Integrating Wearable Sensing Devices and Computer Vision for Safety Management in Steel Mills

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ABSTRACT

Worker safety is paramount in the steel manufacturing industry, particularly considering the prevalent hazards such as caught-in/between incidents, struck-by accidents, fire, heat stress, slips, trips, and falls, in the work environment. Traditional hazard identification methods which are predominantly manual and reliant on safety personnel observation, are weakened by subjectivity and a high propensity for human error. To address this critical issue, this paper presents a potential approach to bolster steel mills’ safety management by integrating wearable sensing devices (WSDs) and advanced computer vision technologies (CVT). This study delves into the synergistic application of these technologies, proposing a conceptual framework that harmonizes WSDs with computer vision. This framework is aimed at implementing a proactive and effective safety management system. The paper outlines the methodology for integrating these technologies and characterizes the specific safety hazards that this integration targets. The expected outcome of this research is a potential shift in safety protocols in steel mills, characterized by a notable reduction in risks and a paradigm shift in hazard management, primarily attributed to the minimization of human error, and enhanced real-time monitoring capabilities. This paper not only contributes to industrial safety literature but also offers insight into the application of sensing technologies and AI in high-risk environments.

Keywords: Computer vision, Safety management, Steel mill, Wearable sensing device

INTRODUCTION

The steel manufacturing industry forms an integral part of modern infrastructure, with its products serving as the backbone of numerous engineering and construction projects worldwide. The significance of steel in contemporary society cannot be overstated, given its widespread use in everything from building construction to automotive manufacturing¹,². However, the process of steel production is embedded with safety risks, making it one of the most hazardous industries for workers³. These risks range from high-temperature operations, proximity to unsafe areas, and the handling of heavy machinery to exposure to potentially harmful substances¹,². Ensuring the safety of workers within steel mills is not only a moral and legal imperative but also crucial for the efficiency and sustainability of the industry. In the steel industry, safety programs are a cornerstone, constantly reinforcing safety as a primary concern. Steelmakers employ a comprehensive approach to risk management, which includes engineering controls, extensive training, lock-out/tag-out/try-out (LOTO) procedures, physical separation techniques, and the use of personal protective equipment (PPE)³. These measures aim to minimize exposure to the myriad risks present in steel mills. However, despite these robust safety protocols, the dynamic and complex nature of steel mill operations still presents significant challenges. The reliance on manual processes and the need for constant human vigilance can lead to gaps in safety management. These limitations underscore the necessity for more advanced, technology-driven solutions to enhance existing safety frameworks.

This paper proposes an approach to complement traditional safety measures by the integration of wearable sensing devices (WSDs) and computer vision technologies (CVT). This integration leverages sensing technologies and artificial intelligence to provide a more sophisticated, real-time monitoring system. It aims to reduce the reliance on manual hazard identification and
increase the overall safety and efficiency of steel mill operations. WSDs, by their very nature, offer individual-level data that is critical in monitoring and ensuring the safety of each worker. These devices can track vital signs such as heart rate and body temperature, alerting to any signs of physical stress or heat-related illnesses which are common risks in the intense environment of a steel mill. Additionally, they can monitor a worker’s exposure to hazardous chemicals or extreme noise levels and even provide real-time location tracking to ensure that workers are in safe zones. WSDs have been thoroughly examined in numerous existing studies. These devices have the potential to enhance safety practices by effectively gathering and analyzing data concerning worker well-being. Furthermore, WSDs provide real-time information to personnel, aiding in the prompt response and mitigation of safety and health risks in different work environments. Concurrently, computer vision, a field of artificial intelligence, provides an overarching environmental perspective. Through the use of cameras and advanced image processing algorithms, this technology could monitor the entire workspace, identifying potential hazards that may not be visible or immediately apparent to human supervisors. This includes detecting unsafe behaviors, monitoring the proper use of machinery, and identifying environmental risks such as spills or equipment malfunctions.

