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MODELS FOR ASSESSING ACCURACY AND RELIABILITY OF FIBRE-OPTIC GYROSCOPE-BASED NAVIGATION SYSTEMS

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Abstract. *Fibre-optic gyroscope (FOG) navigation systems are widely used in autonomous, aerospace, and terrestrial applications due to their high stability and independence from external navigation signals. While significant progress has been made in improving FOG performance at the sensor level, fewer studies have investigated the system-level impact of residual gyroscope errors, particularly during periods of GNSS unavailability. This study addresses that gap by analysing the accuracy and reliability of navigation in FOG-based inertial navigation systems under various operational modes: GNSS-aided, unaided, and intermittently aided. A mathematical model of navigation is implemented in a MATLAB/Simulink environment to assess error propagation. Performance is evaluated using practical metrics such as heading drift, position error accumulation, and recovery efficiency after GNSS signal restoration. Simulation results show that during unaided navigation, heading errors reach approximately 2–3 degrees over 600–900 seconds, while position errors grow to 40–80 meters during 300–600 seconds of GNSS outage. Upon GNSS reacquisition, error reduction of 80–90% is observed within 30–60 seconds. These results demonstrate that system-level modelling can significantly enhance navigation reliability without requiring modifications to the FOG hardware.*

Keywords: fibre-optic gyroscope, inertial navigation system, navigation accuracy, GNSS outage, system-level analysis

MODELE OCENY DOKŁADNOŚCI I NIEZAWODNOŚCI SYSTEMÓW NAWIGACYJNYCH OPARTYCH NA ŻYROSKOPACH ŚWIATŁOWODOWYCH

Streszczenie. *Systemy nawigacyjne oparte na żyroskopach światłowodowych (FOG) są szeroko stosowane w aplikacjach autonomicznych, lotniczych oraz naziemnych ze względu na wysoką stabilność i niezależność od zewnętrznych sygnałów nawigacyjnych. Chociaż osiągnięto znaczący postęp w poprawie parametrów FOG na poziomie czujnika, znacznie mniej badań poświęcono wpływowi resztkowych błędów żyroskopu na poziomie systemowym, szczególnie w okresach niedostępności sygnału GNSS. Niniejsza praca wypełnia tę lukę poprzez analizę dokładności i niezawodności nawigacji w inercyjnych systemach nawigacyjnych opartych na FOG w różnych trybach pracy: z wspomaganiem GNSS, bez wspomagania oraz z okresowym wspomaganiem. Matematyczny model nawigacji został zaimplementowany w środowisku MATLAB/Simulink w celu oceny propagacji błędów. Wydajność systemu oceniano przy użyciu praktycznych miar, takich jak dryf kursu, narastanie błędu położenia oraz efektywność odzyskiwania dokładności po przywróceniu sygnału GNSS. Wyniki symulacji pokazują, że podczas nawigacji bez wspomagania błędy kursu osiągają około 2–3 stopnie w czasie 600–900 sekund, natomiast błędy położenia rosną do 40–80 metrów w trakcie 300–600 sekund zaniku sygnału GNSS. Po ponownym pozyskaniu sygnału GNSS obserwuje się redukcję błędów o 80–90% w ciągu 30–60 sekund. Uzyskane wyniki wskazują, że modelowanie na poziomie systemowym może znacząco zwiększyć niezawodność nawigacji bez konieczności modyfikacji sprzętu FOG.*

Słowa kluczowe: żyroskop światłowodowy, inercyjny system nawigacyjny, dokładność nawigacji, zanik GNSS, analiza na poziomie systemowym

Introduction

Fibre-optic gyroscope (FOG) navigation systems are essential in modern autonomous, aerospace, and terrestrial operations, where consistent position and attitude estimation must be maintained, even in the absence of external navigation support. Due to their solid-state construction [7, 12], long-term stability, resistance to electromagnetic interference, and ability to operate in harsh or GNSS-denied environments, FOG-based inertial navigation systems (INS) are widely regarded as robust alternatives or complements to satellite navigation technologies [1–4].

