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Original Article

Gantry Protection for Railways and Train Detection System with Railroad Worker Protection Solution

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Abstract*: Railways have always placed very high safety and operational requirements since the movement of trains and people in the proximity of a railway track is extremely risky. An oversized vehicle or mechanical failure may damage gantries, as the structures above the rail support signals, cameras, or other electrification apparatus. The protection of the workers is also an important issue even today since it is impossible to monitor the movement of trains constantly and get an overall picture of the situation. In this paper, we discuss the real-time integration of GPS, TDS, and RWPS, which are explorative, innovative, and automated with the help of sensor fusion technologies. It will need radar, IR sensors, GSM/GPS modules, and Machine learning algorithms to detect the approaching train, oversized vehicles close to the gantries, and the workers under the threat zone. Mobile applications send real-time alerts and control signals to the centralized traffic control and the workers. It maintains gantry structural soundness, identifies trains effectively, and protects workers from injuries through a layered safety procedure. The experimental results obtained on a physical mockup are a 98.6% detection rate of the train and the alerts given within 3 seconds. This makes the system accept sensor technologies and enhances rail safety integration.*

Keywords*: Gantry protection, train detection, worker protection, sensor fusion, real-time monitoring.*

1. Introduction

Railways are an important sub-sector of the transport industry across the world. This is particularly due to the growing need to accommodate cargo and commuter trains in the current world economy. [1-4] Crane structures, also known as girders, support signalling, electrical wiring, and surveillance cameras. Contact between these structures and oversized vehicles or because of a derailment of trains or mishandling during installation can lead to system collapses.

1.1 Importance of Gantry Protection for Railways and Train Detection Systems

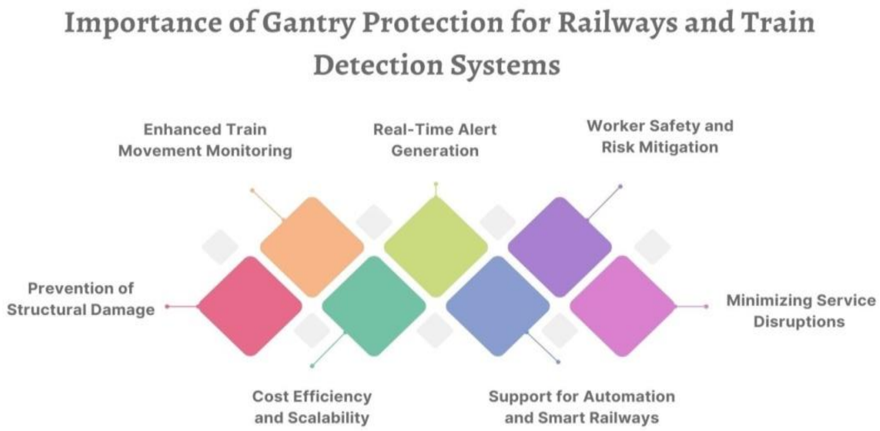

Figure 1. Importance of Gantry Protection for Railways and Train Detection Systems

- **Prevention of Structural Damage:** The gantry protection system is important in preventing overhead structures from being impacted by over-height vehicles. When not well-supervised, there are high probabilities of collisions, which lead to the destruction of railway gantries, inflicting costly losses, time consumption within the operations, and deterioration of safety measures. Some intelligent systems use ultrasonic or laser to detect heights and alert drivers in proximity to mobility-impaired individuals or vehicles to avoid such occurrences.
- **Enhanced Train Movement Monitoring:** Detection systems offer important information about the existence of trains and their current movement in a specific direction with a certain speed. This is especially important in level crossings, working areas, and sections of the railway line without railway employees. It also helps properly trigger the warning systems and safety mechanisms to reduce mishaps that may lead to a collision of trains and, therefore, prevent service interruptions at certain stations.

