Asian Journal of Social Science and Management Technology
ISSN: 2313-7410
Volume 7, Issue 6, November-December, 2025
Available at www.ajssmt.com

Development of IMU-Based ERGODRIVE Driving Simulator for Cognitive Ergonomics Analysis and Driver Fatigue Detection

Desinta Fitarini[1], Haris Ainur Rofiq[2], Immanuel Aryo Prasojo[3], Kezia Vita Christiana[4], Qonita Annisa' Aprillia[5], Zarith Zahwan[6], Rahmaniyah Dwi Astuti[7], Andreas Wegiq Adia Hendix[8]
[1,2,3,4,5,6]*(Department of Industrial Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia)*

ABSTRACT : Driver fatigue and reduced cognitive alertness are major contributors to road accidents, while existing monitoring systems remain costly and inaccessible for training or ergonomic studies. This research introduces ERGODRIVE, a low-cost IMU-based driving simulator developed using ESP32 and a cockpit built from locally sourced materials. Sensor data including acceleration, angular velocity, and orientation are processed through filtering and sensor-fusion algorithms to provide stable real-time motion tracking. These movement patterns are visualized in two modes, Driving Simulation and Free Drive, and used to derive preliminary cognitive-fatigue indicators such as steering deviation, micro-corrections, and body sway. ERGODRIVE provides an accessible platform for studying cognitive ergonomics and observing driver behavioral patterns, offering a low-cost alternative for research, training, and early fatigue monitoring. Future work includes expanding analytical capabilities and integrating machine-learning-based fatigue detection.

Keywords - Driving Simulator, IMU Sensor, Cognitive Ergonomics, Driver Fatigue, Low-Cost System

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1. INTRODUCTION

Traffic accidents involving logistics drivers remain a serious safety issue in Indonesia, with national data reporting 139,258 cases in 2022 and increasing to 148,643 cases in 2023, resulting in significant fatalities and losses [1], [2]. A large proportion of these accidents is caused by human error, particularly driver fatigue and decreased alertness during driving activities [3]. Fatigue is not limited to physical exhaustion but also includes cognitive fatigue, which negatively affects attention, information processing, situational awareness, and decision-making [4]. However, real-time monitoring of cognitive fatigue remains challenging, as most existing fatigue detection systems focus primarily on physical indicators and rely on expensive commercial devices that are difficult to access for education and research purposes [5]. In addition, high-fidelity driving simulators commonly used for fatigue assessment are costly and depend on imported components, limiting their implementation in local institutions and small-to-medium industries. To address these limitations, this paper introduces ERGODRIVE, a low-cost cockpit driving simulator based on Inertial Measurement Unit (IMU) sensors and a cognitive ergonomics approach. ERGODRIVE enables real-time monitoring of driver behavior and fatigue indicators while providing an affordable platform for training and research in the logistics sector, supporting Sustainable Development Goals (SDGs), local component utilization (TKDN), and practical industrial needs [1].

2. LITERATURE REVIEW

This section reviews key concepts and prior research relevant to the development of ERGODRIVE, including driver fatigue and its safety implications, cognitive ergonomics and fitness to drive, technological approaches to fatigue detection, the role of driving simulators, and the potential of IMU-based low-cost systems for educational and research purposes. The aim is to position ERGODRIVE within the existing body of knowledge and to highlight the specific gaps that motivate a low-cost, sensor-based cockpit simulator for logistics drivers.

2.1. Driver Fatigue and Logistics Safety

Driver fatigue is a major contributor to road traffic accidents, especially in commercial and logistics operations where long driving hours and monotonous highway conditions are common [6]. Prolonged or partially sleep-deprived driving produces a clear increase in subjective fatigue and sleepiness, with drivers approaching unsafe levels of drowsiness after several hours of continuous driving [6][7]. Fatigue is therefore recognized as a critical safety issue in transport work, and reducing fatigue-related risk is repeatedly identified as a key priority in occupational and road safety research [6][8].

2.2 Physical and Cognitive Fatigue in Driving

Fatigue in driving tasks has both physical and cognitive components that together degrade performance. Physical fatigue is related to musculoskeletal strain and prolonged postures, whereas cognitive fatigue is characterized by reduced attention, slower information processing, and impaired decision-making in demanding or monotonous conditions [9]. Simulator and EEG-based studies show that prolonged driving leads to increased subjective fatigue and measurable changes in neural or physiological indicators, supporting the view that mental workload and time-on-task jointly drive cognitive fatigue behind the wheel [7][9].

