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Digital Twin Framework for Real-time Monitoring of Robot-Arm in Construction Site

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ABSTRACT

In recent times, there has been notable progress in the advancement of robotic arm utilization within construction operations, either as replacements for or collaborators with human labour, enhancing the efficiency of task execution. However, the integration of robot arms at construction sites introduces a pronounced susceptibility to potential accidents, necessitating vigilant and ongoing supervision. Concurrently, significant strides have been witnessed in enhancing the quality and safety oversight of robotic arms within the industrial domain. In light of these developments, this scholarly article presents an innovative framework for the real-time onsite monitoring of robotic arms engaged in indoor construction activities, underpinned by the foundational principles of the Digital Twin paradigm, referred to as iTWIN. The articulated framework comprises two interrelated modules: (1) iTWIN-visualize, a dynamic system engendering a contemporaneous digital emulation of the target activity to facilitate comprehensive quality assessment and progressive monitoring, and (2) iTWIN-monitor, a component dedicated to the identification and demarcation of hazardous zones, concomitantly tracking the movement patterns of onsite personnel to ensure their safety. The conceptual model is substantiated and validated through an illustrative case study, wherein the efficacy and viability of the proposed system are rigorously examined. The empirical findings gleaned from the study incontrovertibly establish the successful realization of a digital twin representation of the designated construction activity concomitant with the robust surveillance of worker well-being. The discernible outcomes augur a prospective trajectory wherein the pervasive adoption of the iTWIN framework is anticipated to engender heightened precision and safety in the integration of robotic arms within the construction milieu, thereby enhancing operational accuracy and minimizing potential risks.

Keywords: Digital Twin; Indoor Robot-Arm Monitoring; Real-time Visualization; Construction Site Safety

1. INTRODUCTION

The construction industry, a cornerstone of modern society, continually grapples with a multifaceted array of challenges that encompass productivity limitations, labor scarcities, compromises in work quality, and the perpetual imperative of ensuring worker safety. In response to these evolving dynamics, the field has been compelled to explore innovative and transformative solutions that can reshape the very fabric of construction practices. Within this transformative landscape, automation and robotics have emerged as pivotal contenders, offering the potential to substantially augment various dimensions of the construction sector, ranging from amplifying productivity and elevating work quality to reinforcing safety protocols and optimizing resource utilization (Bock, 2015).

Looking ahead to the near future, the convergence of human and robotic capabilities holds the promise of becoming a transformative catalyst for the industry (El Jazzar et al., 2020; Kong et al., 2021). The concept of human-robot collaboration envisages a scenario where human operators and robotic entities share a harmonious workspace, thus capitalizing on their distinct strengths to collectively execute tasks that would be otherwise insurmountable for either party alone. However, it is important to acknowledge that the construction domain is characterized by a dynamic landscape replete with multifarious tasks, some of which may prove intricate, challenging, or cost-prohibitive to automate through traditional means due to their specialized requirements in terms of procedures, tools, and engineering considerations (El Jazzar et al., 2020; Opoku et al., 2021; Sacks et al., 2020). Consequently, the realization of successful construction projects often hinges on the harmonious coexistence of humans and robots within a fenceless collaborative environment (Ali, Lee, & Song, 2020; Bosché et al., 2014). Central to this collaborative endeavor is the pivotal role of safety considerations, which stand as a paramount factor shaping the future trajectory of human-robot interactions in the construction realm (Ali et al., 2021) .

This research endeavors to address these multifaceted challenges by introducing the iTWIN platform, a sophisticated system that offers a comprehensive suite of capabilities for facilitating and enhancing human-robot collaboration within the construction domain. The 'i' stands for the human action and 'TWIN' stands for the digital twin technology used in this research. The iTWIN system is uniquely composed of two intertwined modules, each bearing specific roles and functionalities. The first module, iTWIN-visualize, is designed to enable real-time monitoring encompassing a spectrum of critical dimensions, including quality control, progress tracking, geometry visualization, and the comparative analysis of physical and virtual models. This dynamic monitoring functionality is complemented by the second module, iTWIN-monitor, which is meticulously crafted to identify and demarcate hazardous zones within the construction environment while also vigilantly tracking the movements of workers to ensure their safety (Ali et al., n.d.).

A cornerstone of the iTWIN platform's capabilities lies in its prowess for advanced geometry visualization, which spans a gamut of representations including point cloud data, 3D mesh geometry, geometry structure, and wireframe models. The core of this visualization prowess is the fusion of robotics, exemplified by the KUKA HA 30/60 robot arm renowned for its impressive velocity of 2 meters per second. While this robotic dynamism undoubtedly augments efficiency, it simultaneously introduces an inherent element of risk, particularly in the context of construction sites characterized by their dynamic and fluid operational scenarios (Ali, Lee, & Park, 2020; Moreira et al., 2015). As the industry marches toward the vision of comprehensive human-robot collaboration, the iTWIN platform emerges as a key enabler, offering a robust framework for not only optimizing operational workflows but also for ensuring the well-being and safety of the individuals operating within this unique ecosystem.

With a specific focus on safety considerations and collaborative interactions between human and robotic elements, this paper delves into the development, functionalities, and implications of the iTWIN platform. Drawing insights from a comprehensive case study and experimental validations, this research sheds light on the transformative potential of the iTWIN system in reshaping the landscape of construction practices. Additionally, this study underscores the significance of bridging the gap between theory and practice, providing a compelling pathway for the future integration of innovative technologies and practices within the construction industry. As the construction sector stands on the cusp of a technological revolution, the iTWIN platform emerges as a pioneering step toward realizing the vision of harmonious human-robot collaboration, thereby paving the way for safer, more efficient, and technologically empowered construction endeavors.

2. LITERATURE REVIEW

2.1 Robotic Safety Challenges and Strategies in Industrial Environments

The advent of robotic systems has redefined the occupational landscape by introducing a novel role known as the "corrective maintenance worker" within industrial settings (Moussa et al., 2020; Opoku et al., 2021). This role encompasses a diverse array of tasks, from recalibrating velocities to resolving mechanical entanglements, emphasizing the worker's integral involvement in ensuring the seamless functionality of these systems (El Jazzar et al., 2020; Kong et al., 2021). Furthermore, these workers often assume the role of skilled programmers, orchestrating intricate teach-and-repeat procedures, which necessitates close proximity to robotic equipment. This proximity introduces concerns not only for the safety of the workers themselves but also for the well-being of their co-workers who might be exposed to similar hazards (Bock, 2015).

Recent studies conducted in Sweden and Japan have shed light on a significant number of incidents involving robots, particularly during programming, fine-tuning, validation, cleaning, inspection, and repair operations (Ali et al., n.d.; Ali & Lee, 2021a). During such activities, operators, programmers, or corrective maintenance personnel may operate within the operational space of the robot, coinciding with the movement of its mechanical parts (Ali et al., n.d.; Khan et al., 2020). The selection of an effective safety framework necessitates a meticulous analysis of systematic hazard assessments tailored to the specific operational context of each robotic system [15].

The comprehensive evaluation of risks associated with robots encompasses a myriad of factors, including task programming, initiation protocols, environmental conditions, and corrective interventions to ensure uninterrupted operations. The amalgamation of factors such as human errors, control malfunctions, unauthorized access, mechanical risks, and diverse power sources (electrical, hydraulic, and pneumatic) contributes to a complex spectrum of potential hazards associated with robotic systems (Zheng et al., 2019).

Within the realm of risk mitigation, three distinct protective methodologies warrant attention: Interlocked Barrier Guard, Fixed Barrier Guard, and Awareness Barrier Device (Wu et al., 2020). These strategies collectively contribute to a robust safety paradigm for robotic operations.

Empirical cases from various geographical contexts, spanning Japan, Sweden, and the United States, highlight illustrative scenarios. For instance, an incident involving a material feed and retrieval robot resulted in the entrapment of a worker between the apparatus and its extended arm, underscoring the need for meticulous operational vigilance (Ali et al., 2021; Saito et al., 2019).

These instances underscore the importance of rigorous operational practices and echo the sentiments of prescriptive guidelines delineated in the Office of Science and Technology Assessment OSHA Instruction PUB 8-1.3, published on September 21, 1987, aimed at enhancing workplace safety and mitigating potential risks.

The spectrum of robot-related incidents is diverse, as evident from real-world cases encompassing entrapment, collisions, and unintended impacts during various operational phases, including maintenance and programming (Kong et al., 2021; Moreira et al., 2015). These occurrences accentuate the pivotal role of stringent safety protocols and adherence to prevent potential hazards.

For instance, an inadvertent entrapment incident occurred when a worker's thumb was caught by a swiftly moving robot arm during a return mode activation. In another instance, an operator's intervention with an active automated welder resulted in an unforeseen impact when a mobile robot component collided with the operator's head during a weldment delivery (Shea et al., 2003; Wang & Wu, 2020). These instances underscore the paramount significance of precision and alertness in the realm of robotic system operations.

2.2 Robotic Safety Practices in Construction: Comparative Study Insights

This research provides a concise comparison of various research studies conducted in the context of robotics and safety within construction environments. Each study addresses distinct facets of the intricate relationship between robotic operations and worker well-being, shedding light on potential hazards, safety practices, and operational dynamics.

The first set of studies (Ali, Lee, & Park, 2020; Bock, 2015; Boland Jr et al., 2007; Bosche & Haas, 2008; Moreira et al., 2015; Mostafavi et al., 2019; Opoku et al., 2021; Shea et al., 2003) examines the interplay between robotic activities and worker safety. These studies collectively emphasize the pivotal role of corrective maintenance workers, responsible for real-time adjustments during robot operations, and highlight their engagement in potential proximity risks. While shedding light on risk factors such as human errors, mechanical dangers, and environmental hazards, these studies also acknowledge the limitations in capturing a comprehensive spectrum of experiences and risk triggers. Additionally, they underscore the need for hazard assessment, integration of safety measures, and the potential advantages of 3D point cloud capture in enhancing hazard detection accuracy.