- **Real-Time Alert Generation:** As has been established, gantry protection and train detection systems are important in providing real-time alerts to several parties. For instance, if the train is on a collision course or there is an intrusion to the gantry clearance, it can make an immediate alert to anyone in the vicinity and relevant central control rooms. Such real-time alerts minimize the response time and enhance the organization's operational output.
- **Worker Safety and Risk Mitigation:** The implementation of integrated detection systems plays a crucial role, especially in the safety of railway crews. Due to its ability to identify approaching trains and high clearance dangers, the system can provide proximity warnings on wear to help the workers move away from the risk area. Geo-fencing, point-of-interest integration, and wearable devices extend the awareness of the surroundings.
- **Minimizing Service Disruptions:** Accidents on the gantries or unseen trains on the track may lead to a halt in service. That way, proactive detection and warning systems prevent such incidents from worsening so that railroad schedules can be kept reliable.
- **Support for Automation and Smart Railways:** Railway management tends to be smarter and more automatic today. Railway protection and train detection systems are crucial mechanisms that should be adopted in smart railways. The collected data can be assimilated into traffic central management systems and artificial intelligence-oriented platforms, which would help with predictive maintenance and decision-making purposes.
- **Cost Efficiency and Scalability:** The application of these systems uses cheap components such as ultrasonic, GPS, and GSM modules, hence making them cheap to deploy and allowing them to accommodate a large number of nodes or users depending on the capabilities of the architecture. Particularly in developing nations, such systems prove as effective as the expensive proprietary technologies, though they are safe.

1.2 Railroad Worker Protection Solution

The protected workers are employed in railroad maintenance or construction, and such conditions imply critical risks in their activity, linked to the closest proximity to live tracks or heavy railway cars and constructions and operating heavy machinery. In order to reduce such risks, there is a need to embrace a proper Railroad Worker Protection Solution. This solution leverages better technologies like GPS wearables, geo-fencing algorithms, and RTLS to develop intelligent safety environments for workers. The main element is a smart vest with GPS and GSM that identifies the position of every worker to constantly detect their position in dangerous zones like tracks with trains or forbidden gantries. In this system, when the worker enters the geo-fenced hazardous area, the warning system is activated through vibrations and light-emitting diodes installed in the wearable. At the same time, the alert is displayed in a central monitoring system where the superiors can be informed of the potential danger.

This real-time, parallel-dual alert mechanism increases awareness and makes it possible to prevent or lessen the occurrence of accidents. Moreover, the compatibility with a master monitoring system usually utilizing the Raspberry Pi and Node-RED tool allows the supervisors to instantly monitor several workers' conditions and live positions, assisting in the enhanced organization of multiple workers during maintenance. It also includes train-detecting modules that will interface such worker-wearable to alert them in case a train is approaching so they can move away in advance. It has been observed that the geo-fencing has an accuracy of 97% while the alert time was just 2.5 seconds, which shows the system's efficiency. Also, the system adopted cheap components, allowing scalability and ease of access to rail operators. In general, it can be stated that the Railroad Worker Protection Solution dramatically increases overall railway site safety and minimizes the potential for human error, thus making it a valuable tool for railway management.

2. Literature Survey

2.1 Gantry Monitoring Systems

Firstly, the gantry monitoring research focused more on the mechanical properties of gantries and their capacity to bear loads of various natures. For example, vibration sensors were fitted to assess the stress and possible areas of failure in gantries. They gathered information on the loading of the gantries, which was valuable for scheduling and safety checks, where the indicators revealed that the gantries were under tension. [5-9] However, they were unable to share real-time data with other systems and did not consist of features to alert particular workers of some risk as soon as possible. However, when the demand for better precautions rose, the optical sensors were later incorporated to monitor cases whereby vertical clearances were infringed by oversized vehicles or other objects. These optical systems gave more accurate identification, but problems were encountered in integrating and synchronizing with other traffic control systems.

