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IoT Integration in Railway Signaling Systems: Opportunity Analysis and Application of Track Guard Fatigue Monitoring (Pjl)

Integrasi Iot Dalam Sistem Persinyalan Kereta Api : Analisis Peluang Dan Aplikasi Monitoring Kelelahan Penjaga Jalan Lintasan (Pjl)

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Abstract

The integration of IoT into railway signalling offers a transformative opportunity to enhance safety, particularly at level crossings. Traditional mechanisms relying on scheduled maintenance often fail to address real-time human-factor risks like operator fatigue. This manuscript analyzes IoT integration to monitor the alertness of Level Crossing Guards (PJL), proposing a shift from reactive to proactive safety management. The core problem is the lack of continuous, objective systems to detect fatigue, as conventional methods like self-reporting are intermittent and subjective. The objective is to utilize IoT technologies—sensor networks, data analytics, and wireless communication—to develop a reliable, non-intrusive fatigue monitoring application. The proposed methodology involves a multi-layer architecture where wearable sensors collect physiological data. This data is transmitted via low-latency protocols like LoRaWAN to a central unit, where machine learning algorithms assess fatigue levels in real-time. The system interfaces with signalling infrastructure to trigger automated alerts or backup protocols when critical thresholds are detected. Anticipated results indicate a paradigm shift, significantly reducing accident risks through continuous vigilance and data-driven decision-making. Beyond safety, collected data can optimize shift patterns and wellness programs. Despite challenges regarding privacy and costs, IoT-based fatigue monitoring is concluded to be a feasible, highly impactful application. Its success could serve as a model for enhancing human-factor safety across critical transport domains, moving towards intelligent railway ecosystems.

***Keywords**: IoT Integration, Signalling, Crossing Guard*

Abstrak

Integrasi Internet of Things (IoT) dalam sistem persinyalan kereta api meningkatkan keselamatan dan efisiensi melalui keterhubungan komponen secara real-time. Penelitian ini mengeksplorasi peluang dan tantangan penerapan IoT, dengan fokus pada sistem monitoring kelelahan penjaga palang pintu menggunakan kamera inframerah dan mikrokontroler. Sistem ini mendeteksi pola kedipan mata, durasi penutupan mata, dan pergerakan kepala sebagai indikator kelelahan, kemudian mengirimkan peringatan otomatis via jaringan IoT. Metode yang digunakan meliputi studi literatur, perancangan prototipe, dan pengujian performa pada kondisi pencahayaan rendah. Hasilnya, integrasi IoT terbukti meningkatkan akurasi pemantauan, mempercepat deteksi risiko di perlintasan sebidang, serta menyediakan data operasional kontinu untuk pengambilan keputusan. Meskipun demikian, implementasi menghadapi tantangan infrastruktur jaringan stabil, keamanan siber, integrasi dengan sistem konvensional, dan kesiapan SDM.

Kata Kunci: Integrasi Iot, Pensinyalan, Penjaga Jalan Lintasan

2.1. INTRODUCTION

The safe and efficient operation of railway networks remains a key concern for global transportation infrastructure. While significant progress has been made in the automation of mainline signalling and train control, the safety of level crossings—especially those manned by human personnel—presents persistent and complex challenges. Level way Guards (LEWs) are a critical human component of these systems, responsible for direct observation, decision-making, and manual operation of level crossing gates and signals to prevent collisions between road and rail traffic.

LEWs' roles require continuous vigilance, particularly in areas with high traffic density or complex operational environments. However, human performance is inherently variable and susceptible to degradation due to fatigue, a state of reduced mental and physical capacity caused by prolonged exertion, sleep deprivation, or disruption of circadian rhythms. In safety-critical domains like railway operations, fatigue impairs cognitive functions such as situational awareness, reaction time, and judgment, increasing the risk of catastrophic human error. Data shows that human factors, particularly driver and operator fatigue, contribute significantly to transportation accidents globally. In Indonesia, these challenges are exacerbated by the often hot, noisy, and monotonous environmental conditions of guard posts, which are physiological catalysts for the onset of microsleep.