In the collaborative framework of wearable sensing devices (WSDs) and computer vision, a comprehensive safety management system is realized, predominantly enhancing worker safety in steel mills. This integration deftly combines the detailed, individual-specific data from WSDs including biometric parameters like heart rate and body temperature, indicative of physical exertion or heat-related stress with the expansive observational scope of computer vision, which monitors environmental conditions and worker interactions within the mill. For instance, WSDs can detect early signs of heat exhaustion in workers by monitoring increases in body temperature and heart rate. When such physiological changes are identified, the system, through its integration with computer vision, can pinpoint the exact location of the affected worker. This enables immediate intervention, such as automated alerts for rest breaks or deployment of medical assistance, thereby averting potential heatstroke incidents. Furthermore, this integrated approach enhances the monitoring of compliance with safety protocols. Computer vision can identify situations where workers might be at risk due to non-adherence to safety guidelines, such as not maintaining safe distances from high-risk machinery. Additionally, WSDs can monitor physiological responses to these situations, like spikes in stress levels, providing a comprehensive view of both the environmental risks and their impact on worker well-being. By correlating data from WSDs and computer vision, predictive models can be developed to anticipate and mitigate risks.

For example, a correlation between certain environmental conditions captured by computer vision such as increased activity around heavy machinery and physiological data from WSDs indicating elevated stress or fatigue levels among workers, can prompt preemptive actions like scheduling additional breaks or rotating staff to less strenuous tasks. This worker-centric approach represents a significant advancement in safety management within steel mills. It ensures a heightened level of worker protection by leveraging real-time data to proactively address both immediate and potential safety concerns, significantly reducing the risk of accidents and health-related issues in one of the most hazardous industrial environments.

The primary objective of this research is twofold: first, to develop a conceptual framework that illustrates the integration of WSDs and computer vision, leveraging detailed individual-level data alongside broad environmental surveillance. Second, the paper seeks to characterize the specific safety hazards prevalent in steel mills by applying this integrated technological approach. Insights from this study could demonstrate an enhanced technological application for managing immediate and latent safety risks in steel manufacturing.

**LITERATURE REVIEW**

**Overview of the Steel Mill Hazards**

The steel manufacturing industry plays a critical role in modern infrastructure, contributing extensively to sectors like construction, mining, agriculture, and infrastructural development. Despite its importance, the process of steel production is inherently filled with various occupational hazards, significantly impacting worker health and safety. In the dynamic environment of a steel mill, workers engage in various operational activities, each associated with specific risks. These activities range from the handling of raw materials to operating high-temperature furnaces for smelting and casting, and intricate tasks like rolling, cutting, and finishing steel products. During these processes, workers face a spectrum of hazards. Physical hazards are prominent, encompassing exposure to extreme noise from heavy machinery, vibrations from industrial tools, intense heat from smelting operations, and both ionizing and non-ionizing radiation risks. Chemical hazards are also a significant concern, with workers exposed to harmful substances like carbon monoxide and sulfur oxides emitted during smelting, as well as asbestos used in some insulation materials. The work environment is further complicated by safety hazards including the dangers of working in confined spaces, navigating around heavy, fast-moving machinery, risks of falling objects in the warehouse and production areas, potential electrocution from industrial equipment, and commonplace incidents such as slips, trips, and falls. Additionally, ergonomic hazards arise from repetitive and physically demanding tasks such as lifting heavy materials, operating tools for cutting and welding, and maintaining prolonged postures during assembly or inspection processes, all contributing to musculoskeletal injuries and chronic physical strain.

The complexity of steel mill operations, involving a combination of manual labor and mechanical processes, increases the likelihood of worker exposure to these hazards. While advancements in specialized machinery and automation have aimed to
minimize direct human involvement in high-risk tasks, workers’ proximity to these operations continues to present significant risks. In response, steel manufacturing industries have instituted robust safety programs, focusing on personal protective equipment (PPE) usage, extensive safety training, and strict adherence to operational protocols. Despite the stringent safety measures in place, the dynamic and often unpredictable nature of steel mill environments challenges the effectiveness of traditional safety approaches. The variability of human factors, coupled with the complex interplay of various operational risks, underscores the limitations of current safety protocols. This gap highlights an emerging need for innovative technological solutions that can offer more comprehensive and adaptive safety management.