2.3 Existing Driver Fatigue Detection Technologies

Recent reviews describe a wide range of driver fatigue detection technologies, including vision-based, physiological, and multi-sensor systems [10][8]. Multi-sensor approaches often combine cameras, inertial sensors, and vehicle signals with machine-learning algorithms to classify drowsiness, achieving high accuracy but at the cost of increased system complexity [10]. Over the last 15 years, driver fatigue detection has evolved from simple threshold-based methods to advanced deep-learning models using multi-modal signals, yet implementation in real-world fleets remains limited by cost, robustness, and user acceptance [8][11][12].

2.4 Cognitive Ergonomics and Fitness to Drive

Cognitive ergonomics provides a useful lens to understand how mental workload, attention, and human–system interaction influence fitness to drive [9]. From this perspective, a driver's readiness is determined not only by physical condition but also by the capacity to maintain situation awareness, process multiple information streams, and make timely decisions under time pressure. Simulator-based studies that incorporate cognitive performance tasks, secondary tasks, or complex traffic scenarios help operationalize cognitive aspects of fitness to drive and reveal how fatigue impairs higher-level information processing even before gross control errors become obvious [6][7][9].

2.5 Driving Simulators and Cost Barriers

Driving simulators are widely used to investigate driver behavior and fatigue and to evaluate engineering or training interventions under controlled yet safe conditions [6][7][13]. High-fidelity simulators can reproduce long, monotonous driving periods known to induce fatigue, and they allow continuous recording of performance metrics such as lane-keeping, speed control, and reaction to events [6][7]. However, such systems are often expensive, proprietary, and infrastructure-intensive, which limits their adoption in universities and smaller institutions that need accessible platforms for education and research [13].

2.6 IMU-Based and Low-Cost Sensing

Inertial Measurement Units (IMUs) are compact sensor modules that measure linear acceleration and angular rate and are widely used in navigation, robotics, and motion tracking because of their small size and relatively low cost [14][15]. IMUs can be used to simulate or capture vehicle dynamics and control inputs, and software tools are available to generate realistic IMU signals for testing algorithms and control systems [16]. These characteristics make IMUs attractive for building low-cost driving simulators and driver monitoring systems, where steering motion, pedal activity, or cockpit movement can be measured without relying on expensive proprietary hardware [14][15][16].

2.7 Research Gap and Positioning of ERGODRIVE

Despite advances in fatigue detection and simulator technology, there remains a gap between highcost, highfidelity systems and affordable platforms that integrate realtime sensing with cognitiveergonomicsbased assessment [8][10][11][13]. Many multisensor fatigue detection systems are technically sophisticated but difficult to deploy for routine training or research in resourceconstrained settings [10][13]. A lowcost cockpit simulator built around IMUbased sensing and designed explicitly to capture fatiguerelated changes in driver control behavior and cognitive performance would therefore occupy an important niche, enabling broader access to experimental fatigue assessment and training aligned with logisticssector needs [6][8][14][13].

3 METHODS

This research follows a technological engineering framework that includes literature studies, system design, and implementation to build the ERGODRIVE driving simulator. Literature studies were conducted to identify the needs for IMU sensor technology, cognitive ergonomics concepts, and low-cost simulator references as a basis for design. In the hardware design stage, a mechanical design consisting of a cockpit, steering wheel, pedals, and H-shift was developed using multiplex and wood materials, which were chosen because they are easy to make and low cost. The electronic system was designed using ESP32 as the main microcontroller, IMU sensors to read and analyze the driver's movements in real-time, and potentiometers as analog sensors for steering, pedal, and transmission lever inputs. In the software development stage, the core mechanics system was built to read and process high-frequency sensor data through filtering and smoothing processes to produce stable orientation. The processed data is mapped to the driver's steering behavior and body movements through an angle mapping algorithm and combined with an analysis of movement variability, such as steering deviation, micro-correction frequency, body sway, and response timing, as early indicators of cognitive fatigue. The ERGODRIVE interface was then developed to display driving simulation visualizations in two modes: Driving Simulation with specific scenarios and Free Drive. All the hardware and software that had been created were fully integrated so that the system could operate synchronously, from sensor reading to the presentation of evaluation data on the screen. After integration, testing was carried out to evaluate sensor accuracy, data pipeline stability, interface response, and ease of use, so that all components worked synchronously and reliably to support the objectives of simulation and cognitive ergonomics analysis.