Recent research has primarily focused on improving the performance of FOGs at the sensor level. Studies have analysed error sources, proposed compensation techniques, and examined sensor behaviour under both steady and varying environmental conditions [2, 10]. Comprehensive reviews have also categorized FOG designs, signal-processing techniques, and emerging technological trends [8, 16]. As a result, the physical behaviour of FOG sensors and methods for mitigating sensor-level errors are now well understood [9, 17].

However, improvements at the sensor level do not automatically translate to enhanced navigation performance. In practical INS applications, gyroscope outputs are integrated over time, and even small residual errors can accumulate, leading to significant degradation in position, heading, and attitude estimates [11]. The navigation system functions as a dynamic entity where sensor errors propagate nonlinearly and interact with algorithm assumptions, initial conditions, and the availability of external corrections. Despite this, much of the literature continues to focus on the gyroscope itself, often neglecting the performance of the overall navigation solution.

In particular, the relationship between FOG error characteristics and navigation accuracy at the system level remains underexplored. Key factors such as error growth rates, navigation stability, and system resilience during GNSS outages are often simplified or overlooked [15, 18]. This limits the ability to design systems that not only function under ideal conditions but also maintain reliability in uncertain or degraded environments.

Importantly, improving navigation reliability does not necessarily require modifications to the gyroscope hardware. Greater benefits can be achieved by integrating an understanding of FOG error behaviour into system-level modelling, error propagation analysis, and robustness-focused design [19]. This approach shifts the focus from sensor optimization to full-system optimization, which is especially relevant for autonomous platforms operating over extended periods or in GNSS-denied environments.

This study investigates how the reliability and accuracy of FOG-based navigation systems can be enhanced through system-level analysis. It examines how realistic gyroscope error profiles influence the performance of strap down inertial navigation and explores system-level strategies to improve robustness and accuracy [14, 20, 21]. Navigation performance is assessed using practical metrics such as attitude drift, heading error growth, position error accumulation, and recovery following periods of limited or absent GNSS availability [23, 30].

Building on existing experimental and theoretical research on FOGs, this study shifts focus toward navigation outcomes rather than sensor characteristics alone. Simulation-based results offer deeper insights into the interaction between gyroscope behaviour and navigation algorithms, and they support the development of effective FOG-based navigation systems designed for autonomous or GNSS-denied environments.

1. Materials and methods

A simulation-based study was conducted to evaluate the accuracy and reliability of FOGs within a hierarchical navigation system context. Unlike traditional sensor-focused approaches, the proposed method emphasizes how gyroscope errors propagate through the navigation states and contribute to system-level performance degradation. A mathematical model of the navigation system was analysed in a controlled simulation environment to assess its behaviour under different operating scenarios [5].

1.1. Navigation system model

The system examined is a typical strap down inertial navigation system (INS), where angular rate data from fibre-optic gyroscopes is processed within a navigation algorithm to estimate attitude, velocity, and position [6, 22]. The gyroscope is modelled as a source of angular rate input, without simulating its internal physical structure or compensation mechanisms.

Let $\omega_g(t)$ denote the angular-rate output of the gyroscope. At the system level, it can be represented as [13, 29]:

$$\omega_g(t) = \omega_{true}(t) + b_g(t) + n_g(t) \tag{1}$$

where $\omega_{true}(t)$ is the true angular rate of the platform; $b_g(t)$ – the residual gyroscope bias; $n_g(t)$ – represents stochastic disturbances affecting the measurement.

In this work, $b_g(t)$ and $n_g(t)$ are interpreted as effective error components acting at the navigation-system input.

The navigation algorithm integrates angular-rate measurements to obtain attitude estimates [24]. For small attitude errors, the evolution of the attitude error vector $\theta(t)$ can be approximated by:

$$\theta_{k+1} = \theta_k + \left(b_g + n_g(k)\right)\Delta t \tag{2}$$

where Δt is the discrete integration step; index k – denotes the discrete time instant.

This relation highlights the cumulative nature of gyroscope errors in inertial navigation.

Attitude errors propagate further into velocity and position estimates. In a simplified form, the error dynamics can be expressed as [25, 27]:

$$\begin{aligned} \delta v_{k+1} &= \delta v_k + C\theta_k \Delta t \\ \delta p_{k+1} &= \delta p_k + \delta v \Delta t \end{aligned} \tag{3}$$

where δv and δp denote velocity and position errors, respectively; C – coefficient matrix determined by the adopted kinematic model.