**WSD Applications for Industrial Safety**

Wearable sensing devices (WSDs), applied across diverse sectors including healthcare, manufacturing, mining, and construction, present significant potential to enhance industrial safety, particularly in monitoring and managing workplace hazards. Characterized by their multifunctionality, super integration, and ultra miniaturization, these devices are integrated into workers’ gear or worn independently and are equipped with sensors that provide continuous monitoring of various physiological and environmental parameters. This technology offers an advanced, approach to occupational health and safety. WSDs encompass a range of devices such as smartwatches, smart glasses, smart shoes, smart helmets, smart bracelets, fitness trackers, and specialized wearable sensors, each tailored to capture specific data points relevant to worker safety. For example, smart helmets can detect the presence of harmful gases, while wrist-worn devices monitor vital signs like heart rate and body temperature.

The applications of WSDs in industrial settings are varied and crucial. A key function is fatigue and stress monitoring, particularly in sectors such as mining and construction, where workers are subject to long, strenuous shifts. Devices equipped with heart rate and skin temperature sensors can identify early signs of fatigue, allowing for timely intervention and potentially averting fatigue-related accidents. In environments like steel mills, where exposure to extreme heat is a constant challenge, WSDs play a vital role in monitoring body temperatures to prevent heatstroke. Additionally, WSDs are instrumental in detecting environmental hazards. In the oil and gas industry, for instance, wearables equipped with environmental sensors can alert workers to dangerous gas levels or other hazardous conditions, thereby preventing potential incidents. Ergonomic assessment is another significant application of WSDs. In manufacturing and warehouse operations, motion sensors in these devices can track and analyze workers’ movements, identifying patterns that may lead to ergonomic injuries and guiding corrective measures. Real-time location tracking is a critical feature of WSDs in large industrial facilities. During emergencies, GPS or indoor location technologies in these devices can swiftly locate workers, enhancing the efficiency and effectiveness of emergency responses. This feature is particularly vital in large-scale operations where the immediate localization of personnel is crucial. In construction, wearables with location tracking can ensure workers maintain safe distances from high-risk areas, especially near heavy machinery.

The benefits of WSDs in safety management are extensive. Primarily, their real-time monitoring capability is essential for immediate response in hazardous situations. This continuous surveillance significantly boosts worker safety, ensuring quick action to prevent minor issues from escalating into major accidents. Additionally, the data collected by these devices offer invaluable insights into workplace safety trends and patterns, enabling more informed decisions about safety measures and protocols. Consequently, this leads to the development of a safer work environment, driven by data and proactive safety management strategies.

**Computer Vision Technology and its Applications for Industrial Safety**

The advent of computer vision technology (CVT) in industrial safety has introduced a positive shift in hazard identification and risk management. At its core, computer vision (CV), a field in artificial intelligence that encompasses the use of cameras, advanced image processing, and pattern recognition algorithms, offers a unique approach to analyzing visual data within industrial environments. A pivotal aspect of CV’s functionality in industrial settings is the application of deep learning, a subset of machine learning in artificial intelligence (AI), for the processing of images and videos. Deep learning algorithms, particularly convolutional neural networks (CNNs), are employed to analyze visual data. These algorithms can identify patterns, recognize objects, and detect anomalies by processing vast amounts of image and video data. For instance, in a manufacturing setting, CVT systems equipped with deep learning capabilities can analyze footage to identify instances where machinery deviates from its standard operating patterns, or where workers are not adhering to prescribed safety protocols.