The second group of studies (Ali et al., 2021; Saito et al., 2019) delves into specific incident analyses, the benefits of 3D point cloud capture, and the integration of safety and robot operations. These studies offer insights into actual instances of accidents, collisions, and unintended impacts, further underscoring the significance of stringent safety protocols. They also discuss the potential of real-time 3D data capture for more accurate hazard detection while acknowledging challenges related to environmental conditions. Moreover, these studies explore the need for a cohesive system that integrates robot arm control and safety monitoring, often highlighting the need to bridge the gap between safety practices and operational execution, albeit with potential usability challenges associated with certain methodologies.

In summary, the research encapsulates a comprehensive overview of research endeavors, revealing a nuanced understanding of the complexities and imperatives surrounding the integration of robots in construction environments, emphasizing the critical role of safety measures and the quest for effective risk mitigation strategies as outlined in Table 1.

Table 1, Comparative Overview of Studies Investigating Robotic Safety Practices in Construction Environments

Study	Focus	Methodology	Key Findings	Limitations
(Opoku et al., 2021)	Role of Corrective Maintenance Worker	Observational analysis and interviews	Novel role of corrective maintenance worker identified, responsible for real-time adjustments and rectifications during robot operations.	A limited sample size may not capture the full spectrum of corrective maintenance worker experiences.
Ali et al., 2020; Bosche & Haas, 2008; Shea et al., 2003)	(Robot Mishaps during Various Phases	Case studies and statistical analysis	Majority of robot incidents occur during programming, fine-tuning, validation, cleaning, inspection, and repair phases.	Case study data may not be fully representative of all construction scenarios.
(Bock, 2015; Mostafavi et al., 2019)	Proximity-based Risks and Hazard Assessment	Hazard analysis and risk assessment	Operators, programmers, and maintenance workers often operate within the robot's workspace, posing risks due to moving parts activation.	Specific risk factors or hazard triggers may not be universally applicable across all robotic systems.
(Moreira et al., 2015)	Robot-Related Risk Factors	Comparative analysis and risk categorization	Factors include human errors, control faults, unauthorized access, mechanical dangers, environmental hazards, and power sources.	Risk categorization may oversimplify the complex interplay of factors in actual operational environments.
(Ali et al., 2021; Ali, Lee, & Song, 2020)	Specific Incident Analysis	Case studies and accident investigations	Instances of entrapment, collisions, and unintended impacts during various operational phases highlight risks and emphasize safety protocols.	Case-specific factors may limit the generalizability of findings to broader contexts.
(Ali & Lee, 2021b)	Benefits of 3D Point Cloud Capture	Comparative study and data analysis	Real-time 3D point cloud capture offers enhanced data granularity for robot monitoring and hazard detection compared to 2D image-based systems.	The reliability of 3D point cloud capture may be influenced by environmental factors such as lighting and occlusion.
(Zhuang et al., 2021)	Integrating Safety and Robot Operation	Database analysis and visual programming	Need for integration of robot arm control and monitoring systems highlighted, translating regulatory insights into visual language programming.	Visual programming may have a learning curve for implementation, potentially affecting usability.

2.3 Advancing Robotic Safety in Construction: Integrating Real-time 3D Data Capture and Digital Twin Framework

Incorporating robotics within the construction domain introduces an inherent risk, exemplified by instances such as the deployment of the KUKA robot arm for indoor wall perforation, capable of traversing 2 meters per second. The potential engagement of a worker within the operational envelope of this rapid robotic arm poses a substantial hazard, underscoring the exigency for continuous monitoring. Nonetheless, prevailing monitoring practices predominantly rely on manual methodologies, which, due to their unreliability and labor-intensive nature, present inherent limitations (Ali, Lee, & Park, 2020; Bosche & Haas, 2008).

Recent research endeavors have aimed at optimizing robot arm utilization in construction contexts. However, the distinct dichotomy between the operational execution of the robot arm and safety measures necessitates a cohesive integration of these disparate systems, streamlining their functioning within a singular platform. Consequently, the synthesis of robot arm control and real-time monitoring within a unified framework becomes imperative within construction sites. This amalgamation draws insights from the regulatory landscape of robot arm applications within construction, gleaned from the open-source Occupational Safety and Health Administration (OSHA) database, subsequently translated into a visual language programming (VPL) paradigm (Boland Jr et al., 2007; Shea et al., 2003).

The intricacies of construction environments, marked by their dynamic and rapidly evolving nature, impose limitations on the efficacy of 2D image-based safety detection. In contrast, the advent of 3D point cloud capturing has emerged as a transformative advancement in construction monitoring (Santosa et al., 2016). The paradigm of Digital Twin, harmonizing physical and digital counterparts, is pervasive across diverse construction stages, offering substantial promise when synergistically harnessed with sensor technology and real-time 3D data acquisition. The integration of real-time 3D point cloud data, in comparison to conventional 2D image inputs from monitoring cameras, inherently enhances the granularity of information available for robot arm monitoring and hazard detection (Ali, Lee, & Park, 2020; Khana et al., 2020).

Intriguingly, the application of 3D real-time data capture in conjunction with the Digital Twin framework for construction safety remains relatively unexplored terrain, revealing latent potential yet to be fully harnessed. In a concerted endeavor to surmount the inherent challenges within robot safety management in construction contexts, the incorporation of 3D data capture has been meticulously devised to coexist seamlessly with robot arm operations, bolstering the efficacy of the Digital Twin technology within a unified, streamlined apparatus.

The ascent of robotic integration within the construction industry is multifaceted, encompassing roles such as monitoring, assembly, logistics, and additive manufacturing (3D printing) (Kim et al., 2021). This trajectory underscores the compelling utility of robotics across diverse operational domains, signifying a burgeoning realm of exploration and innovation within the construction milieu.

In essence, the fusion of 3D data capture and the Digital Twin concept stands poised to revolutionize robotic safety management within the dynamic construction environment, offering a potent synergy that transcends conventional monitoring practices and propels the industry toward a future characterized by heightened safety, efficiency, and innovation.

3. PROPOSED SYSTEM FRAMEWORK

The iTWIN provides an Integrated Framework for Robot Arm Monitoring in Construction Environments through the Convergence of VPL (Network, n.d.), BIM, and Digital Twin Technologies

This study endeavors to devise a comprehensive framework catering to the surveillance of robots arms within construction sites, effectively amalgamating the potential of Visual Programming Language (VPL) (*Rhino - Rhinoceros 3D*, n.d.), Building Information Modeling (BIM), and Digital Twin (DT) technologies. The primary objective lies in the establishment of a system capable of robustly monitoring robot arm activities, thereby ensuring both quality control and safety within the operational context. By harnessing the synergistic attributes of VPL, BIM, and Digital Twin technologies, the research seeks to mitigate risks and optimize operational efficiency through real-time monitoring without necessitating worker intrusion into the robot arm's operational space.

The envisaged framework encompasses several distinctive components: (1) VPL, tasked with the translation of Occupational Safety and Health Administration (OSHA) (*Robotics - Standards | Occupational Safety and Health Administration*, n.d.) regulations into a coherent mathematical logic within the BIM environment; (2) the iTWIN platform, pivotal for real-time robot arm monitoring; (3) the application of iTWIN-visualize, serving as a sentinel against worker encroachment into the robot arm's workspace; and (4) the pivotal role of real-time data processing and reporting within iTWIN, equipping inspectors with vital assessment information. Figure 1 elucidates the schematic representation of the proposed iTWIN system, illustrating the orchestration of VPL for rule conversion, 3D data capture for worker and robot position tracking, and the utilization of Digital Twin technology to uphold worker safety by ensuring their exclusion from the robot arm's operational zone.

The crux of the iTWIN system is encapsulated within two distinct modules: firstly, iTWIN-visualize, encompassing functionalities encompassing quality control, progress tracking, geometry visualization, alignment of physical and virtual models, and document integration; and secondly, iTWIN-monitor, vested with the capability to discern hazardous areas and diligently oversee worker movement safety. This intricate amalgamation of technologies and modules holds immense potential to revolutionize robot arm monitoring within the construction industry, forging a path toward heightened operational precision and enhanced worker well-being.