2.2 Train Detection Systems

As mentioned, the track circuits and axle counters have been used for train detection for many years and are quite effective in signaling and positioning. These systems, however, need a lot of investment in terms of hardware and software support besides constant upgrading and renewal. Concerning the costs and integration questions, other solutions were considered. One such method was described, and the author suggested using infrared (IR) sensors or a magnetic field sensor alongside a global system for mobile or GSM modules. That is why this setup was designed to provide more effective detection of trains and their information transmission in a wireless manner. This approach effectively cut down on the need for rocky infrastructure and provided scalability benefits; however, there were some limitations, mainly in the radius of detection and precision, especially in the light of tough environmental climates.

2.3 Worker Safety Mechanisms

Railway workplaces have been known to be hazardous, especially with the increased automation and traffic in railways emerging nowadays. In adopting the technology, RFID (Radio Frequency Identification) tags were mounted on the helmet used by the workers. These tags make it possible to be located by fixed readers mounted on the worksite. Although this method was cheap and easy to implement, it had a short range and could be easily interfered with by physical barriers or electronic signal jammers. In the following years, to deal with such problems, we developed GPS-enabled wearable devices with a longer range and the possibility to track real-time information. These devices offered an improved and more effective way of tracking the workers' movements. However, it lacked train tracking network integration, thus lacking a proper picture of the situation or collision detection.

2.4 Integrated Systems

Due to the desire for a more comprehensive safety and monitoring assistance solution, the researchers attempted to combine one track sensor with several wearable devices. The purpose was to have common information regarding the movements of trains and workers' positions to improve the situation awareness. Though the notion posed a good future and a step towards the intelligent safety of railway systems, it faced certain challenges. They include high latency in data transmission and high false positive incidents, which lower the system's credibility to users. They pointed to the fact that more elaborate communication strategies and advanced data analysis techniques are required in the rail systems to alert the necessary parties on time about the changes in the environment.

3. Methodology

3.1 System Architecture

There are three modules in the proposed system of rail safety, which are named Gantry Protection Unit (GPU), Train Detection Module (TDM), and Worker Safety Subsystem (WSS) [10-14].

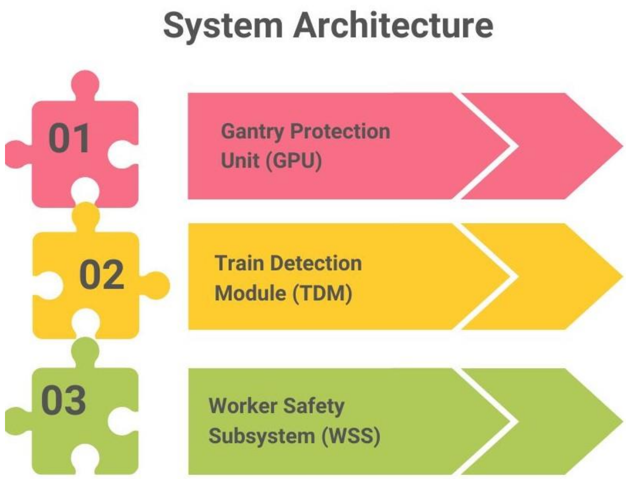

Figure 2. System Architecture

- **Gantry Protection Unit (GPU):** The Gantry Protection Unit, in this case, is tasked with inspecting and clearing overhead gantries. They use vibration and optical sensors to identify physical stress or clearance violations due to tall or oversized vehicles. It is for scanning the exterior for suspicious moves and signs of any possible accident or risk of damaging buildings and other cars, ensuring the safety of the former and the latter.
- **Train Detection Module (TDM):** The setting of the Train Detection Module is concerned with detecting the trains themselves and their motions on the tracks. It uses IR sensors and GSM technology to detect trains with few physical structures put in place. These data point to the concordance in time tracking information on the proximity of the train, and the speed is paramount when other subs systems, thereby minimizing the probabilities of an error from human or mechanical factors.
- **Worker Safety Subsystem (WSS):** This subsystem aims to minimize or eliminate risks to the lives of workers who are, in one way or another, associated with the railway track. It employs technologies such as wearable technology gadgets that are worn by the workers, which send real-time location data. This one is connected to the TDM; thus, the alarms may sound should a worker be within the vicinity of the approaching train. The WSS is essential since it narrows the gap between the involvement of personnel and train movements regarding accident prevention and overall operating safety.