In addition to monitoring equipment and operational procedures, CVT systems are invaluable in observing worker behavior and ensuring compliance with safety standards. They can, for example, detect whether workers are properly utilizing personal protective equipment (PPE) and adhering to safety regulations within hazardous zones. Moreover, CVT, when embedded with deep learning algorithms, can recognize complex patterns that precede safety incidents. For example, these systems might analyze historical footage of near-miss incidents or actual accidents in a manufacturing setting. By identifying the visual precursors to these events, the deep learning model can be trained to recognize similar patterns in real-time feeds, thereby predicting potential risks before they materialize into accidents. This predictive function is particularly crucial in industrial environments where early detection of hazards can lead to proactive measures, significantly reducing the likelihood of accidents.
and enhancing overall workplace safety. Furthermore, deep learning enables CVT systems to continually improve their predictive accuracy over time. As these systems are exposed to more data, they refine their algorithms, becoming more adept at identifying subtle anomalies or changes in the environment that could indicate impending risks\textsuperscript{46}. This aspect of machine learning, where the system evolves and adapts based on new data, represents a significant advancement over traditional, rule-based safety monitoring systems. This predictive capability extends beyond immediate physical hazards. For instance, CVT systems can monitor the flow of operations and worker movements, identifying patterns that might indicate workflow inefficiencies or ergonomic risks. By alerting supervisors to these issues, measures can be taken to reorganize workflows or provide additional training, thereby preempting situations that could lead to injuries or reduced productivity\textsuperscript{47}.

However, the implementation of CVT in industrial environments necessitates overcoming several challenges. These include addressing privacy concerns, ensuring the reliability and accuracy of visual data under variable industrial conditions, and seamlessly integrating these systems with existing safety protocols. Recent advancements in this field are focused on improving the precision of image processing algorithms, enhancing the reliability of AI predictions, and developing user-friendly interfaces for easier interaction and interpretation of safety data.

**Potential Benefits of Leveraging Wearable Sensing and Computer Vision for Enhanced Industrial Safety**

The integration of WSDs and CVT leverages the strengths of both technologies, addressing their limitations and enhancing overall safety monitoring efficacy. WSDs, primarily focused on biometric and environmental data acquisition at a micro-level, face constraints in global environmental perception and suffer from data isolation issues, limiting their utility in comprehensive risk assessment\textsuperscript{6,10}. CVT, on the other hand, excels in macro-level environmental analysis through advanced image processing and pattern recognition but lacks the granular physiological data capture essential for individual health monitoring. CVT’s reliance on high-quality visual inputs also poses challenges in industrial settings with variable lighting and occlusions\textsuperscript{48}.

The integration of these technologies could harness the robust data capture and personal monitoring capabilities of WSDs\textsuperscript{15} with the expansive environmental surveillance of CVT\textsuperscript{44}. Employing advanced data fusion techniques as in this case, sensor fusion, this integrated system could achieve a comprehensive safety monitoring mechanism. The system utilizes machine learning algorithms, particularly deep learning models like convolutional neural networks (CNNs)\textsuperscript{49}, to analyze and interpret the combined data streams. This approach could enable the detection of complex patterns and anomalies indicative of potential safety incidents. In predictive analytics, this integration could advance risk assessment models. By correlating biometric data from WSDs\textsuperscript{34}, with visual analytics from CVT, the system could predict potential hazards with enhanced precision. For instance, the detection of physiological markers of fatigue from WSDs, in conjunction with CVT’s analysis of operational anomalies\textsuperscript{46}, enables the early identification of risk scenarios. Moreover, this integration optimizes emergency response protocols. In critical situations, CVT could provide visual context to alerts generated by WSDs, enabling rapid and precise location-based responses. This capability is augmented by real-time data processing and edge computing, ensuring minimal latency in emergencies.

Although WSDs and CVT generate fundamentally different types of data, advancements in data processing technologies have made their integration feasible. WSDs typically produce structured data, like time-series measurements from various sensors, while CVT generates unstructured data, visual data such as surveillance footage\textsuperscript{29,48}. The fusion of data overcomes their inherent data format differences through sophisticated integration techniques. For instance, in a manufacturing environment, WSDs might record elevated heart rates signaling worker stress, while CVT systems capture video data indicating unsafe operational conditions. Through data preprocessing, CVT's raw images are transformed into analyzable features, and WSDs' time-series data is standardized. These harmonized data streams are then integrated into a centralized analytics platform. Applying machine learning algorithms to this combined dataset enables predictive safety modeling. Correlating physiological markers from WSDs with environmental patterns from CVT can preemptively identify potential hazards.