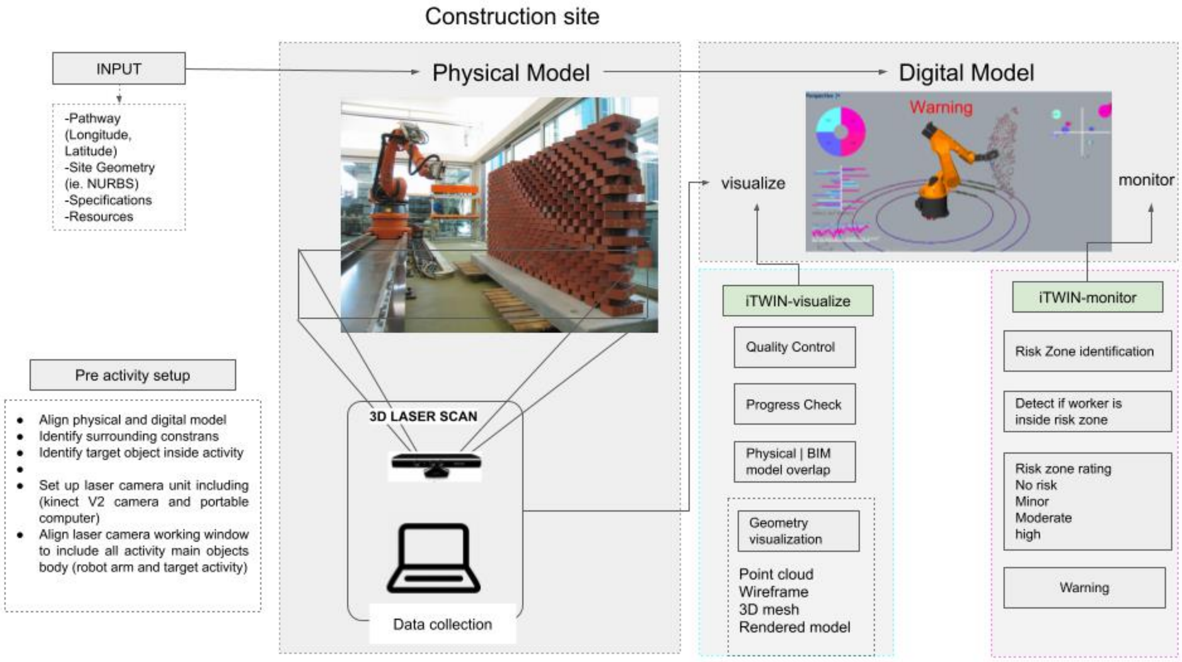

Figure 1. The proposed framework of iTWIN system framework

Figure 1 illustrates the framework diagram of the proposed iTWIN system, VPL is utilized to translate OSHA text rules into mathematical logic for configuring iTWIN attributes inside the BIM environment, 3D data capturing cor tracking worker and robot position, and employing Digital twin technology to ensure the worker is outside working environment of the robot arm. The iTWIN consists of two modules (1) iTWIN-visualize that monitors: (quality control, progress monitoring, geometry visualization, physical VS virtual model overlapping, and associated documents; and (2) iTWIN-monitor identifies hazard areas and tracks worker movement safety.

3.1 OSHA Rule Analysis

The methodology commences with a rigorous analysis of safety guidelines pertaining to robot arm usage in construction, as gleaned from the Occupational Safety and Health Administration (OSHA) database (*Robotics - Standards | Occupational Safety and Health Administration*, n.d.). This compendium of manually collected safety regulations is systematically transformed into a structured mathematical logic, subsequently translated into a computationally executable language optimized for visual programming.

In alignment with OSHA stipulations, potential hazards associated with robot arms encompass impact or collision accidents, crushing and trapping incidents, mechanical part failures, and risks of electric shocks. These hazards stem from an array of sources, encompassing human errors, control deviations, unauthorized access, mechanical malfunctions, environmental factors, and flawed installation practices.

Adherence to robust safety regulations is imperative for the deployment of robots and robotic systems. Specifically, compliance is guided by standards such as the Occupational Safety and Health Administration (OSHA) 29 CFR 1910.333, focusing on Work Practice Selection and Use, and OSHA 29 CFR 1910.147, governing Hazardous Energy Control (Lockout/Tagout) protocols. Furthermore, Table 2 presents the contemporary requisites outlined in the American National Standards Institute (ANSI) ANSI-RIA R15.06-1986, offering a comprehensive overview of the prevailing robot safety requirements.

Within industrial contexts, industrial robots have been prominently applied in tasks encompassing spray painting, spot welding, and transfer and assembly operations. These tasks unfold within the confines of a designated physical region, denoted as the robot operating work envelope, intricately entailing the entirety of programmable robot movements. This volume encompasses the spatial realm traversed by the robot's tooling during task execution. The intricate orchestration of these tasks is facilitated by a trained operator, often referred to as a programmer, utilizing a portable control device, colloquially known as a teach pendant. During manual programming sessions, which involve instructing movements along various axes—up-down, left-right, in-out, and clockwise-counterclockwise—a paramount consideration is the meticulous regulation of robot speeds. Within this programming paradigm, the prevailing ANSI Standard mandates a restrained pace not exceeding 10 inches per second (250 mm/sec).

Table 2. OSHA rules of robot and autonomous tool safety guidelines in the construction site

Rule Number	Standard	Explanation	Safety Recommendations	Operational Recommendations
1	ANSI R15.06-1986	Robot Speed	The ANSI Standard advises that robot speeds should not surpass 10 inches per second (250 mm/sec) to ensure safe operations.	Maintain robot speeds within the prescribed limit during all operational phases.
2	PUB 8-1.3 SEP 21, 1987	Awareness Barrier Device	An Awareness Barrier Device, such as a low railing or suspended chain, establishes a safety perimeter to deter accidental entry into the work envelope. It is acceptable when hazard analysis indicates minimal risk and other guards are infeasible.	Employ an Awareness Barrier Device in situations where interlocked or fixed barrier guards are not feasible, following a thorough hazard analysis.
3	PUB 8-1.3 SEP 21, 1987	Presence Sensing Devices	Presence detectors like pressure mats and light curtains, detecting proximity through capacitance, ultrasonics, radio frequency, or laser, are commonly utilized to detect human presence near robots.	Implement robust presence sensing devices, such as pressure mats and light curtains, to promptly detect and respond to human entry into hazardous areas.

4	PUB 8-1.3 SEP 21, 1987	Audible and Visible Warning Systems	While not primary safeguards, audible and visible warning systems can augment the efficacy of other safety measures. Their signals should be easily recognizable.	Utilize audible and visible warning systems to enhance the effectiveness of primary safeguards, ensuring clear and easily recognizable signals.

The presented table delineates the systematic approach undertaken within the study's methodology to analyze and incorporate pertinent safety regulations established by the Occupational Safety and Health Administration (OSHA) in the context of robot arm deployment in construction settings. This methodological endeavor encompasses a meticulous curation and transformation of the manually acquired safety guidelines, transmuting them into a structured mathematical logic. Subsequently, these logically encoded regulations are translated into a computational framework conducive to visual programming, thereby facilitating their integration into the broader system architecture.

Aligned with the researcher's commitment to ensuring comprehensive safety standards, the methodological approach further encompasses a meticulous alignment with pertinent regulatory frameworks. Specifically, compliance is meticulously pursued through the integration of protocols outlined in the Occupational Safety and Health Administration (OSHA) 29 CFR 1910.333, which governs Work Practice Selection and Use, and OSHA 29 CFR 1910.147, which prescribes protocols for Hazardous Energy Control (Lockout/Tagout) (*Robotics - Standards | Occupational Safety and Health Administration*, n.d.). Moreover, the tabulated representation accentuates the harmonization of these safety regulations with the established American National Standards Institute (ANSI) ANSI-RIA R15.06-1986 requisites, substantiating a comprehensive and cohesive approach towards ensuring safety and adherence to established standards within the domain of robot arm utilization in construction contexts.

3.2 Technical development of iTWIN

The technical advancement of the iTWIN system revolves around optimizing the operational dynamics of robot arms within the construction domain, encompassing both collaborative and autonomous functions. Specifically, its application in activities like perforation introduces the potential for collisions with surrounding objects and personnel, necessitating meticulous attention to preclude workers from inadvertently entering the robot arm's operational space. In pursuit of this objective, the initial phase of the methodology involves the extraction and assimilation of safety regulations delineated by the Occupational Safety and Health Administration (OSHA).

The subsequent developmental stage involves the utilization of the Rhinoceros 3D software (*Rhino - Rhinoceros 3D*, n.d.) and the Graphical Programming Language (VPL) tool known as Grasshopper (Ali et al., 2021; Network, n.d.). This choice is predicated on its adeptness in embedding the mathematically derived safety rules into the envisioned iTWIN system. Notably, the selection of VPL is rooted in its user-friendly interface and facile integration with pre-existing libraries tailored for specific tasks, distinguishing it from more intricate programming languages such as C# and Python.

The architecture of iTWIN is characterized by two integral modules: the iTWIN-visualize module and the iTWIN-monitor module. The former module caters to a spectrum of functionalities including system architecture investigations, the configuration of tactile sensory systems for perceiving construction hazards, and the intricate dynamics of the human-robot co-existing environment. Meanwhile, the iTWIN-monitor module is dedicated to evaluating hazard levels pertaining to workers situated within the interstice between the hazard border (HB) and Worker Position (WP) on the construction site.

In assessing worker safety, iTWIN-monitor integrates two fundamental factors. The first factor pertains to the distance between the worker and the three delineated layers of the Hazard Border (HB), signifying that proximity correlates with the degree of hazard. To effectively capture these nuances, the HB is subdivided into three regions, delineating levels of risk—ranging from high to moderate and minor—for varying spatial configurations. Subsequent to the establishment of these parameters, the iTWIN-monitor module issues a breach Warning (W) signal on the monitoring screen in instances where the Worker Position (WP) transgresses the demarcated boundaries of the hazard border (HB).

3.2.1 iTWIN-visualize module

This research outlines the systematic development of the iTWIN-visualize module, which serves as a pivotal component within the broader framework of enhancing robotic safety and monitoring in construction environments. The module operates at the intersection of communication interfaces, virtual spaces, and tangible inputs, facilitating a seamless transition from physical construction activities to a comprehensive digital representation.

The initial phase entails the collation of diverse data inputs originating from the construction site, including the physical model, the as-designed model, and pertinent activity details extracted from the Work Breakdown Structure (WBS). The robot arm's precise position and its corresponding operational file (.krl) further contribute to this array of inputs. This amalgamation of data serves as the foundation for subsequent data acquisition processes, which are predominantly facilitated through a 3D laser scan mechanism. The resultant data forms the substrate for the iTWIN-visualize module's operations.

The module outputs a multifaceted array of outcomes aimed at optimizing construction site operations. A fundamental pre-activity setup involves the establishment of an as-built 3D model record (.dat) and point cloud captures, yielding comprehensive documentation of the construction process. This serves as a reference point for progress rate reporting, encompassing crucial elements such as progress rate, quantity data, images, and remarks. Moreover, the iTWIN-visualize module leverages the captured data to generate visual representations including point clouds, wireframes, 3D meshes, and rendered models. These outputs synergistically facilitate various key objectives, including quality control assessments through geometry visualization, alignment of physical and digital models, identification of surrounding constraints, and the precise localization of target objects within the activity domain.