This article explores the integration of the Internet of Things (IoT) into railway signalling systems, with a particular analytical focus on the opportunities and practical applications for monitoring fatigue in track guards. The central thesis is that IoT-based monitoring systems represent a significant opportunity to improve railway safety by providing objective and continuous insights into the fitness-for-duty of frontline personnel.

The data fusion and real-time analytics enabled by IoT platforms can trigger timely alerts—to the officers themselves, to remote supervisors, or to the signalling system—to prompt intervention before safety thresholds are breached. However, integrating such systems into the safety-critical architecture of railway signalling is fraught with technical, ethical, and operational challenges, including cybersecurity and privacy.

2.2. METHODOLOGY

This research adopts an Applied Experimental Engineering design within a Systems Engineering V-Model framework. The methodology focuses on the development and validation of a non-intrusive fatigue monitoring system for Level Crossing Guards (PJL) by integrating biomedical informatics, computer vision, and low-power telecommunications. The research process is divided into four phases: hardware integration, algorithm calibration, laboratory simulation, and statistical validation.

2.2.1. Research Location and Environmental Context

The primary research and prototyping activities are conducted at the **Faculty of Engineering, Universitas Pancasila (FTUP)**, specifically within the Electrical Engineering Laboratory (Universitas Pancasila, 2025). The laboratory environment is configured to simulate the operational conditions of a railway crossing post (Pos PJL).

To replicate the visual challenges faced during night shifts, the laboratory lighting is controlled to vary between 300 lux (standard office lighting) and <10 lux (low-light night conditions). This variation is critical for validating the performance of the active Infrared (IR) illumination system used for gaze tracking. Furthermore, the communication modules are tested within the electromagnetic environment of the laboratory to ensure compliance with Indonesian frequency regulations.

2.2.2. Research Philosophy and Approach

The development of safety-critical systems in the railway domain demands a rigorous, evidence-based methodological approach that goes beyond simple prototyping. This research adopts the Systems Engineering V-Model framework, modified for the rapid prototyping cycles inherent in IoT development. The core philosophy driving this methodology is "Safety by Design," where the integration of fatigue monitoring is not treated as a peripheral add-on, but as an integral subsystem within the broader railway signalling ecosystem.

This research design is characterized as Applied Experimental Engineering with a Quantitative Validation Phase. This research operates at the intersection of three distinct technical disciplines:

1. Biomedical Informatics: Quantification of human physiological states (fatigue) into computable metrics using non-invasive sensors.

2. Computer Vision and Machine Learning: Real-time behavioral feature extraction from video streams to infer cognitive states.

3. Telecommunications Engineering: Robust transmission of safety-critical data over Low Power Wide Area Networks (LoRaWAN) in Indonesia's spectrum allocation regulatory environment.

This multidisciplinary approach required a comprehensive methodology for component selection, rigorous algorithmic definition, and clinically valid testing protocols. The study progressed through four distinct phases: Requirements Analysis & System Architecture, Hardware/Software Integration, Laboratory Simulation & Data Collection, and Statistical Performance Evaluation. Each phase was designed to reduce uncertainty and validate the hypothesis that IoT-based sensor fusion can reliably detect PEF fatigue before a safety incident occurs.

2.2.3. System Development Life Cycle (SDLC)

The methodology follows a specific SDLC tailored for embedded safety systems. Unlike standard software development, which might prioritize feature speed, this lifecycle prioritizes determinism and reliability.

- Phase I: Sensor Characterization: Evaluates the sensitivity and specificity of optical (camera) and contact (PPG) sensors under varying environmental conditions relevant to railroad crossings (e.g., low light, vibration).
- Phase II: Algorithm Calibration: Adjusts thresholds for Eye Aspect Ratio (EAR) and Heart Rate Variability (HRV) metrics based on baseline physiological data to minimize false positives, which can lead to "alarm fatigue"—a critical failure mode in safety operations.
- Phase III: Integrated Prototyping: Assembles separate modules into a cohesive unit controlled by a central processing node (Raspberry Pi), ensuring synchronization between visual and physiological data streams.
- Phase IV: Ecological Validation: Testing the system in a high-fidelity simulator that replicates the psychomotor alertness tasks required of a PJL guard, using a standard subjective scale (Karolinska Sleepiness Scale) as ground truth.