These relations demonstrate how small orientation errors induced by gyroscope imperfections can lead to growing navigation errors over time.

1.2. Error-state navigation framework

An error-state representation is used to study the accuracy and reliability of navigation in various operating situations [26]. The state vector of navigation error can be defined as:

$$x = \left[\theta^T \ \delta v^T \ \delta p^T \ b_g^T\right]^T \tag{4}$$

which includes attitude, velocity, and position errors, as well as slowly varying gyroscope bias components.

The discrete-time error-state dynamics are described by:

$$x_{k+1} = Fx_k + Gw_k \tag{5}$$

where F is the state-transition matrix; G – the noise-distribution matrix; w_k – represents process noise capturing unmodelled dynamics and stochastic disturbances.

Measurement updates, when available, are represented as:

$$z_k = Hx_k + v_k \tag{6}$$

where z_k denotes external aiding measurements (e.g., GNSS-derived position or velocity); H – the measurement matrix, v_k – the measurement noise.

When there is a failure in GNSS coverage or poor external supporting signals, the measurement update is turned off, only inertial propagation is used to come up with the solution [16, 30]. This model allows the analysis of navigation efficiency when working in an aided and unaided mode and offers a uniform model of analysing errors accumulation and recovery.

1.3. Simulation framework and implementation

The error-state model and navigation model are applied to a simulation setup in a MATLAB/Simulink environment. The simulation architecture is based on the functional structure of the navigation system, such as the generation of gyroscopes signals, inertial mechanization and the propagation of the error states, and optional external aiding [2, 28].

Fig. 1 illustrates a block-level diagram of the simulation setup, showing how gyroscope measurements are fed into the navigation algorithm, how states are propagated, and how external aiding is integrated into the error-state framework.

The navigation system was tested under multiple conditions, including fully aided scenarios, complete GNSS outages, and partial aiding. Table 1 summarizes the key simulation parameters, including integration step size, simulation duration, external aid availability, and gyroscope error profiles used in each scenario.

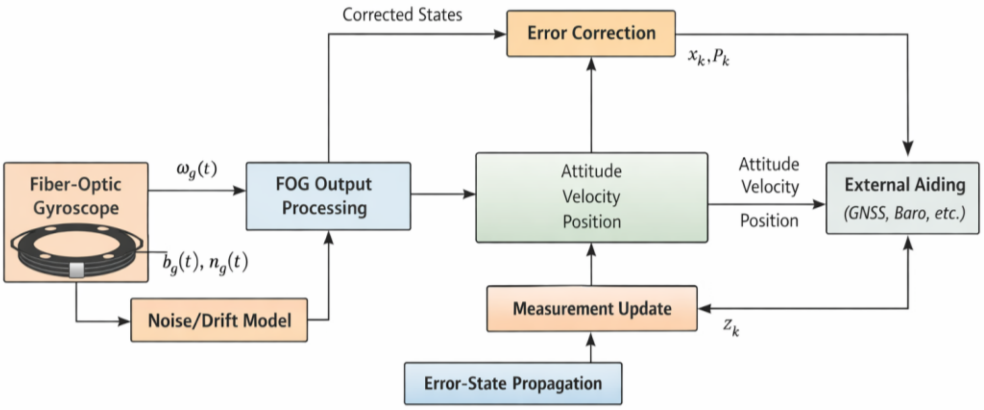

Fig. 1. Block diagram of the fibre-optic gyroscope-based navigation system architecture implemented in the simulation framework

Table 1. Simulation parameters and navigation scenarios

Parameter	Symbol	Value / Range
Simulation time step	Δt	0.01–0.05 s
Total simulation duration	T_{sim}	300–3600 s
Navigation mode	–	Aided / Unaided / Intermittent aiding
Gyroscope bias level	b_g	0.01–0.1°/h
Gyroscope noise level	n_g	$(1–5)\times10^{-3}$°/√h
Initial attitude error	θ_0	0–1°
Initial velocity error	Δv_0	0–0.1 m/s
Initial position error	Δp_0	0–5 m
GNSS update rate (if available)	f_{GNSS}	1–5 Hz
GNSS outage duration	T_{out}	60–600 s
Intermittent GNSS duty cycle	D	20–80%
Performance metrics	–	Heading error, position error, drift rate

2. Research results

This section presents the outcomes of a system-level simulation study aimed at assessing the accuracy and reliability of navigation systems that rely on FOGs. The primary focus lies in the time-dependent behaviour of navigation performance under various operational scenarios, including nominal external aiding, complete GNSS outages, and conditions following GNSS signal re-acquisition. Unlike sensor-level investigations, these results reflect the performance of the navigation system as a whole.