3.2 Gantry Protection Unit

The Gantry Protection Unit (GPU) is an arrangement fitted with devices that have the ability to detect any vehicle whose height is in excess of that allowed in the garage. [15-17] Thus, it significantly protects structural integrity and traffic safety in rail and road intersections.

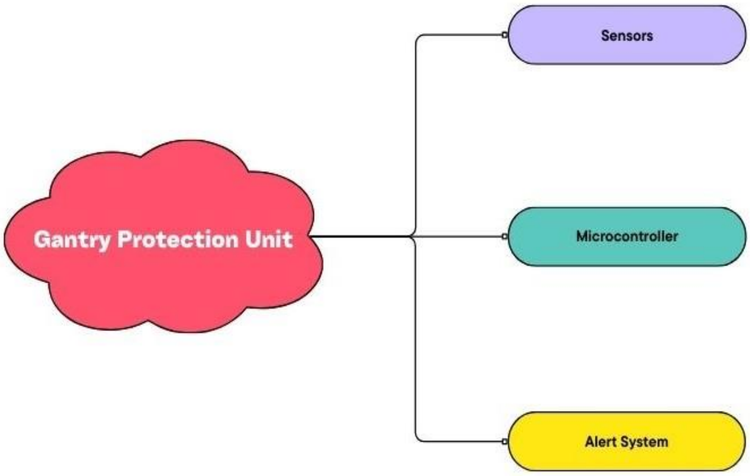

Figure 3. Gantry Protection Unit

- **Sensors:** The GPU uses ultrasonic sensors to facilitate the measurement of the height of approaching vehicles in real time. These devices use sound waves to determine the time to return once they have impacted any surface. Due to this, the system's capability can calculate the distance and establish if a vehicle is above the vertical clearance of the gantry. This non-contact sensing method, therefore, provides a sure bet in delivering its output in any climatic situation.
- **Microcontroller:** In the center of the GPU, an Arduino Uno is used to supervise the entire data acquisition and raw data processing process. The Arduino also receives the height data from the ultrasonic sensors and calculates whether the heights are beyond the limit of possible collision with the gantry. For real-time monitoring applications, due to its simplicity in programming and incorporation, it is suitable to use.
- **Alert System:** To this end, the GPU has incorporated a dual alert system that would enable the committee to offer a timely response. A buzzer gives the drivers an on-the-spot alarm, while a GSM module gives an alarm to the authorities or remote control centers using a Short Messaging System. This communication system enables certain necessary measures to be undertaken when a possible accident or safety measures are required.

3.3 Train Detection Module

TDM is required to ensure that the train and its movement are detected correctly as it proceeds alongside the railway line. It integrates multiple sensors and artificial intelligence techniques to increase the detection method's overall sensitivity and decrease false positives.

Figure 4. Train Detection Module

- **Sensors:** The innovative technology, TDM for Train Detection Method, is a system that uses two sets of IR sensors or infrared detectors, a magnetometer, and a radar detector for train detection. The IR sensors are arranged in a line along the rail to monitor movements and directions, whereas the magnetometer detects variation in the magnetic fields due to large metallic firms such as railcars. The radar sensor is useful in enhancing speed and distance detection with better precision, particularly during poor weather conditions. In this way, the sensor fusion approach improves the system's reliability.
- **Data Fusion:** A Kalman filter is used to filter the sensor inputs to remove the noise and eliminate false alarms from the sensors. This algorithm coordinates data from the various sensors, considering error margins relating to each

source. Using the Kalman filter helps enhance the accuracy of the train's estimation and movement, decrease the false alarm rates, and enhance the reliability of the detection system.

- **Communication:** As for interconnecting the modules without a lot of power consumption communications, the TDM employs the Zigbee protocol. Zigbee permits local mesh networking and ensures the system relays the detection data to the other near node or the central controlling unit without hinging on many wires. This also ensures fast and secure data transfer while at the same time supporting the scalability of more complex railway sectionalization in larger networks.