**METHODOLOGY**

To characterize the specific safety hazards prevalent in steel mills while integrating wearable sensing devices (WSDs) and computer vision technologies (CVT), a thorough review of common hazards within the steel manufacturing environment was conducted. This foundational step was crucial in highlighting the frequency and severity of incidents such as falls, heat exposure, and equipment-related risks. Following this, the applications of WSDs were meticulously reviewed aimed to pinpoint their core functions that directly enhance worker safety and health. This review was focused on the core functions of WSDs capable of physiological monitoring, environmental sensing, and precise location tracking and how each aligns with the hazards identified. Parallel to the WSD analysis, the role of CVT in safety management was evaluated, assessing compatible vision-based sensors alongside proposed analytical methods that could be applied within the steel manufacturing context to monitor and mitigate workplace hazards.

The culmination of these comprehensive reviews facilitated a detailed characterization of hazards, correlating specific WSD functionalities and CVT tasks to the identified risks. This integrative approach provided a broad understanding of how the convergence of WSDs and CVT could be strategically implemented to bolster safety in the steel manufacturing sector. This
process is aimed at not only identifying but also aligning technological solutions with the specific hazards, laying the groundwork for a technology-enhanced, safer work environment. Figure 1. Shows the flow process.

RESULTS AND DISCUSSION

Hazard Characterization in Steel Manufacturing with WSDs and CVT Integration
The initial result obtained from this study was based on the first objective which aimed to characterize the safety and health hazards in steel manufacturing for an integrated WSD and CVT application. This is seen in Table 1. The six (6) prevalent hazards in steel mills identified from existing literature were highlighted emphasizing how they could be mitigated by integrating WSDs and CVT.

Falls from Height
The application of smart harnesses, featuring gyroscopes and accelerometers, adeptly signals falls by detecting abrupt shifts in motion. This data is enriched by CVT, where RGB cameras could detect potential fall risks in the worker's surroundings. The dual data stream facilitates a prompt alert system and informs preventive safety measures. For instance, in a steel mill environment where workers could be elevated on scaffolding or catwalks, smart harnesses equipped with gyroscopes and accelerometers are crucial. They could detect abnormal movements, such as a sudden acceleration indicative of a fall. CVT systems, strategically positioned around high-risk areas, could use RGB cameras to continuously monitor for unsafe conditions, like unsecured ladders or open ledges, providing visual confirmation and analysis of a fall, which can be crucial for rapid response and investigation.

Slips and Trips
In areas where the flooring may be uneven or prone to spillages, smart boots with pressure sensors can detect irregularities in gait that may precede a slip or trip. Combined with CVT which employs RGBD cameras to scan the floor for spills, misplaced tools, or debris, the system alerts workers or maintenance crews to address the hazard before an incident occurs.

Heat Hazards
Near furnaces or molten metal processing areas, the risk of heat stress is significant. Wearable devices like smart bands measure the skin temperature of workers and environmental heat levels. Complementing this, CVT with thermal cameras could identify hotspots and areas with rising temperatures, providing early warnings to workers and enabling heat management strategies to be enacted, such as initiating cooling systems or rotating staff.

Fire and Explosion Risks
In sectors of the plant where flammable materials are processed or stored, wearable gas detectors could sense the presence of combustible gases. Simultaneously, CVT could utilize infrared cameras and LIDAR to detect the thermal signatures of overheating materials or equipment, potentially identifying the early stages of combustion. This dual monitoring system can trigger evacuations and activate fire suppression systems before a small incident escalates into a catastrophic event.

Caught-in or between Hazards
In areas with heavy machinery and moving parts, smart vests with RFID technology could ensure workers keep a safe distance from operational equipment. CVT could support this by monitoring the operational zone with RGB and RGBD cameras, alerting control room operators if a worker inadvertently enters a dangerous proximity to machinery, thereby allowing for immediate machinery shutdown if needed.
Struck-by Incidents
In transportation lanes where overhead cranes move heavy loads, helmet-mounted sensors with LIDAR technology could track the movement of large objects overhead. Stereo vision cameras from the CVT system could then provide a three-dimensional view of the work area, identifying if a worker is in the potential path of moving equipment. This system can signal the crane operator to halt operations or warn the worker to move to a safe location.

By detailing the practical application of each WSD and CVT against the backdrop of steel mill operations, this integrated approach not only maps out potential hazards but also delineates the actionable steps and responses to mitigate these risks.