4 RESULTS AND DISCUSSION

The ERGODRIVE system was successfully constructed as a low-cost driving simulator integrating mechanical steering, pedal modules, an H-shift system, and an MPU9250 IMU connected to an ESP32-C3 controller. Mechanical testing showed that the laminated-wood cockpit provided sufficient rigidity for short-duration sessions, with the steering mechanism maintaining smooth rotation across repeated cycles. A minor dead zone of approximately 2.1–2.8° emerged due to shaft–bearing tolerance, while pedal linearity remained stable with a coefficient of variation of 3.4% across 50 repeated pressure cycles. The H-shift mechanism produced consistent tactile feedback with no measurable drift in position detection. These findings indicate that the mechanical structure performs adequately for task-based cognitive evaluation, although improvements in fabrication tolerance could further suppress micro-movement noise.

Figure 1. Hardware Ergodrive

Building on the stable mechanical performance, the IMU assessment demonstrated that the MPU9250 accurately tracked orientation changes during slow and moderate rotations, maintaining an average deviation of ±1.7°. Rapid rotations exceeding 180°/s produced transient drift peaks of up to ~6°, which stabilized within 2–3 s, consistent with expected mid-range MEMS IMU behavior. Noise amplitude remained low (mean variance 0.012 rad²), and repeated measurements across 30 trials displayed consistent error patterns. Overall, sensor performance was sufficiently reliable for capturing steering-angle variability and micro-correction the behavior during simulated driving tasks. Complementing the sensor evaluation, the web-based drowsiness-testing interface provides a platform for visualizing user responses and monitoring cognitive-performance indicators in real time.