2.2.4. Tools and Materials: Hardware Architecture

The "PJL Guard Smart Monitor" requires a robust hardware stack capable of handling heavy computational loads (image processing) while maintaining the stability required for a safety device. The architecture is divided into a **Sensing Layer**, a **Processing Layer**, and a **Network Layer**.

Central Processing Unit: Single Board Computer Selection

The core of this system is a Raspberry Pi 4 Model B (4GB RAM). This selection was made after a comparative analysis of microcontroller-based solutions and high-end edge AI devices.

Feature	**Raspberry Pi 4 Model B**	**ESP32-CAM**	**NVIDIA Jetson Nano**	**Justification for Selection**
Processor	Quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz	Dual-core Xtensa® 32-bit LX6	Quad-core ARM Cortex-A57	The Pi 4 offers the optimal balance of CPU power for OpenCV/MediaPipe without the high cost/power of the Jetson.
RAM	4GB LPDDR4-3200	520 KB SRAM	4GB LPDDR4	4GB is essential for loading the MediaPipe Face Mesh model into memory while running the OS and telemetry stack simultaneously.
Video Processing	Software-based (OpenCV/MediaPipe)	Limited (Low FPS, low res)	Hardware-accelerated AI	The Pi 4 can sustain 15-20 FPS for face tracking, which is the minimum viable threshold for detecting rapid microsleeps.
I/O Connectivity	40-pin GPIO, USB 3.0, CSI Camera Port	Limited GPIO	40-pin GPIO	Rich I/O allows for the simultaneous connection of the LoRa HAT, PPG sensor, and alert buzzers/displays.
Power Consumption	~3.4W (Idle) - 7.6W (Load)	~1 W	~5W - 10W	Manageable for battery/solar deployments typical in remote rail infrastructure.

The Raspberry Pi runs Raspbian OS (Bullseye), a Debian-based Linux distribution. This OS is configured in “headless” mode (without a graphical interface) to maximize system resources for the computer vision pipeline. The camera system used is a NoIR Camera Module v2 (8MP) with a Sony IMX219 sensor. The "NoIR" designation indicates the absence of an Infrared cutoff filter, allowing the camera to "see" in near-darkness when aided by active IR LED illumination—a critical requirement for monitoring guards during high-risk night shifts.

2.2.5. Software Architecture and Algorithmic Frameworks

The software architecture is built primarily using Python 3.9, leveraging its extensive ecosystem for computer vision and scientific computing. The fatigue detection logic is a hybrid system that combines visual and physiological signal analysis.

a) Visual Fatigue Detection (Computer Vision)

The visual subsystem uses the Google MediaPipe Face Mesh library. Unlike the legacy Haar Cascade classifier, which only detects facial bounding boxes, MediaPipe infers the 3D surface geometry of the face, tracking 468 dense facial landmarks in real time. This density allows for highly granular analysis of eyelid and mouth movements.

1. **Eye Aspect Ratio (EAR):** To detect drowsiness characterized by eye closure (microsleeps), the system calculates the Eye Aspect Ratio. EAR is a scalar value derived from the relative distances between six facial landmarks per eye, P_1 to P_6. The formula used, as defined by Soukupová and Čech, is:

$$EAR = \frac{||P_2 - P_6|| + ||P_3 - P_5||}{2 \times ||P_1 - P_4||}$$

Where P_1, P_4 is the horizontal angle of the eye, and P_2, P_3, P_5, P_6 is the vertical eyelid point. The algorithm monitors this ratio; a sharp decrease in EAR indicates blinking, while a sustained low value (below the calibrated threshold of 0.25 for more than 15 consecutive frames) triggers a drowsiness warning.

2. **Mouth Aspect Ratio (MAR):** To detect yawning, a similar metric is applied to mouth landmarks. An increase in the vertical distance between the lips relative to the mouth width beyond a certain threshold indicates a yawn.

b) Physiological Signal Processing (HRV)

Complementing the visual system is a PPG (Photoplethysmography) sensor (MAX30102) connected via an I2C interface. This sensor measures the pulse volume of blood at the fingertip. The raw signal is processed using the open-source software PyHRV and SciPy to extract Heart Rate Variability (HRV).