Fig. 2 displays the evolution of heading error over time under both aided and unaided operational modes. When aided by external measurements, the heading error remains small and stable, typically constrained within 0.3–0.5° throughout the entire observation period. This result reflects the stabilizing influence of measurement updates within the navigation algorithm.

In contrast, under unaided conditions, heading error accumulates over time due to the integration of small residual gyroscope errors. Simulations conducted under representative parameters show that heading error gradually increases, reaching approximately 2–3° after 600–900 s of operation without aiding. These findings demonstrate how even minimal residual biases at the sensor level can lead to noticeable degradation in orientation accuracy when external corrections are absent.

Fig. 3 provides insight into the impact of GNSS signal loss on position accuracy. The position error increases progressively during GNSS outages, initially growing at a slow rate but accelerating over time due to the compounding effects of attitude and velocity inaccuracies. For outage durations between 300–600 s, position error can increase from a few meters to approximately 40–80 meters, depending on the level of gyroscope error and the accuracy of initial alignment. These results highlight the vulnerability of inertial navigation systems to error accumulation over extended unaided intervals, reinforcing the importance of system-level robustness evaluations.

Recovery behaviour following GNSS signal restoration is also examined as a key indicator of navigation system reliability. As shown in Fig. 4, the reintroduction of external aiding causes the navigation solution to return toward the corrected state, with accumulated errors significantly reduced. In the tested scenarios, navigation errors decrease by approximately 80–90% within 30–60 s after GNSS re-acquisition, with residual position errors falling to the 5–10 m range. The speed and completeness of recovery depend on the extent of error accumulation during the outage. Nonetheless, the simulations confirm that the navigation solution converges smoothly without instability or oscillation, demonstrating the structural resilience of the system under intermittent aiding conditions.

Overall, the obtained results demonstrate that navigation accuracy and system reliability are strongly influenced by how gyroscope errors are managed and by the availability of external measurements. The clear patterns of error growth during unaided operation and error reduction after aiding recovery confirm that system-level modelling offers essential insight into the limitations and behaviour of FOG-based navigation systems, especially in autonomous or GNSS-denied environments.

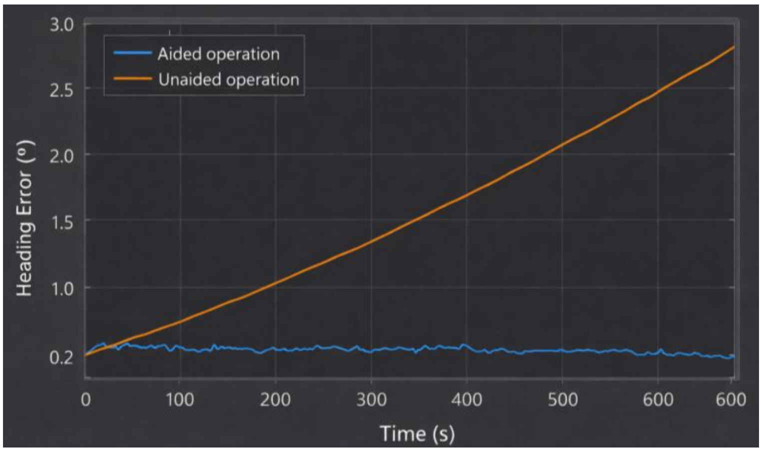

Fig. 2. Heading error evolution of the navigation system under aided and unaided operation modes