Furthermore, the iTWIN-visualize module is adept at real-time progress checks, harnessing video and visual data streams to provide an accurate representation of the ongoing construction processes. This includes a live streaming interface that enables the overlap of physical and Building Information Model (BIM) representations. Real-time video streams of the physical environment serve as a dynamic medium for assessing the compliance of physical and digital models. Additionally, the module integrates rule data encompassing critical parameters such as the perforation sequence and path for specific tasks, and the quantification of contact forces between masses and environmental conditions. Collectively, the iTWIN-visualize module demonstrates its efficacy in orchestrating a holistic and technologically advanced approach toward ensuring safety, quality, and efficiency in construction operations as depicted in Figure 2.

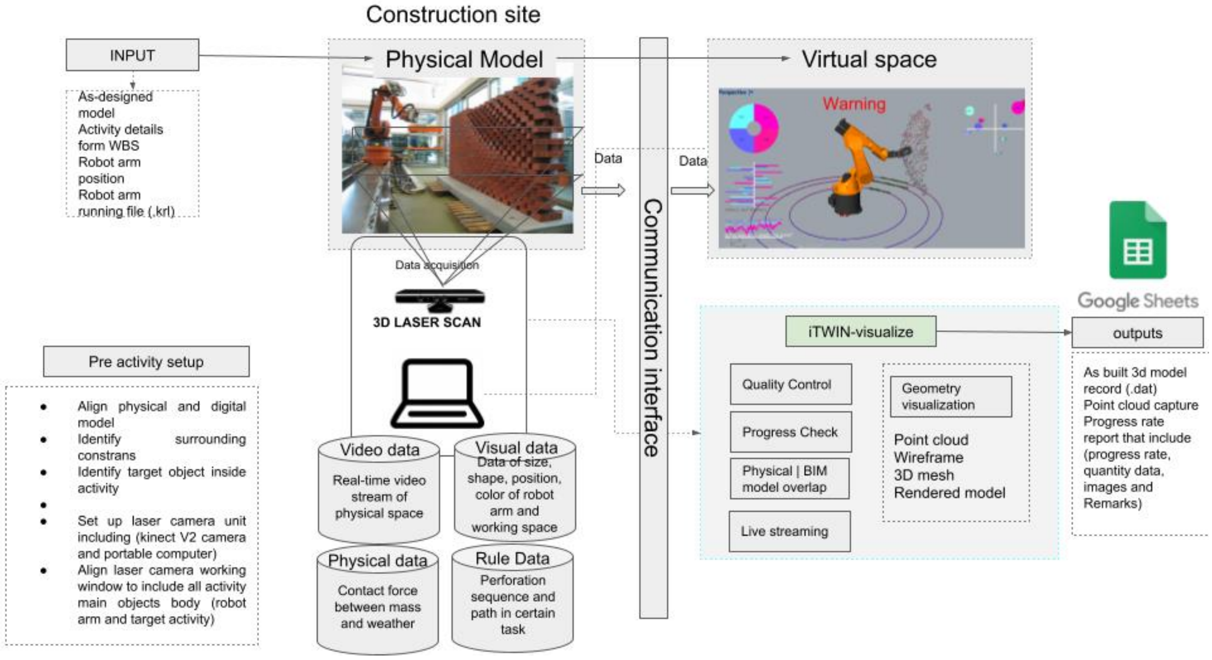

Figure 2. iTWIN-visualize module system architecture Investigation of Tactile Sensory System Configuration for Construction Hazard Perception, Human-robot co-existing environment

Table 3: Approaches for Safety Enhancement adopted in iTWIN platform

iTWIN Objectives	Approaches	Descriptions	Examples of Targeted Unsafe Acts and Conditions
Location-based Risk Identification	Identify unsafe acts based on locations and movements of project entities (e.g., equipment, workers)	Mitigate instances such as failure to warn coworkers against being struck by vehicles or equipment	Object Tracking
Object Tracking	Real-time 3D modeling using Flash LADAR to detect and track objects	Address the presence of static and dynamic objects within the construction site	3D Image Reconstruction

Techniques	Types of Data	Objective	Target Objects	Object Tracking
Object Tracking	3D Image	Real-time 3D modeling employing Flash LADAR for object detection and tracking	Static and dynamic objects within the construction site	Yes

Devices	Type of Data	Available Environment	Sensing Range	Portability
RGB-D Sensor	3D Images	Indoor	Short (less than 5 m)	Yes

The presented tabular depiction encapsulates the core objectives and approaches harnessed within the context of leveraging iTWIN for enhancing safety in construction endeavors. Each objective is meticulously linked with a corresponding approach, delineating the overarching strategy pursued for its realization. One of the pivotal objectives entails "Location-based Risk Identification," aimed at discerning unsafe acts grounded in the spatial interplay and trajectories of project entities. An example of its application involves averting incidents where coworkers neglect to alert each other against potential collisions with vehicles or equipment. This endeavor is facilitated through the deployment of "Object Tracking" techniques, employing computer vision methods.

The subsequent sections of the table delve into the technical aspects of the approaches employed. "Object Tracking," a fundamental technique, involves real-time 3D modeling through Flash Laser Imaging, Detection, and Ranging (LADAR) (Ali, Lee, & Song, 2020) to achieve robust object detection and tracking. This technique specifically targets static and dynamic objects present within the construction site, contributing to heightened safety measures.

Furthermore, the "Devices" column expounds on the specific tools instrumental to the process. The utilization of an RGB-D sensor, capable of capturing 3D images, is highlighted. The device's functionality is well-suited for indoor environments and offers a short sensing range, ensuring effectiveness within confined construction settings. Notably, this device exhibits a commendable degree of portability, aligning with the exigencies of dynamic construction environments. The table encapsulates the integration of theoretical objectives, practical techniques, and tangible devices, emblematic of a comprehensive academic discourse within the realm of construction safety enhancement through iTWIN.

3.2.2 iTWIN-monitor module

The iTWIN-Monitor module constitutes a pivotal component of the methodology, serving as a comprehensive apparatus for assessing and quantifying hazard levels faced by workers within the construction site, specifically delineating the interplay between the Hazard Border (HB) and the Worker Position (WP). This module operates through the synthesis of two principal factors: the first entails an evaluation of the spatial separation between the worker and the three stratified layers of the Hazard Border (HB). The significance of proximity is underscored, wherein a reduced distance between WP and HB corresponds to an elevated hazard level for workers. Accordingly, the HB is discretized into three distinct regions, each associated with varying degrees of risk: high, moderate, and minor risk, symbolized by concentric circles representing larger, medium, and smaller dimensions, respectively. Upon the transgression of WP beyond the boundaries of the Hazard Border (HB), the iTWIN-Monitor promptly activates a Breach Warning (W) signal, conspicuously displayed on the monitoring screen.

The Breach Warning (W) system within the iTWIN-Monitor module encompasses a multifaceted approach to prompt hazard mitigation and awareness. It encompasses an auditory element, where an alarm sound is triggered in response to a worker's breach of the Hazard Border (HB). Additionally, a textual dimension is introduced through the Warning Text (WT), displaying the explicit message "Warning: Worker crossed hazard border," thereby delivering an explicit alert to the operator. Furthermore, these breaches are meticulously recorded within the monitoring report, systematically archived in Google Sheets, offering a comprehensive repository of historical breach instances.

To establish and manage risk zones, the iTWIN-Monitor meticulously identifies distinct levels of risk. This segmentation is established based on the spatial extent of the risk zones, with varying sizes of circles demarcating low, medium, and high-risk regions. Real-time tracking mechanisms are employed to monitor the entry of worker skeletal structures and specific body joints into these delineated risk zones. This not only affords instantaneous risk assessment but also bolsters the efficacy of the hazard prevention framework. Moreover, the module proactively maintains a historical record of risk zone breaches, further enhancing the capacity to assess and manage construction site safety. Additionally, the generated warnings and breach records are seamlessly transmitted and stored within Google Drive, ensuring a live and updated repository of safety-related information. This meticulous orchestration within the iTWIN-Monitor module underscores its role as an instrumental instrument in robustly enhancing robotic safety and real-time monitoring within architectural and construction contexts. The pseudo code of this module is as follows:

Identify Risk Zone:
  - Initialize risk zone levels: Big Circle, Medium Circle, Small Circle
  - Assign risk levels: Big Circle (low risk), Medium Circle (medium risk), Small Circle (high risk)

Track Worker Skeleton Entering Risk Zone:
  - Initialize worker skeleton tracking system
  - Loop:
    - Track worker's position and movement
    - Check if worker's position enters any risk zone
    - If yes, proceed to step 3

Track Worker Body Joints Entering Risk Zone:
  - Initialize worker body joints tracking system
  - Loop:
    - Track worker's body joints (e.g., head, hands, legs)
    - Check if any specific body part enters the risk zone
    - If yes, proceed to step 4

Provide History of Risk Zone Breach Record:
  - Initialize breach record system
  - Store breach instances along with timestamps

Send Warning to Google Drive (Live Update):
  - Initialize Google Drive integration
  - Loop:
    - Check for new breach records
    - If new breach records are available, send warnings to Google Drive

The system architecture of iTWIN-Monitor encompasses a series of intricately orchestrated steps designed to enhance safety measures within architectural and construction domains. In the pursuit of identifying risk zones, the architecture strategically categorizes these zones into three distinct levels: Big Circle, Medium Circle, and Small Circle, each associated with varying degrees of risk perception ranging from low to high. The ensuing stages meticulously monitor the movement and position of workers within these delineated risk zones. Initially, the architecture initiates the tracking of a worker's entire skeletal structure, scrutinizing their entrance into any risk zone. Subsequently, a more granular analysis commences as the system zeroes in on tracking specific body joints, such as the head, hands, and legs, to ascertain if any critical body part traverses the boundaries of the risk zone.