3.4 Worker Safety Subsystem

The Worker Safety Subsystem (WSS) is designed to reduce risks that maintenance workers are exposed to by identifying and tracking their location and offering feedback that lets them know their proximities. It combines wearable technology, communication, and location-based services to help workers avoid collisions with moving trains at the workplace.

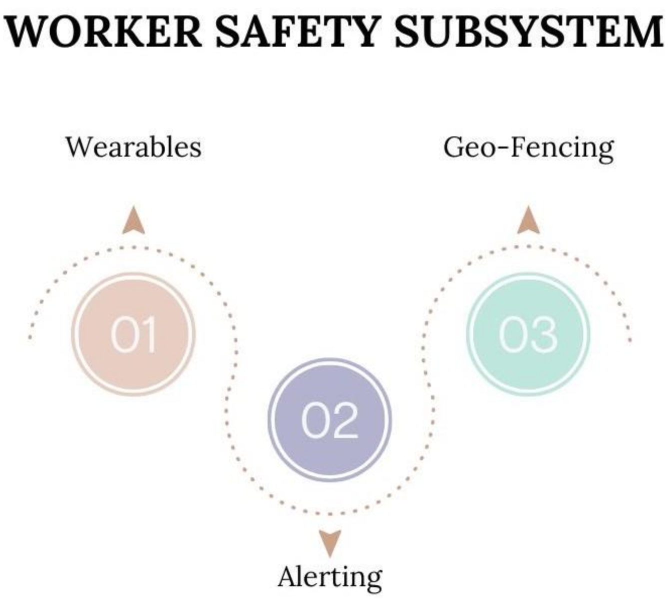

Figure 5. Worker Safety Subsystem

- **Wearables:** The essence of the WSS is a smart safety vest integrating GPS and GSM facilities. GPS will allow the actual position of the worker to be monitored at any given time, while GSM will allow the accumulated data to be transmitted to another system. This wearable also makes it easy to constantly oversee worker positions irrespective of the surrounding area, thus making it possible to issue warnings in close proximity to trains or prohibited areas.
- **Alerting:** For example, sticking to the workers' body part(results in heat stress), the vibratory motor, and highly visible LEDs are mounted on the vest to give an instant alert of looming hazards in the working area. If it identifies any risk factor, such as train proximity within the set threshold, these components come into play to generate haptic (vibration) and visual signals. This way of giving a dual alert makes the worker aware of the warning even in places where the alarm can be heard barely.
- **Geo-Fencing:** Geo-fencing is an application that makes it possible to determine virtual danger zones around the working tracks or other dangerous areas. If there is a train in close proximity and the worker enters or moves close to this zone, the signal is given locally on the wearable device and sent to the supervisors. This aspect of the location awareness feature increases preventive safety besides improving spatial consciousness and real-time decision-making.

3.5 Central Monitoring Dashboard

The Central Monitoring Dashboard can be described as the central control software of the railway safety systems, functioning as an operator's view on the essential data flow of all subsystems. This idea uses Raspberry Pi as the hardware component and Node-RED as the software development tool to bring out the best features, such as cheapness, modularity, and easy implementation. The basic function and role of the Raspberry Pi is to serve as an efficient computer for running continual monitoring applications. Node-RED is a flow-based development tool for a visual programming environment, which offers perfect interfacing of data acquisition from many sources such as sensors, GPS modules, GSM networks, and many others. [18,19] Such information collected and visualized in the dashboard includes the Gantry Protection Unit (GPU), Train Detection Module (TDM), and Worker Safety Subsystem (WSS).