Table 1. Hazard Characterization in Steel Manufacturing with WSDs and CVT Integration

<table>
<thead>
<tr>
<th>Function</th>
<th>Wearable Device</th>
<th>Sensing technology</th>
<th>Hazards</th>
<th>Computer Vision Technologies</th>
<th>Analysis method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiological monitoring</td>
<td>Smart harness</td>
<td>Gyroscope, Accelerometer.</td>
<td>Falls from height</td>
<td>Object detection</td>
<td>RGB- cameras, DL technique - CNN</td>
</tr>
<tr>
<td></td>
<td>Smartwatch, smart boots</td>
<td>Gyroscope, Accelerometer, and pressure sensors assessing foot placement and weight distribution</td>
<td>Slips and Trips</td>
<td>Object detection</td>
<td>RGB &amp; RGBD cameras, DL technique - CNN, ML – Decision Tree</td>
</tr>
<tr>
<td>Environmental Sensing</td>
<td>Smartwatches, smart bands</td>
<td>Heat flux sensors and thermometer</td>
<td>Heat</td>
<td>Image classification, segmentation, object detection</td>
<td>Thermal cameras, DL technique- deep CNN</td>
</tr>
<tr>
<td>Proximity detection and Location tracking</td>
<td>Smart protective clothing (PPE), wearable gas detectors</td>
<td>Gas sensors, heat flux sensors</td>
<td>Fire and explosion</td>
<td>RGB &amp; RGBD cameras, infrared cameras, flash LIDAR</td>
<td>DL technique- deep CNN</td>
</tr>
<tr>
<td></td>
<td>Smart safety vest, Smart glasses</td>
<td>Radio frequency identification (RFID), I, Radar, Bluetooth</td>
<td>Caught in or between</td>
<td>Object detection</td>
<td>RGB &amp; RGB-D Cameras, Stereo vision cameras, DL technique- Faster Regional CNN (R-CNN)</td>
</tr>
<tr>
<td></td>
<td>Helmet-mounted sensors</td>
<td>RFID, Light Detection and Ranging (LIDAR) Infrared, Radar, Bluetooth, GPS</td>
<td>Struck-by</td>
<td>Object detection</td>
<td>RGB &amp;RGB-D Cameras, Stereo vision cameras, DL technique- hybrid models</td>
</tr>
</tbody>
</table>

Conceptual Framework for Integrating WSDs and CVT for Hazard Mitigation in Steel Mills
The second objective of this study aimed to develop a conceptual framework, which demonstrates a practical approach to how WSDs and CVT could be integrated towards enhancing safety in steel manufacturing work environments. This framework consists of sixteen (16) actionable steps, and this section explains the process. This framework is shown in Figure 2.
Review Incident Statistics in Work Environment
This initial step involves a meticulous analysis of historical safety incident data within the work environment. It aims to identify prevalent patterns and trends in workplace accidents and safety breaches, providing a data-driven foundation for risk assessment. This review will quantify the frequency, severity, and causes of past incidents, offering a benchmark against which the impact of the WSD and CVT integration will be measured.

Identify Work-Related Hazards
Following the review of incident statistics, the framework calls for a detailed identification of specific work-related hazards present in the operational setting. This process is critical for determining the types of risks that WSDs and CVT must monitor. It includes an assessment of physical, chemical, ergonomic, and environmental hazards that could lead to workplace injuries or accidents.

Specify WSD Monitoring Objective
Once hazards are identified, the framework requires the specification of monitoring objectives for WSDs. This entails defining the precise parameters that WSDs will track, such as heart rate, temperature, or motion, which are pertinent to the identified risks. It also involves setting the criteria for alerts and the thresholds for normal and abnormal readings.

Assess and Select Optimal WSDs
This phase involves evaluating commercially available WSDs to select the most suitable devices based on the previously specified monitoring objectives. The assessment criteria include sensor accuracy, device durability, worker comfort, and interoperability with existing systems. The selected WSDs should align with the identified hazards and be capable of providing the required data for safety monitoring.