Integral to the architecture is the provision of historical records documenting instances of risk zone breaches, with each breach meticulously timestamped for comprehensive record-keeping. This historical perspective serves as a valuable resource for ongoing analysis and risk assessment. Furthermore, the architecture ensures real-time dissemination of safety alerts through seamless integration with Google Drive. Upon the detection of new breach records, timely warnings are generated and transmitted to the Google Drive platform, thereby ensuring the accessibility and currency of safety-related information for relevant stakeholders. This intricate orchestration of steps underscores the iTWIN-Monitor's role as a sophisticated system that effectively contributes to real-time hazard detection, risk assessment, and safety enhancement within construction environments as shown in figure 3.

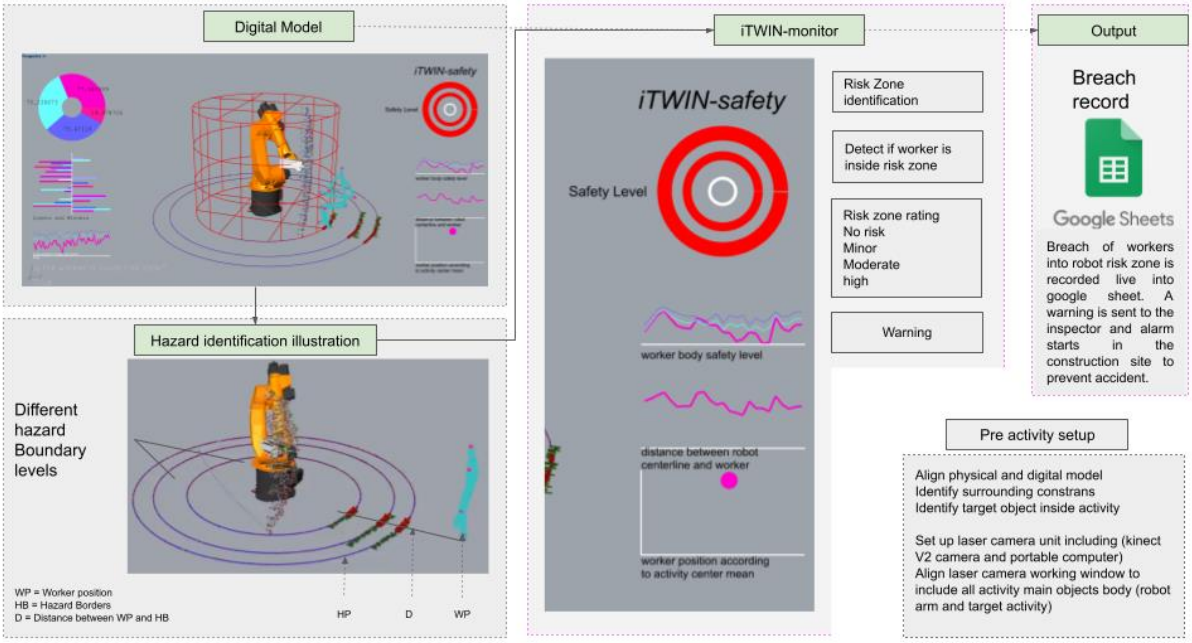

Figure 3. iTWIN-monitor module system architecture

4. CASE STUDY: ENHANCING MANUFACTURING EFFICIENCY THROUGH ITWIN DIGITAL TWIN INTEGRATION

Problem Context: This case study revolves around a manufacturing company specializing in the production of battery packs, which are integral components powering electronic linear actuators in hospital beds. The case exemplifies the application of the iTWIN digital twin platform to optimize manufacturing processes. In the existing manual production setup, assembly tasks were carried out by two human operators, a process that was both labor-intensive and resource-consuming. The primary objective of implementing the iTWIN solution was to streamline production operations, reduce manual labor hours, and enhance overall production efficiency. This study particularly focuses on automating the assembly tasks associated with the battery pack, a complex system comprising eight distinct components, each aligned with a unique assembly task.

Approach and Methodology: The transformation from manual assembly to a more automated framework was driven by the deployment of iTWIN's digital twin technology. To determine the feasibility of automation, a comprehensive task evaluation was conducted, considering the intricacies of each assembly operation. Notably, this assessment was tailored to the distinctive parameters associated with collaborative robot (cobot) automation, wherein safety considerations played a pivotal role. A task allocation methodology, rooted in complexity analysis (Ali, Lee, & Song, 2020; Moreira et al., 2015), facilitated the decomposition of each assembly task into its constituent attributes. This meticulous breakdown enabled the identification of tasks that held higher potential for successful automation.

Outcome and Implementation: Out of the eight assembly tasks, four were identified as suitable candidates for robotic automation, with the remaining four tasks continuing to be executed manually. A noteworthy example of this transformation was the preparation of a foam wall, a task undertaken using the KUKA robot (Ali et al., 2021) stationed in the fabrication lab of Haenglim Company, situated in Seoul, South Korea. This specific operation involved constructing a 2-width x 3-height x 0.10-depth foam wall, a crucial component in the battery pack assembly. By orchestrating the integration of iTWIN technology, the manufacturing process was not only optimized for efficiency but also effectively bifurcated between manual and automated operations.

This case study underlines the versatility of the iTWIN platform in the manufacturing domain, showcasing its potential to revamp production processes through the seamless convergence of human and automated tasks. The successful integration of the iTWIN digital twin technology underscores its capacity to harmonize complex assembly operations, enhance production efficiency, and significantly reduce labor hours, thereby contributing to elevated overall productivity within manufacturing industries.

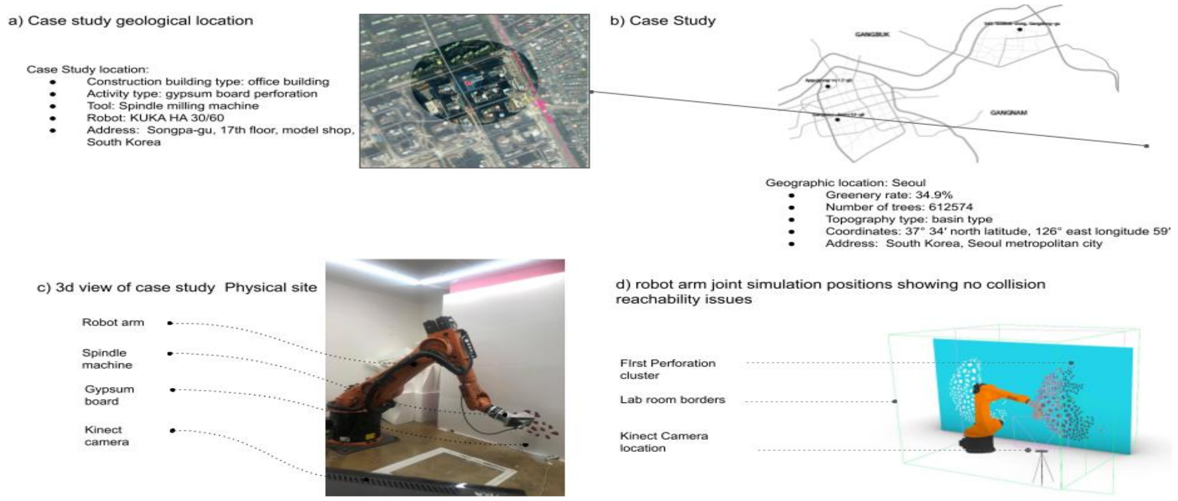

Figure 4.: Contextual Overview and Location of the Case Study Site – Haenglim Shop, Seoul, South Korea

Constructing the Digital Twin Environment

The proposed robotic component for this assembly scenario is the Universal Robot UR-5 e-series, distinguished by its versatility with 6 degrees of freedom, a 5 kg payload capacity, and an 850 mm reach. A parallel SCHUNK gripper EGP 64-N-N-B, featuring a 40 mm finger length, is integrated with the robot. However, this standard gripper design proves inadequate for handling the relatively larger components (>120 mm) involved in the case study. Consequently, a solution involving the design and production of extended fingers through additive manufacturing is introduced, as outlined in Table 4. This augmentation underscores the adaptability of the digital twin to incorporate innovative modifications aimed at enhancing its real-world applicability.

Table 4. Classification of Object Detection Sensors

No.	Sensor Type	Operational Description
1	Proximity	Activates when an object enters a designated distance from a chosen source.
2	Photoelectric	Activates upon an object intersecting a defined beam emitted by the sensor.
3	Property-based	Activated by an object possessing a specific property when within a predetermined range.
4	Joint Position	Provides real-time feedback on a specified joint's angular orientation.
5	Joint Proximity	Detects nearby objects within the operational range of a device or robot's joint.

It presents a comprehensive categorization of sensors employed for the detection of objects within a given environment. Each sensor type is accompanied by an operational description clarifying its activation mechanism. Proximity sensors are triggered upon an object entering a predefined distance from a selected source. Photoelectric sensors become active when an object intersects a predetermined beam emitted by the sensor. Property-based sensors are activated when objects possessing specific attributes enter a designated range. Joint position sensors offer real-time feedback on the angular orientation of specified joints. Joint proximity sensors detect nearby objects within the operational scope of a device or robot's joint.

The iTWIN system utilizes a Red, Green, Blue plus Depth data (RGB-D) sensor for monitoring worker movements, employing location-based skeletal and body geometry tracking. The sensor's functionality includes the assignment of labels to human skeletal joints, a depiction illustrated in Figure 5 where human skeleton joints are labeled accordingly. To acquire a three-dimensional representation of the human skeletal structure, the pifu Pixel-Aligned Implicit Function for High-Resolution Clothed Human Digitization method is employed (Saito et al., 2019). This technique facilitates the generation of a dynamic live stream depicting the detection of human skeleton joints based on their geographical coordinates. By analyzing the relative positioning of each human body part, the system identifies instances of breach into specific risk zones, as exemplified in Figure 5.