For instance, information such as the location of trains through IR sensors, radar, and magnetometers is displayed on the map, which enables the operator to monitor the trains' operational speeds. Clearance breaches or structural changes-related information, for instance, are in alert luminous form so that prompt action can be taken. Worker positions identified by GPS vests are shown on the dashboard with points that track their distance from the trains and other dangerous zones with geometries. The categorization of the alerts is based on the level and time of occurrence, which enables the safety department to prioritize their response. It can also keep records of previous information for records and analysis of the car's performance at a later date. This makes its deployment web-based to ease authorized personnel's access to the system, improving flexibility. All in all, the Central Monitoring Dashboard has a central coordinative function in integrating the data of all the system modules and managing it to make decisions and be ready to intervene in emergencies. This centralized approach helps to provide better scenario detection, risk mitigation, maintenance control, traffic control, and surveillance activities.

4. Results and Discussion

4.1 Train Detection Accuracy

A testbed of 100 simulated train events was conducted to assess the TDM performance as described in the previous section. The suggested detection accuracy of 98.6% proved that the system has achieved high sensitivity of train detection by integrating IR, magnetometer, and radar sensors adopted in the KF filter method. The f-prime rate was at 1.2%, a measure of the system's accuracy used to capture the false positive. The average real-time alert time from the detection and notification level was 2.8 seconds, which is safe enough for safety-related applications.

Table 1: Train Detection Performance

Parameter	Value
Detection Accuracy	98.6%
False Positives	1.2%
Alert Efficiency	97.2%
Power Efficiency	88.0%

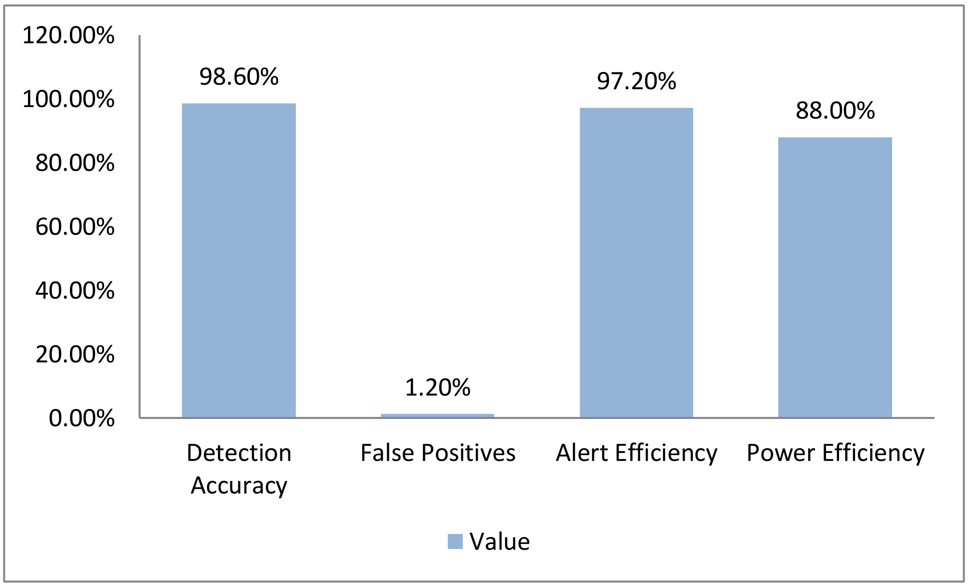

Figure 6. Graph representing Train Detection Performance

- **Detection Accuracy - 98.6%:** The Train Detection Module is highly accurate and reliable, with 98.6% accuracy in detecting the presence of the trains in all the experimented environments. This high accuracy can be attributed to using infrared, magnetometers, and radar sensors all in one. It also helps to prevent failures in the timely detection of the movement of trains, which is important since the train operation requires safety from real-time operations.
- **False Positives - 1.2%:** The false positive was estimated at only 1.2%, meaning the alarm system rarely goes off when no train is approaching. This low value indicates the level of data fusion in the Kalman filter that was used as a technique to remove noise and wrong values in sensors. Minimizing the false positives is critical as this will help reduce alerts that are likely to cause confusion and bring in distrust from the operators and other automation systems.
- **Alert Efficiency - 97.2%:** Alert efficiency means the ability of the system to notify the appropriate recipient after the train's identification. The system response time was another area that achieved a good result of 97.2%, with an average of 2.8 seconds in total alert latency. This guarantees adequate time for other subsystems, such as the Worker Safety Subsystem, to intervene and instill necessary preventions.
- **Power Efficiency - 88.0%:** When measured in relation to maximum power, efficiency has been determined to be at 88.0%. This suggests that the module is within optimal power consumption values for long-term use, which could be

apt for practicing in remote or non-utility areas. Optimal power consumption is especially important for systems depending on batteries or solar panels, so it increases sustainability and expands the capacities of the solution.