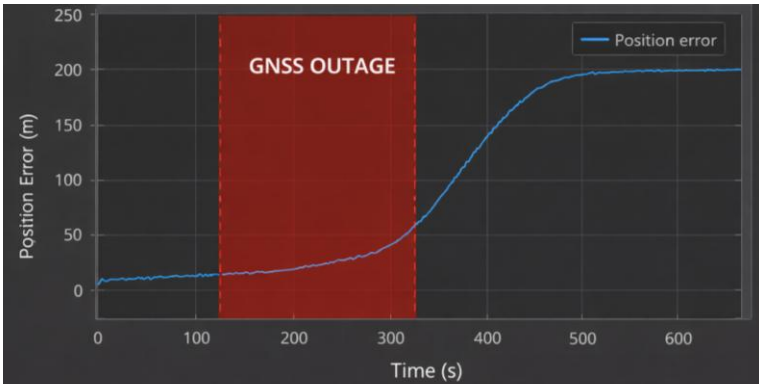

Fig. 3. Position error growth during a continuous GNSS outage interval

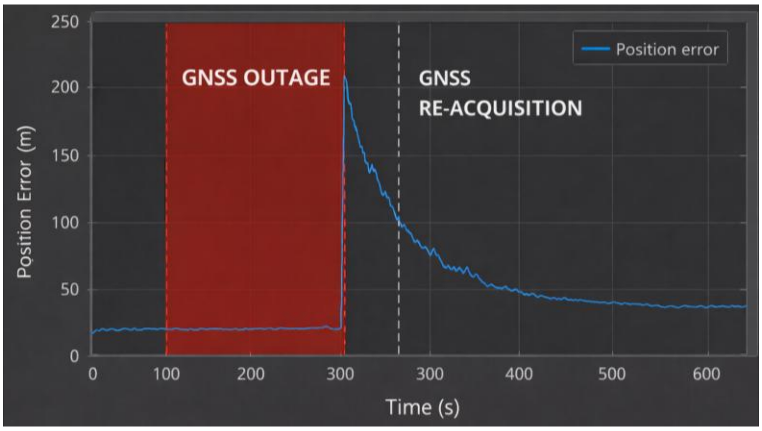

Fig. 4. Recovery of navigation error after GNSS re-acquisition following an outage period

3. Conclusions

This study addressed the challenge of improving the accuracy and reliability of FOG-based navigation systems from a system-level perspective. In contrast to sensor-focused research that concentrates on internal gyroscope behaviour or error compensation methods, the presented work explored how residual gyroscope errors propagate through the navigation algorithm and influence the overall performance of the system under realistic operational conditions.

The navigation performance was evaluated through a simulation framework implemented in MATLAB/Simulink, using a mathematical model of a strap down inertial navigation system operating in aided, unaided, and intermittently aided modes. The results clearly show that cumulative gyroscope error integration significantly affects navigation accuracy, particularly in the absence of GNSS signals. Under typical system settings, unaided operation leads to heading errors of several degrees within 10–15 minutes, while position errors can increase to tens of meters.

The simulations confirmed that heading errors grow steadily over time during unaided operation, resulting in faster accumulation of position errors. Prolonged GNSS outages were shown to degrade navigation performance considerably, emphasizing the importance of system-level robustness over sensor-level performance indicators. At the same time, the simulations demonstrated that the navigation system retains stability and is capable of returning to a corrected state once external aiding becomes available again.

A notable outcome of the study is the evidence of reliable recovery behaviour following GNSS re-acquisition. After a period of unaided operation, the navigation error is reduced by more than an order of magnitude in under one minute, with the system converging smoothly to a limited residual error without exhibiting instability or oscillations. This finding supports the robustness of the error-state framework under conditions of intermittent aiding and defines practical limits on autonomous operation time.

Overall, the results indicate that improving navigation accuracy and reliability does not necessarily require hardware modifications or enhancements within the fibre-optic gyroscopes themselves. Instead, significant performance gains can be achieved through system-level modelling, careful integration of gyroscope error dynamics into the navigation algorithm, and thorough evaluation under realistic aiding conditions. The proposed framework provides valuable insight into the performance boundaries of FOG-based navigation and supports the development of reliable navigation solutions for autonomous, terrestrial, airborne, and GNSS-denied environments.

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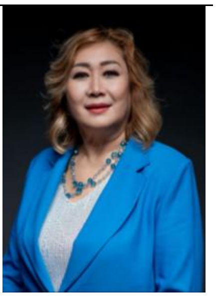

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