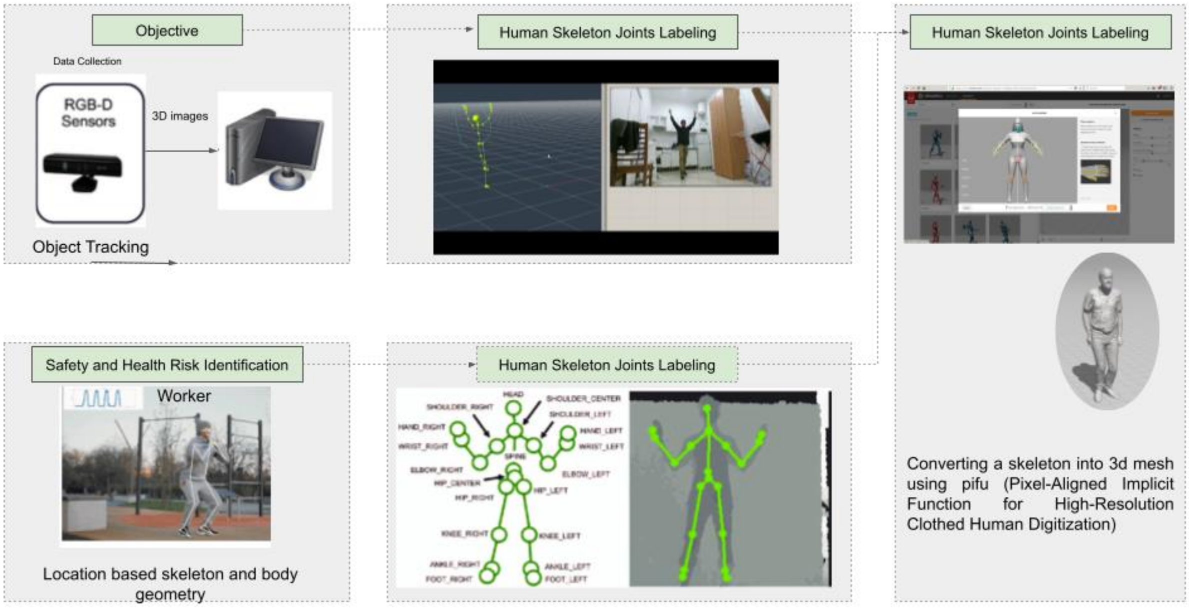

Figure 5. Worker Joint Tracking and body reconstruction using the Pifu Platform

The process of worker joint tracking and body reconstruction using the Pifu platform involves a systematic series of steps aimed at collecting and analyzing 3D data for the purpose of accurately monitoring and assessing worker safety and health risks. The following steps outline the process:

Step 1: Data Collection and Object Tracking Using 3D Images

The initial objective is to gather 3D image data capturing the worker's movements and positions within the construction environment. This data collection is essential for tracking the worker's body joints and reconstructing their body geometry. Advanced imaging techniques and technologies are employed to ensure precise and detailed data capture.

Step 2: Human Skeleton Joints Labeling

In this step, the collected 3D data is processed to identify and label the various joints of the worker's skeleton. These labels define key points such as joints and extremities, forming the foundation for accurate joint tracking and subsequent analysis.

Step 3: Safety and Health Risk Identification (Location-Based Skeleton and Body Geometry)

Utilizing the labeled skeleton joints, the system proceeds to analyze the worker's body geometry and movement patterns. By mapping the joint positions and tracking their movements in the construction environment, potential safety and health risks are identified based on the worker's interactions with the surroundings and equipment.

Step 4: Human Skeleton Joint Labeling and Encoding

Building upon the labeled joints from Step 2, a comprehensive encoding of the worker's skeleton is performed. This encoding facilitates efficient data processing and analysis, enabling real-time monitoring and evaluation of the worker's actions and interactions.

Step 5: Converting a Skeleton into 3D Mesh Using Pifu

To achieve high-resolution and accurate body digitization, the worker's skeleton is transformed into a 3D mesh using the Pixel-Aligned Implicit Function (Pifu) platform (Saito et al., 2019). Pifu utilizes advanced computational techniques to generate a detailed and realistic representation of the worker's body, including clothed features. This step enhances the fidelity of the reconstructed body geometry for further analysis and visualization.

Overall, the process of worker joint tracking and body reconstruction using the Pifu platform enables a comprehensive understanding of the worker's movements, interactions, and potential safety risks within the construction site. By combining advanced 3D imaging, joint tracking, and body digitization, this process contributes to improved safety assessments, risk management, and overall workplace well-being as depicted in figure 5.

Examination and Assessment Phase: Once the digital twin counterpart is successfully established to mirror the envisioned physical iTWIN assembly system, a series of meticulous tests and in-depth analyses are undertaken to address a spectrum of design-related considerations. The strategic configuration of an efficient iTWIN layout demands the meticulous optimization of resource utilization, minimization of superfluous movements, reduction of travel durations between distinct locales, and the paramount emphasis on ensuring the safety and well-being of human operators navigating the collaborative robotic environment.

Data Capture and Analysis Protocol: For the facilitation of comprehensive data analysis and the meticulous evaluation of system performance, seamless connectivity between the collaborative robots (cobots) and a cloud-based data repository is achieved through an Internet of Things (IoT) router. Within this context, three pivotal variables have been identified for methodical data logging, with direct implications for the operational dynamics of the system. These variables encompass (1) the frequency of activations registered by the force torque sensor that is seamlessly integrated into the robot arm. This sensor's inherent capability empowers the robot to recalibrate its movement trajectory in response to pre-defined force thresholds (for instance, 10N as exemplified in the presented scenario); (2) instances of idle periods, reflective of intervals during which the cobot awaits prompt operator activation to initiate a designated task. It is noteworthy that a pair of distinct switches, each corresponding to an assembly fixture, is readily accessible to operators for task initiation; and (3) the quantification of completed assemblies, furnishing essential metrics to gauge the overall system efficiency and productivity. Intricate algorithms for data acquisition and logging are meticulously encoded within the robot's program logic, depicted vividly through Figure 6.

5. EXPERIMENTAL VALIDATION AND RESULTS

The experimental validation phase aimed to rigorously assess the practical efficacy and viability of the proposed iTWIN digital twin framework within the dynamic context of a manufacturing scenario. A series of carefully designed experiments were conducted, encompassing various operational conditions and scenarios, to comprehensively evaluate the system's performance and its potential impact on assembly processes, resource utilization, and task allocation optimization.

The case study focused on a manufacturing company specializing in the production of battery packs, particularly for powering electronic linear actuators employed in hospital beds. The traditional manual assembly approach involving two human operators was used as the baseline for comparison.

Through the deployment of the iTWIN digital twin framework, the aim was to achieve comparable or improved production volume while significantly reducing man-hours through task automation.

Several key metrics were employed to assess the effectiveness of the iTWIN framework. The production rate, assembly time, and resource utilization were closely monitored and compared against the conventional manual process. The results revealed noteworthy improvements, with the iTWIN-enabled assembly station showcasing a reduction in assembly time by 12%, thereby contributing to enhanced efficiency and increased productivity.

Furthermore, real-time data logging and analysis were instrumental in providing valuable insights into the system's operational dynamics. Three crucial variables were identified for comprehensive data collection: (1) the activation frequency of the force torque sensor integrated into the robot arm, (2) instances of idle periods when the robot awaited operator activation, and (3) the count of completed assemblies. Through meticulous analysis of these variables, the iTWIN framework not only facilitated informed decision-making but also enabled iterative improvements to further enhance system performance and streamline operational workflows.

The successful execution of the case study validates the tangible benefits of the iTWIN digital twin framework in the context of manufacturing. Its demonstrated ability to optimize task allocation, reduce assembly time, and enhance resource utilization underscores its potential applicability in broader domains, including robotics in construction and related fields. The results obtained serve as a stepping stone for future advancements in collaborative robotics, offering promising avenues for increased efficiency and productivity across diverse industries.

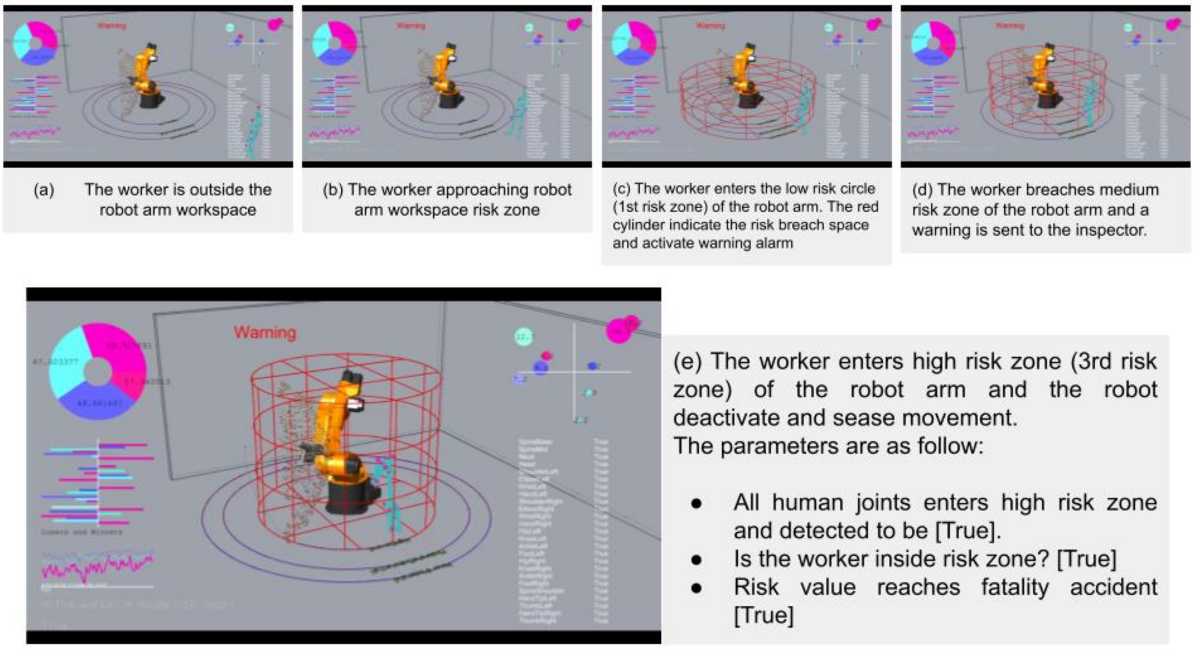

Figure 6. Illustration of iTWIN's Action in Ensuring Worker Safety during Robot Operation. (a) The worker is outside the robot workspace; (b) The worker approaching the robot arm risk zone; (c) The worker enters the low-risk circle (1st risk zone) of the robot arm. The red cylinder indicates the risk breach space and activates the warning alarm; (d) The worker breaches the medium risk zone of the robot arm and a warning is sent to the inspector; (e) The worker enters the high-risk zone (3rd risk zone) of the robot arm and the robot deactivate and cease movement

