kalman filtering (EKF/UKF), South Africa can achieve precision rail navigation, enhanced safety, and improved efficiency, which are key requirements for modern high-speed train systems.

6. RECOMMENDATION

South African rail authorities and transport ministries should consider implementing this technology in the upcoming high-speed rail project to ensure world-class accuracy, reliability, and future-proof rail automation.

South Africa's high-speed rail project should adopt a hybrid navigation system integrating IMU/INS (Inertial Measurement Unit/Inertial Navigation System), BeiDou GNSS (Global Navigation Satellite System) and Real-Time Kinematic (RTK) technology to achieve world-class precision and reliability (International GNSS Service, 2022). This combination ensures centimeter-level positioning accuracy, critical for high-speed rail safety and efficiency, while maintaining uninterrupted operation in signal-challenged environments like tunnels or urban corridors (Huawei Technologies, 2023). BeiDou GNSS with RTK provides real-time corrections for ultra-precise tracking, and IMU/INS acts as a fail-safe during GNSS outages, enabling seamless navigation. This system supports future-ready automation, including autonomous train control, predictive maintenance, and AI-driven traffic management, while reducing long-term infrastructure costs by minimizing reliance on physical signal systems (Zhang et al., 2023).

To deploy this technology, South Africa should collaborate with China to expand BeiDou's RTK reference station network across key rail corridors and partner with global firms (CRRC Corporation, 2022). Strategic investments in training programs for local engineers will build domestic capacity, while policy updates should align with international standards for autonomous rail systems. Challenges such as upfront costs and cyber security risks can be mitigated through phased funding, public-private partnerships, and BeiDou's encrypted signals. By prioritizing this advanced navigation system, South Africa can establish itself as a regional leader in smart rail innovation, directly supporting economic growth and the goals of its National Development Plan 2030.

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7.1 Competing Interests

The author declares that no financial or personal relationships exist that could have affected the writing of this article.

7.2 Author's Contributions

Ms. Ratshilingana MM served as the primary author of this paper, with Prof. Yang Dongkai as the supervisor and Qin Zhenwei contributing as a co-author.

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7.4 Data Availability

The data used for generating and analyzing the results in this study can be accessed upon reasonable request directed to the corresponding author.

7.5 Disclaimer

The author affirms that this work does not violate any existing copyrights or intellectual property rights.

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