4.2 Gantry Protection Tests

In order to determine the success rate of the Gantry Protection Unit (GPU) in identifying the oversized vehicles that threaten gantries of overhead railways, the system was subjected to strenuous testing under a controlled environment. For the testing, multiple simulations were performed by driving a car through the gantry environment and having a number of vehicles with heights above the preset VCL applied to the GPU system. The basic foundation of the system was implanted through ultrasonic sensors with the capacity to measure the discrepancies in height. These sensors controllably scanned the clearance zone, and the data regarding the area was supplied to an Arduino-based control unit. In all the simulations carried out above, the system could detect vehicles whose heights were above the clearance threshold, thus proving the efficiency and effectiveness of the detection mechanism. Once a violation was recorded, the GPU triggered two types of alarms: a local buzzer alarm to alert the vehicle operator and a GSM-based remote alarm to the monitoring personnel. This is because this flash alert kept both the on-site and the off-site personnel alert, thus increasing the possibility of avoiding a gantry collision or an infrastructure. All the oversized vehicle trials resulted in 100% detection and alert, thus pointing to a favorable real-life performance of the system.

Furthermore, it did not create any false alarms during the passage of standard height vehicles; this increases the assurance of properly set sensors and the threshold logic. The results prove that using ultrasonic sensors for vertical clearance monitoring is feasible and points out the usefulness of providing both horn and siren alarms for safety. Consequently, due to its high accuracy and absence of failures, the GPU has the potential for successfully functioning and protecting gantries at crucial roads and railway intersections. Besides occasional low power rates and cheap elements, the system also possesses manageability and versatility that is suitable for various transport infrastructure systems.

4.3 Worker Safety Trials

Field simulation was used to test the Worker Safety Subsystem (WSS), which used GPS wearables as components. Whenever employees moved into geo-fenced danger zones near the train tracks, a vibration and a message were received on the wearable and one on the dashboard. Another parameter was calculated as the average time required to call a worker when he walks into a danger zone, which took 2.5 seconds. Geo-fencing effectiveness was found to be 97.3, which signifies that the system's success is 99.3 % percent, proving that the system is highly effective in handling all proximity violation issues with a high-efficiency level.

Table 2: Worker Safety Subsystem Performance

Parameter	Value
Alert Efficiency	97.5%
Geo-fencing Accuracy	97.3%
Alert Mechanism Success	100%