Determine CV Task
This step defines the surveillance and analytical tasks such as object detection, tracking, and segmentation which the CVT will perform. Practically, it involves outlining the types of visual data that CVT will capture and process, such as worker movements, equipment operation, or area occupancy, which are essential for environmental risk monitoring.

Determine Analytical Method
The methodology for data analysis is established in this phase. It includes selecting statistical models, machine/deep learning algorithms, or a combination of both to process and analyze the data collected from WSDs and CVT. This step is fundamental for transforming raw data into actionable insights.

Identify Data Sources for WSDs and CVT
Identifying appropriate data sources is crucial for ensuring that WSDs and CVT capture relevant and high-quality data. This step involves determining the optimal placement of CVT cameras, and the assignment of WSDs to workers or specific locations within the workplace to maximize data collection effectiveness.
Develop Data Integration and Analysis Protocols
Developing protocols for data integration and analysis involves creating a blueprint for how data from WSDs and CVT will be combined and processed. This includes establishing procedures for data cleaning, preprocessing, and fusion to ensure the reliability and validity of safety insights derived from the integrated data.

Pilot Test WSDs in Operational Setting and Pilot Test CVT in Operational Setting
Before full deployment, pilot testing of both WSDs and CVT is conducted in the operational environment. This step tests the functionality, reliability, and user acceptance of the devices and technology in real-world conditions. The pilot testing phase is critical for identifying any practical issues and making necessary adjustments.

Evaluate Integrated Systems Performance
The performance of the integrated WSD and CVT system is evaluated against the set objectives and criteria. This evaluation focuses on the effectiveness of the system in detecting and alerting about the identified hazards, its usability, and the accuracy of the data analysis and predictive insights provided.

Gather Worker Feedback on Device Usability
Worker feedback is a vital component of the framework, ensuring that the devices are practical and user-friendly. Surveys and interviews are conducted to collect feedback on the WSDs’ wearability, the CVT’s non-intrusiveness, and the overall user experience. This feedback is instrumental in refining the system for maximum efficacy and worker compliance.

Deploy WSDs in the Work Environment and Deploy CVT in the Work Environment
The deployment steps involve the full-scale implementation of the selected WSDs and CVT in the workplace. This includes installing the devices, configuring the systems, and training the workforce on their operation and the interpretation of alerts and data.

Safety Impact Assessment
The final step is to assess the impact of the integrated WSD and CVT system on workplace safety. This involves analyzing post-deployment incident statistics, comparing them to the benchmarks established initially, and evaluating improvements in safety outcomes. This assessment determines the success of the integration in reducing workplace hazards and enhancing overall safety.

CONCLUSION
The importance of worker safety in the steel manufacturing industry, especially in the face of prevalent hazards such as caught-in/between incidents, struck-by accidents, fires, heat stress, slips, trips, and falls, cannot be overstated. Traditional methods of hazard identification and safety management, which largely depend on manual inspection and safety personnel, are often subjective and prone to human error. This paper addressed these challenges by proposing a practical and automated approach that integrates wearable sensing devices (WSDs) and computer vision technologies (CVT) for a more dynamic and responsive safety management system. WSDs contribute significantly to this integrated system by providing continuous physiological and environmental monitoring, thereby delivering immediate feedback and alerts to workers. Concurrently, CVT, a branch of artificial intelligence enhances the scope of safety systems, offering broad environmental awareness and advanced threat detection. This paper achieved two main objectives: developing a comprehensive conceptual framework that synergizes computer vision and WSDs, also characterizing specific safety hazards in steel mills to be addressed by this technological integration. Through a thorough review, this study highlighted and proposed mitigation strategies for critical hazards in steel manufacturing. These strategies demonstrated how the integration of WSDs and CVT could effectively tackle issues such as falls, slips, trips, extreme heat, fires, explosions, caught-in/between incidents, and struck-by accidents.

This research opens pathways for future investigations to validate the proposed framework and assess its impact on safety culture, incident rates, and potential economic benefits. Moreover, it sets the stage for developing customized solutions for unique safety needs in various industrial sectors beyond steel manufacturing. This integrated approach to safety management signifies a substantial step forward in reducing risks and fostering safer working environments in the industry.

REFERENCES