- Pre-processing: A bandpass filter (0.5-5 Hz) is applied to remove motion artifacts and electrical hum.
- Feature Extraction: The system calculates the RMSSD (Root Mean Square of Successive Differences) of the R-R intervals. RMSSD is the primary time-domain measure used to estimate vagally mediated changes reflected in HRV. Significant decreases in HRV have been scientifically proven to correlate with mental fatigue and decreased alertness.

2.2.6. Network Layer: LoRaWAN Telemetry

Given the specific constraints of Indonesian railway infrastructure (often remote, with intermittent cellular coverage), the system uses LoRaWAN (Long Range Wide Area Network) for data transmission.

- Frequency: The system is configured to operate on the AS923 frequency plan (920–923 MHz), which is the regulatory standard for Indonesia.
- Modulation: Chirp Spread Spectrum (CSS) is used with a Spreading Factor (SF) of 7 to 9, balancing range and time-on-air.

- Payload Format: Data packets are encoded using the CayenneLPP (Low Power Payload) format to minimize packet size, ensuring high reliability even in environments with high electromagnetic noise. The payload includes critical flags (Fatigue_Status, Sensor_Health) and compressed scalar values (Average_EAR, Current_HR).

2.3. RESULTS AND DISCUSSION

2.3.1. Visual Fatigue Detection Performance

Prototype testing results indicate that integrating the NoIR camera with the MediaPipe Face Mesh algorithm provides robust results across various lighting conditions.

Table 1: System Performance Metrics (Raspberry Pi 4 Model B)

Testing Condition	Average FPS	CPU Usage	Detection Accuracy (EAR)	False Positive Rate
Daylight (300 Lux)	18.2	68%	96.5%	2.1%
Dim Light (50 Lux)	17.5	71%	91.2%	4.5%
Night (IR Assisted)	16.8	74%	94.8%	3.2%
Occlusion (Glasses)	17.1	70%	88.4%	6.8%

A key finding is that the system maintains **94.8% accuracy** in total darkness (simulated night conditions) thanks to active infrared illumination. This is highly relevant for PJL night shifts, which carry the highest fatigue risk. The use of MediaPipe proved superior to conventional *Haar Cascade* methods in handling face rotation and extreme lighting conditions.

2.3.2. Data Transmission Reliability (LoRaWAN)

Connectivity testing in a simulated railway environment showed that the LoRaWAN protocol on the AS923 frequency possesses high resilience against electromagnetic interference (EMI) generated by train traction systems.

Table 2: LoRaWAN Transmission Reliability (AS923 Band)

Distance from Gateway	Spreading Factor (SF)	RSSI (dBm)	SNR (dB)	Packet Delivery Ratio (PDR)
100 m	SF7	-65	+9	99.8%
2 km	SF9	-105	-4	96.5%
5 km (NLOS)	SF12	-118	-12	89.4%

Despite its reliability, there is a *trade-off* in latency. At SF12 (long range), alert data transmission latency can reach 1.5 seconds. Therefore, using SF7-SF9 is recommended for critical alerts to keep latency under 1 second.

2.3.3. Implementation and Security Challenges

Deploying this system faces regulatory and cybersecurity challenges. In accordance with BSSN Regulation No. 8 of 2023, vital infrastructure must adhere to strict information security standards. The primary risks are signal *jamming* and data manipulation. The proposed solution includes *end-to-end* encryption (AES-128) at the LoRaWAN application layer and storing encryption keys on a hardware security module (*secure element*) rather than in easily accessible *firmware*.

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2.4. CONCLUSION

This research successfully demonstrates the technical feasibility of integrating IoT to monitor the fatigue of railway crossing guards. The developed system is capable of detecting signs of *microsleep* with >94% accuracy even in low-light conditions and transmitting real-time alerts via the LoRaWAN network.

Implementing this technology has the potential to significantly enhance national railway safety by shifting the surveillance paradigm from reactive to proactive. However, successful large-scale adoption will heavily depend on providing stable network infrastructure in remote areas and applying strict cybersecurity standards in line with national regulations.

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