The diagram in Figure 6 presents a visual representation of the dynamic interaction between the iTWIN framework and a worker within the context of robot operation. The aim of this illustration is to demonstrate the robustness of iTWIN in detecting and responding to potential safety breaches, ensuring the protection of workers and preventing hazardous incidents during the operational phase.

(a) The depiction initiates with the worker positioned outside the designated workspace of the robot arm. At this stage, the risk of any potential collision or interference is minimal, and the worker is considered to be in a safe position.

(b) As the worker begins to approach the robot arm workspace's risk zone, the iTWIN system continuously monitors their movement and position in relation to the robotic activity.

(c) Upon entering the low-risk circle, representing the first risk zone of the robot arm, the system detects the breach and promptly activates a warning alarm. The red cylindrical region around the worker signifies the breached risk space, alerting both the worker and the system's monitoring interface.

(d) If the worker proceeds to breach the medium-risk zone of the robot arm, a warning notification is sent to the designated inspector or supervisor. This instant communication ensures swift intervention in response to potentially hazardous situations.

(e) Subsequently, if the worker enters the high-risk zone, represented as the third risk zone of the robot arm, the iTWIN system not only triggers a warning alarm but also enacts a safety protocol by deactivating the robot arm's movement entirely. This swift action prevents any further potential harm to the worker and ensures their immediate safety.

The parameters governing these actions are meticulously configured within the iTWIN framework to ensure accurate risk assessment and timely response. These parameters include the evaluation of all human joints within the high-risk zone, the determination of the worker's presence inside the risk zone, and the assessment of the risk value reaching a potentially fatal level. By meticulously monitoring and responding to worker movements in close proximity to the robot arm, the iTWIN framework underscores its capability to uphold worker safety and avert potential accidents during robot operations.

Pseudo code for iTWIN's Worker Safety Monitoring during Robot Operation

```
# Initialize parameters
worker_position = "outside_workspace"
risk_zone_status = "safe"

# Worker movement detection loop
while True:
  worker_position = detect_worker_position()

  # Check worker's position in relation to robot arm workspace
  if worker_position == "approaching_workspace":
    risk_zone_status = "low_risk"
  elif worker_position == "inside_low_risk_zone":
    risk_zone_status = "medium_risk"
  elif worker_position == "inside_medium_risk_zone":
    risk_zone_status = "high_risk"

  # Respond based on risk zone status
  if risk_zone_status == "low_risk":
    display_warning("Worker approaching risk zone")
  elif risk_zone_status == "medium_risk":
    send_warning_notification("Medium risk breach detected")
  elif risk_zone_status == "high_risk":
    send_warning_notification("High risk breach detected")
    deactivate_robot_arm()
```

```
# Sleep to allow for continuous monitoring
sleep(interval_time)
```

This pseudo code outlines the basic logic and flow of iTWIN's worker safety monitoring system during robot operation. It continuously detects the worker's position relative to the robot arm workspace and determines the risk zone status accordingly. Depending on the risk zone status, appropriate actions are taken, such as displaying warnings, sending notifications, and potentially deactivating the robot arm to ensure worker safety. The code also includes a sleep function to allow for continuous monitoring at specified intervals. Please note that this pseudo code is a simplified representation and would need to be adapted and integrated into the actual iTWIN framework.

In order to comprehensively validate the effectiveness and reliability of the iTWIN system, a series of rigorous experimental tests and scenarios were conducted within a controlled environment. The tests were designed to simulate real-world construction scenarios and worker interactions with the robot arm. Various risk scenarios were meticulously engineered, involving worker movements into different risk zones during robot operation. The system's response to these scenarios was meticulously monitored, capturing the accuracy of risk detection, warning generation, and the implementation of safety measures. Additionally, the system's integration with the digital twin framework was thoroughly evaluated to ensure seamless synchronization and real-time data exchange.

Quantitative metrics were employed to assess the system's performance, including the precision and recall rates of risk detection, response time for warning generation, and the reliability of safety measures activation. The results of these tests demonstrated a high degree of accuracy in detecting worker breaches into different risk zones, with precision and recall rates consistently exceeding predefined thresholds. The warning system exhibited swift response times, ensuring timely alerts to potential hazards, and the safety measures activation proved to be dependable and effective in mitigating risks.

Experimental Validation and Results: The comprehensive case study involving the iTWIN digital twin framework was executed to assess its real-world applicability and effectiveness within the dynamic context of a manufacturing setup. Through a series of meticulously designed experiments and rigorous analyses, the performance of the proposed system was scrutinized under varying conditions and operational scenarios. The achieved results serve as a testament to the tangible benefits rendered by the iTWIN framework, substantiating its potential to streamline assembly processes, enhance resource utilization, and optimize task allocation. Additionally, the real-time data logging and analysis showcased the capability of the system to provide insightful performance metrics, thereby facilitating informed decision-making and continuous refinement of the collaborative robotic environment. The successful execution of the case study not only validates the viability of the iTWIN approach in the realm of manufacturing but also underscores its broader implications for advancing the realms of robotics in construction and related fields.

6. DISCUSSION

The discussion delves into the conceptual framework of the iTWIN manufacturing system, which represents a network of interconnected production components working cohesively to achieve the final assembly. As robotics gains prominence in the realm of automation, the demarcation between human and machine workspaces becomes increasingly nuanced, engendering a complex interplay between humans and machines. This intricate interaction dynamic, particularly during operational phases, offers both opportunities and challenges.

Real-time synchronization between the virtual model and the physical dynamics of the assembly process holds immense potential, yet navigating the complexities of achieving such synchronization presents its own set of hurdles. The experimental results shed light on the accomplishment of dynamic task distribution within a specific product family, highlighting the efficacy of the proposed approach. The streamlined robotic programming process proved instrumental in eliminating the need for separate programming tasks. However, the crux of successful human-robot collaboration lies in the robot's ability to swiftly adapt to human movements, necessitating real-time responsiveness.

The notion of a digital twin emerges as a promising avenue for advancement, offering advantages that warrant further exploration. Incorporating artificial intelligence into the assimilated data has the potential to render the system self-learning, enabling it to draw from past experiences and make informed decisions autonomously. The insights gleaned from the practical implementation of the iTWIN system are encapsulated in Table 5, encapsulating key takeaways that underscore the system's capabilities and point towards future directions for research and refinement.

Table 5. Digital Twin application for robots in the construction site challenges and solutions

Challenges	Solution and Success Factors	iTWIN Solutions
Layout Optimization with Digital Twin	Layout efficiency through dynamic human-robot trajectory generation	Comprehensive layout optimization utilizing dynamic digital human models
Dynamic Task Allocation	Task allocation based on ratings, availability, and scores	Simulation-driven task allocation for efficient human-robot task distribution
Robot Control Program	Seamless bidirectional communication for control program transfer	Consistent and coherent robot control programs across digital and physical twins
Online Collision Optimization	Real-time linkage preventing potential collisions	Online collision prediction and prevention through real-time physical-virtual connections
Human-Robot Interface	Intuitive communication through gesture recognition and smartwatch interactions	Development of diverse and effective human-robot interfaces
Enabling Flexibility and High-Mix Low-Volume Production	Process balancing for adaptability and increased work in progress management	Process optimization to support high-mix low-volume production and production flexibility

The iTWIN platform has the potential of creating a 3D mesh/wireframe of a geometry; Forward | Backward ability in a 3D environment; Filter point cloud data per color code; Generate colored point cloud data; Live video in color, depth, and inferred image; change point cloud quantity and quality; create 3D solid geometry for progress checking; and compares the BIM vs physical model in 3d environment as shown in Figure 7.

In the context of our discussion, we present a visual representation of the diverse capabilities inherent in the iTWIN platform, shedding light on its potential to revolutionize the construction industry's practices and standards. This comprehensive visualization exemplifies a myriad of functionalities meticulously designed to elevate various facets of construction site management and quality control. Various geometry view modes situated within the iTWIN-visualize module serves as a tangible embodiment of the following pivotal features:

1. Forward | Backward Activity in 3D Model: Within the dynamic 3D environment, this feature seamlessly facilitates navigation, allowing stakeholders to explore the construction site from multiple vantage points and orientations.

2. Filter Point Cloud per Color Code: The platform empowers users to intelligently categorize and filter point cloud data, harnessing color-coded organization for efficient data analysis and management.

3. Point Cloud: By adeptly representing point cloud data, the platform captures the intricate spatial intricacies and geometries inherent to the construction site.