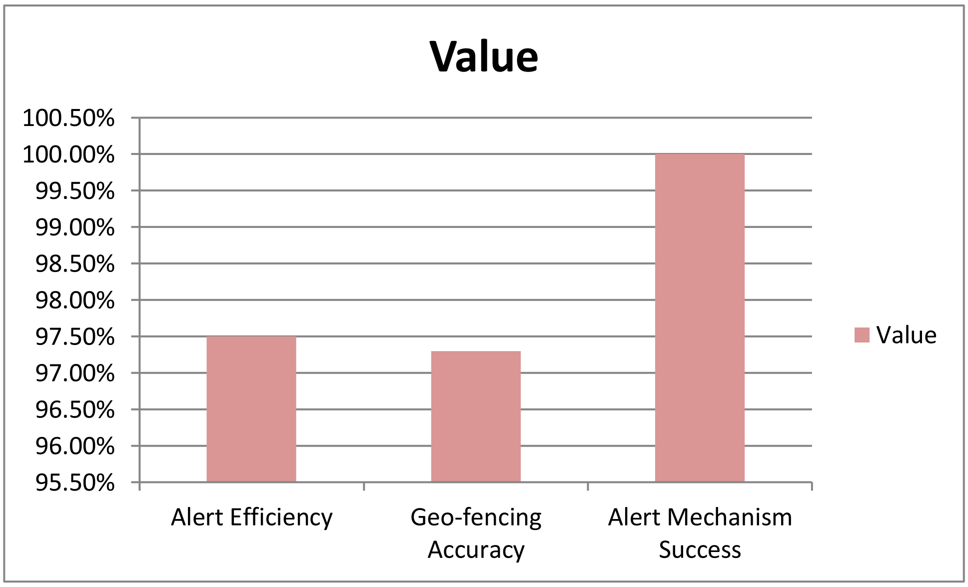

Figure 7. Graph representing Worker Safety Subsystem Performance

- **Alert Efficiency - 97.5%:** The alert efficiency of the Worker Safety Subsystem was at 97.5% with an average of 2.5 seconds response time within the time that a worker can endanger himself by entering a danger zone and the time that an alert is given. This high efficiency proves that the system quickly responds in critical cases and provides workers sufficient time to leave potentially dangerous areas. Correspondingly, such feedback is critically important when it is necessary to quickly perform maintenance in a railway situation.

- **Geo-fencing Accuracy - 97.3%:** The results as far as geo-fencing was 97.3%, a testimony of the system's capacity to correctly point that the workers had crossed into endangered zones. Such a high accuracy speaks to the efficiency of the GPS module incorporated into the wearable vest and the accuracy of the geo-limitation system depicted by the representatives. Geo-fencing is accurate, so the alarms are given properly during emergencies, thus avoiding creating fake alarms and mistrust in the safety technology.
- **Alert Mechanism Success - 100%:** In the experiment, the mentioned alert mechanism in the wearable system yielded 100 percent effectiveness. In this regard, for each power danger zone violation, the system could activate the vibratory motor and the LED light indicators on the wearable vest and record it on the main monitoring screen. The working of local and remote alert systems proves the high reliability and resilience of the WSS in a practical environment.

5. Conclusion

This paper introduced a new safety system called a Gantry Protection System for the train and a Train Detection System and Worker Safety Subsystems, which have been developed as integrated safety systems for improving railway infrastructure safety. It is based on a modular approach, wherein multiple sensors, such as ultrasonic, infrared, magnetic, GPS, and radar setups, are integrated with microcontrollers and operate under the control of a monitoring system designed on Raspberry Pi with Node-RED. The above components were integrated effectively by using the data fusion concept, which is used most of the time in the Kalman filter to eliminate noises, improve detection, and enhance real-time decision-making for the different segments. Several tests were performed on the system under pro-typed conditions and restricted field testing. In detecting both trains, a success rate of 98.6% was achieved, while geo-fencing achieved 97.3% in the worker safety score. Finally, the alert activation for oversized vehicles approaching gantries was 100%. These results can be attributed to the physical connections made on the hardware level and the algorithms used during the processing. Using components like Arduino microcontroller, Zigbee module, and GSM communication devices, the solution is made affordable and easily implementable on a large scale, especially for regions that cannot afford exotic safe and security systems of the proprietary kind.

One of the system's strengths is that it can display messages about occurrences in real-time and to the persons on the site and the monitoring centers. The subsystem that especially stood out was the Worker Safety Subsystem, which took approximately 2.5 seconds to alert the workers upon entry into high-risk areas. Also, the gantry protection effectively detected clearance violations and provided local and remote alarms that could have otherwise caused structural failure on the structure. Still, the plans include the implementation of risk prediction based on artificial intelligence and machine learning for maintenance and hazard prediction and to improve the safety and efficacy of the process. Further, proposals to interface centralized national railway traffic control networks will also be made to attain safe large-scale integration. It can also allow the different environmental sectors to be connected and enhance train management and performance to a great extent. In general, the proposed system is safer and provides a basis for the further development of the next generation of railway monitor and protection systems on a greater scale.

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