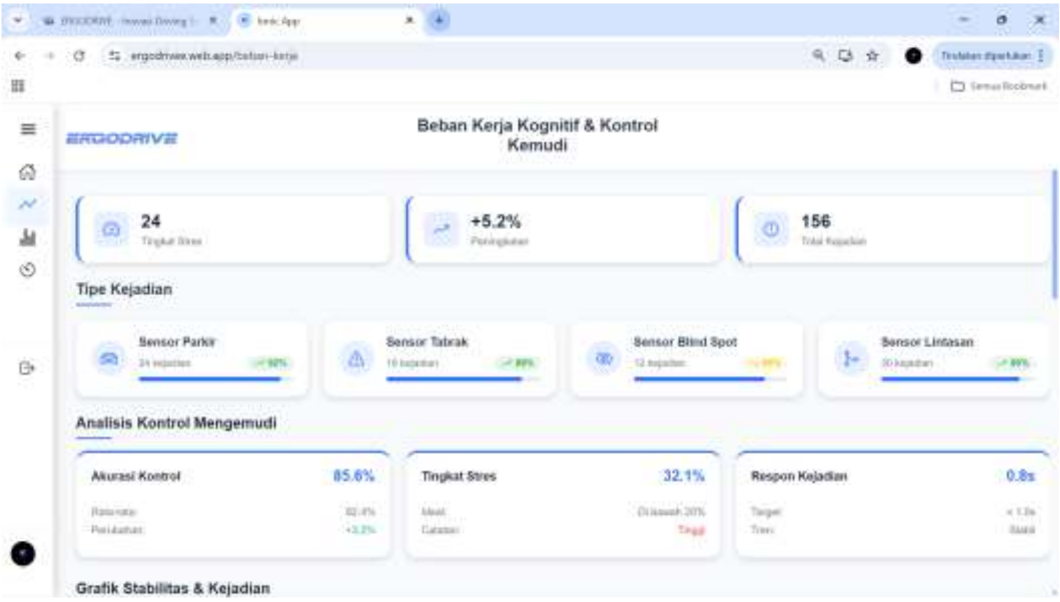

Figure 2. Interface Software

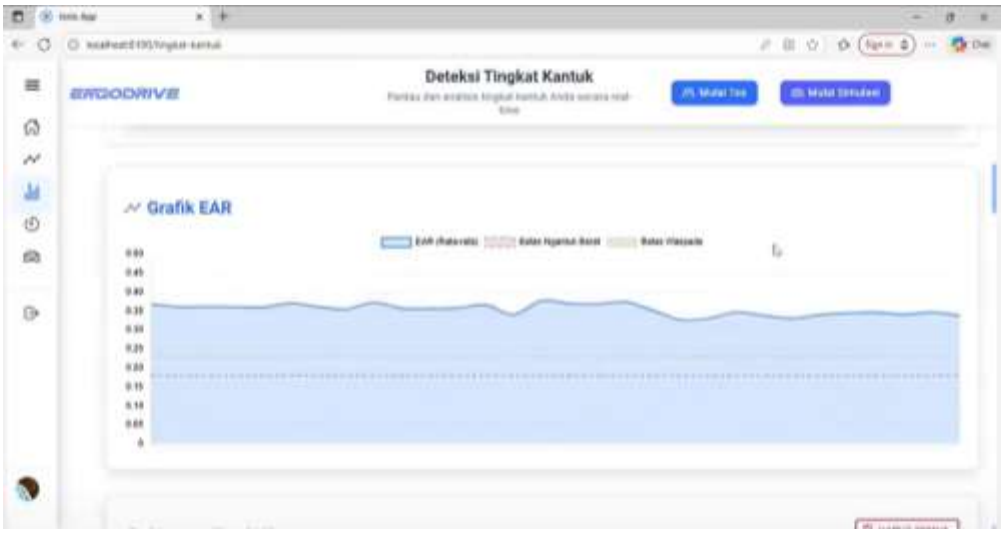

Figure 3. Fatigue Detection

The Cognitive-fatigue detection relied on analyzing reaction-task variability and motor-control patterns during simulation. As users showed reduced alertness, reaction times increased and steering stability declined. Variability in steering angle and micro-corrections became more frequent, accompanied by inconsistent pedal pressure in several cases. These behavioral shifts align with established findings that cognitive fatigue degrades fine-motor control and delay responses to stimuli. The patterns captured by ERGODRIVE indicate that the system can reliably detect early signs of cognitive decline.

Furthermore, user experience evaluation showed that most participants found the interface intuitive and easy to follow. The seating posture and component layout were generally comfortable for 10–15-minute sessions, although some users recommended improving seat stability and allowing more flexible pedal adjustment. Real-time motion visualization and low-latency feedback helped users understand their performance and increased confidence in the system's responsiveness.

Taken together, integrating the mechanical, sensor, and behavioral findings confirms that the system components support one another in producing interpretable cognitive-performance data. Stable mechanical operation reduces noise sources, enabling the IMU to capture cleaner orientation signals. The resulting data, when combined with pedal behavior and reaction-time metrics, forms a coherent pattern consistent with cognitive-fatigue theory. Overall, ERGODRIVE meets its intended purpose as a task-based cognitive evaluation platform, while leaving space for refinement in mechanical precision and sensor-correction algorithms to increase measurement accuracy in future versions.

5 CONCLUSION

This study has presented ERGODRIVE, a low-cost IMU-based cockpit driving simulator designed to support cognitive ergonomics analysis and early detection of driver fatigue. The system integrates mechanical driving components, IMU sensing, and an ESP32-based processing unit with a software platform that visualizes driver behavior in real time through Driving Simulation and Free Drive modes. Experimental results indicate that the mechanical structure provides sufficient stability for short-duration simulations, while the IMU sensor reliably captures steering variability, micro-corrections, and body movement patterns that correspond to indicators of cognitive fatigue.

Overall, ERGODRIVE offers a practical and affordable alternative to high-cost commercial simulators and complex fatigue detection systems, making it suitable for educational institutions, ergonomics laboratories, and preliminary safety research in the logistics sector. Although the current prototype is limited by mechanical tolerances, session duration, and the absence of physiological validation, these limitations open clear directions for future work, including improved mechanical precision, enhanced sensor-fusion algorithms, and the integration of machine-learning-based fatigue classification. With further development, ERGODRIVE has strong potential to support driver training, cognitive fatigue research, and safety-oriented innovation using accessible, locally sourced technology.

6 ACKNOWLEDGEMENTS

The author hereby conveys profound appreciation to Dr. Ir. Rahmaniyah Dwi Astuti, S.T., M.T., as the supervising lecturer, for her unwavering guidance, insightful feedback, and continuous support during the completion of this research. Gratitude is also directed to CV Enuma for granting the opportunity to conduct system testing and for offering meaningful insights into practical ergonomic requirements in real-world settings. Finally, the author conveys heartfelt thanks to the project team members whose collaboration, commitment, and collective efforts greatly contributed to the realization of this work.

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Corresponding Author: **Desinta Fitarini, Department of Industrial Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia.**

How to cite/reference this article: **Desinta Fitarini, Haris Ainur Rofiq, Immanuel Aryo Prasojo, Kezia Vita Christiana, Qonita Annisa' Aprillia, Zarith Zahwan, Rahmaniyah Dwi Astuti, Andreas Wegiq Adia Hendix, Development of IMU-Based ERGODRIVE Driving Simulator for Cognitive Ergonomics Analysis and Driver Fatigue Detection, *Asian. Jour. Social. Scie. Mgmt. Tech*. 2025; 7(6): 310-316.**