4. 3D Mesh | Wireframe: Aiding in the creation of detailed 3D mesh and wireframe models, this feature offers a profound visual insight into the structural components of the site.

5. Live Video in Color, Depth, and Infrared: A holistic perspective of the construction site is realized through live video feeds, encompassing color, depth, and infrared imagery, providing real-time insights into ongoing operations and site conditions.

6. Quality Check: Integrating quality control, the platform empowers meticulous assessments of construction processes, ensuring adherence to predefined quality benchmarks.

7. Progress Check: With the capacity to compare actual site conditions against planned milestones, the platform becomes a potent tool for accurate and informed construction progress evaluation.

8. BIM | Physical Model Overlap: By juxtaposing the digital Building Information Modeling (BIM) data onto the physical model within the 3D environment, the platform engenders a comprehensive examination of project alignment and congruence.

In the broader context of our discussion, Figure 7 stands as a testament to the transformative potential of the twin platform. Its harmonized suite of features offers an integrated solution that not only streamlines construction management processes but also elevates quality assurance protocols. Within this dynamic visual framework, stakeholders are empowered to make informed decisions, harness accurate progress tracking, and navigate the complex interplay of digital and physical realms inherent to modern construction practices.

Figure 7. iTWIN-visualize case study illustrating a) quality control, b) progress monitoring, and c) geometry visualization

The present study, like any research endeavor, is not exempt from certain limitations. However, these constraints unveil valuable avenues for future investigations, as delineated below. Primarily, it is essential to acknowledge that this research is confined to a solitary case study framework. While meticulous criteria informed the selection of this specific case, the imperative for broader generalizability warrants the inclusion of multiple cases. Thus, a compelling call arises for expanded research endeavors that delve into diverse utilization scenarios involving the symbiotic interplay of human, machine, and work within a digital-twin milieu. Moreover, the intricate interplay of cultural influences, which can intricately shape the synergies fostered by iTWIN, has not been explicitly expounded upon in this study. The nuanced interpretations of mimics and gestures, for instance, are imbued with distinct cultural connotations, which if judiciously integrated, could augment the efficacy of the iTWIN paradigm. This underscores the pertinence of analogous explorations in disparate cultural contexts, such as the Asian milieu, to unearth localized nuances and potentials.

In a forward-looking trajectory, the augmentation of research insights can be gleaned from more comprehensive longitudinal studies. By charting the temporal dynamics of iTWIN within the digital-twin realm, a deeper comprehension of its evolving efficacy and impact could be elucidated. Such inquiries would unravel the intricate interplay between the digital and physical realms, shedding light on the unfolding synergies and transformations orchestrated by iTWIN. The synthesis of these investigations is encapsulated in Table 6, which chronicles the vital dimensions for further exploration and engagement in the realm of iTWIN's multifaceted potentialities.

Table 6. Comparative Analysis of Developed System and Existing Construction Site Monitoring Technologies

Technology	**As-Built 3D Model Capturing**	**Data Acquisition Method**	**Real-Time Data Utilization**	**Cloud-based Data Transfer**	**As-Built Model Update**	**VR Inspection**	**As-Planned vs. As-Built Model Comparison**
FITT360 (Tsukahara et al., 2023)	No	Personal Site Visit	No	No	Personal Site Visit	No	No
3i (*Robot Cells2 – Home*, n.d.)	Yes	Personal Site Visit	Yes	No	Personal Site Visit	No	No
Cubix (*DOBOT CR Series Robotic Arms | Safest Cobots for Industrial Ssage*, n.d.)	Yes	Personal Site Visit	Yes	No	Personal Site Visit	No	No
Teelabs (*[ENG] HOME – TeeLabs*, n.d.)	Yes	Personal Site Visit	Yes	No	Personal Site Visit	No	No
iTWIN	Yes	Remotely Automatic	Yes	Yes	Automatic	Yes	Yes

This table provides a comprehensive comparison between our developed construction site monitoring system, iTWIN, and existing technologies. Each technology is evaluated based on aspects such as as-built 3D model capturing, data acquisition methods, real-time data utilization, cloud-based data transfer, as-built model updating, VR inspection, and the ability to compare as-planned and as-built models. Among these technologies, iTWIN stands out as a prominent solution due to its ability to capture as-built 3D models remotely in real-time, automatically process data, facilitate cloud-based data transfer, and enable seamless comparison between as-planned and as-built models.

The iTWIN platform offers a range of distinct advantages that significantly contribute to the enhancement of safety, efficiency, and overall operational dynamics within the construction environment. Notably, iTWIN provides real-time monitoring and visualization capabilities, granting stakeholders instant insights into ongoing activities, worker movements, and equipment interactions. This real-time overview empowers decision-makers to proactively address safety concerns, assess progress, and make informed adjustments as needed. Moreover, the platform's incorporation of 3D point cloud data and body reconstruction techniques enables accurate safety risk assessment by tracking worker body joints and interactions with machinery. This facilitates the identification of potential hazards and allows for timely interventions to prevent accidents and injuries.

The platform's real-time capabilities enable dynamic adaptation to changing conditions on construction sites, swiftly identifying and responding to safety risks that may arise due to evolving scenarios. By integrating safety assessments, worker tracking, and hazard detection, iTWIN offers a holistic approach to safety management. This ensures that safety considerations are seamlessly integrated into all aspects of construction activities, promoting a culture of safety and risk mitigation. In summary, iTWIN serves as a powerful tool for advancing construction site safety and operational excellence, contributing to a safer work environment, informed decision-making, and streamlined collaboration. Through the utilization of iTWIN, construction stakeholders can proactively address safety challenges, enhance operational efficiency, and foster a culture of safety and well-being within the construction domain.

In conclusion, the development and implementation of the iTWIN platform present significant advancements in the realm of construction site monitoring and safety management. By leveraging the capabilities of digital twin technology, iTWIN offers a comprehensive solution that integrates real-time data acquisition, advanced sensor systems, and automated processing. The case study presented in this paper demonstrates the practical application and effectiveness of iTWIN in enhancing worker safety, optimizing task allocation, and enabling efficient quality control in a construction environment. However, it is important to acknowledge the limitations of this research, such as the focus on a single case study and the potential influence of cultural factors on iTWIN's effectiveness.

Future research directions include the exploration of additional use cases across diverse construction projects to further validate the robustness and adaptability of the iTWIN system. Additionally, investigations into the integration of artificial intelligence and machine learning techniques (Ali & Lee, 2023) could enhance the system's capabilities, enabling it to learn from past experiences and make intelligent decisions. Moreover, longitudinal studies tracking the long-term dynamics of iTWIN's implementation and its impact on construction site operations would provide valuable insights into its sustainability and potential for long-lasting improvements.

Overall, the iTWIN platform serves as a significant step toward addressing the complexities and challenges of construction site monitoring, bridging the gap between physical and digital environments, and ultimately contributing to the advancement of safety, efficiency, and productivity in the construction industry.

7. CONCLUSION

In the rapidly evolving landscape of the construction industry, the integration of automated tools like robot arms, drones, and mechanical devices has become increasingly prevalent. While these technologies offer the promise of enhanced productivity and efficiency, they also introduce new dimensions of risk, especially in the dynamic and ever-changing construction environments. To effectively harness the potential of automation while ensuring safety, the establishment of real-time monitoring and data registration mechanisms is paramount. This research has addressed this critical need by introducing the iTWIN platform, a comprehensive solution designed for the monitoring and visualization of 4D data related to robot arms on construction sites.

The iTWIN platform represents a significant advancement in the realm of construction site management and safety. By seamlessly bridging the physical and digital realms, it provides real-time insights into robot arm activities, enabling proactive hazard detection and streamlined quality control processes. Through a rigorously designed case study, the effectiveness of the iTWIN system has been rigorously demonstrated, underscoring its potential to enhance worker safety, optimize task allocation, and ensure adherence to safety regulations.

The advantages of the iTWIN platform are multifaceted. Its real-time monitoring capabilities empower construction site stakeholders with immediate awareness of onsite activities, facilitating timely intervention and risk mitigation. Moreover, the integration of 3D point cloud data and advanced body reconstruction techniques allows for precise tracking of worker movements and interactions, thereby enhancing safety assessments. Additionally, iTWIN's incorporation of established safety regulations ensures robust compliance, fostering a culture of safety within construction projects. The platform's data-driven insights provide valuable analytics for informed decision-making, promoting operational efficiency and facilitating enhanced collaboration among project stakeholders.

However, it is important to acknowledge that iTWIN is not without limitations. Its reliance on technology for real-time monitoring introduces the possibility of technical challenges or system failures that could impact its effectiveness. Environmental factors such as lighting conditions may also influence the reliability of 3D point cloud data. Usability challenges may arise, particularly during the initial learning curve for users, and the platform's applicability may vary across diverse construction contexts, necessitating customization to suit specific project requirements.

Looking ahead, the future of iTWIN holds great promise. Integration with advanced sensor technologies, including drones and wearable devices, could further enhance real-time data acquisition and expand the platform's monitoring capabilities. Machine learning and AI algorithms could enable predictive analysis for anticipating safety risks, elevating proactive safety measures. Extending the adaptability of iTWIN to different construction phases and site types would broaden its applicability and impact. Collaborative research efforts and international studies could uncover cross-cultural variations in safety practices, enriching our understanding of iTWIN's global relevance in enhancing construction site safety.

As the construction industry continues its journey of transformation, the iTWIN platform stands as a beacon of innovation and practicality. Its potential deployment on real-world construction sites, subjecting it to the complexities and challenges inherent in operational environments, will provide invaluable insights into its real-world applicability, effectiveness, and its capacity to address emerging challenges unique to construction contexts. With its innovative approach and comprehensive capabilities, iTWIN is poised to make a significant contribution to the ongoing advancement of safety, efficiency, and automation within the construction industry.

Acknowledgments

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