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**Harmony in Global
Construction Trends: People,
Technology and Society**



**Joint Safety, Health, and Well-Being
in Construction (W099) and People in
Construction (W123) International Conference**

KNUST, Kumasi, Ghana, 08-11 October 2024

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Harmony in Global Construction Trends: People, Technology and Society

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Editors

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Smart Signalperson for Safe Tower Crane Operations on a Future Digital Construction Site

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Keywords: Proactive warning and alerting of workers (riggers, signalperson), Construction safety, Crane load path planning and lift simulation, Equipment operator, Line-of-sight issues, Obstacle avoidance.

Abstract: The construction industry is increasingly adopting modular and off-site construction methods, leading to more frequent use of cranes on construction sites and in fabrication facilities. There, gantry, mobile, and tower cranes significantly contribute to crane-related accidents worldwide. A common cause of these accidents is the insufficient understanding of the rapidly changing work environment and communication issues between the signalperson and the operator. This paper introduces a novel system designed to proactively mitigate risks associated with poor line-of-sight and communication. The system integrates smart technologies to (a) enable a signalperson to rapidly convey safety-critical information during crane lifts to the operator, (b) detect and track the presence of pedestrian workers underneath crane loads, and (c) proactively warn or alert the operator of imminent danger. The system is evaluated in a virtual construction safety learning environment using the game engine Unity. Here, the novel hand gesture recognition technology HandCOMM is integrated with other virtual reality (VR) capabilities. While HandCOMM allows for the evaluation of the workers' communication skills, the Exposure Detection and Warning (EDW) module monitors and alerts workers of the proximity to suspended loads. The results demonstrate the benefits of using gesture recognition for crane operations, particularly in overcoming occlusion issues, although further refinement of HandCOMM is necessary. The explorative study also shows that the system can collect relevant data to evaluate communication among work crews. The insights allow decision-makers to receive data that has not yet been available. Future research needs to refine the technology and validate its real-world application.

Introduction

The construction industry is undergoing a transformative shift towards the adoption of modular and off-site construction methods, necessitating the increased utilization of cranes in construction sites and fabrication facilities. However, this surge in crane operations coincides with a concerning number of struck-by object-related accidents worldwide [1], with gantry, mobile, and tower cranes being significant contributors to such incidents [2]. Up to 84 percent of these incidents relate to human errors, where the deficient communication between signalpersons and crane operators represents an essential role [3].

In response to these challenges, this paper presents a pioneering system integrating safety protocols and smart technologies

designed to address critical safety concerns during crane operations. The system aims to (a) facilitate rapid communication of safety-critical information from signalpersons to operators during lifts, (b) detect and monitor pedestrian workforce beneath crane loads, and (c) proactively alert operators of imminent dangers. The proposed framework endeavors to mitigate risks associated with poor line-of-sight and communication, thereby ensuring the safety of both crane operators and pedestrian workers. A case study was conducted in a virtual environment utilizing the Unity game engine to evaluate the feasibility of the system before testing it in a real-world scenario. This paper includes an explorative study investigating the potential of such a framework, as well as collecting user data and evaluating communication deficits and improvements among hoisting crews.

Related works

Crane operations and safety

Struck-by incidents stand as one of the foremost causes of fatalities in the construction industry. Between 2011 and 2021, struck-by hazards comprised 17% of all construction fatalities in the United States [1], also emerging as the largest contributor to nonfatal injuries, accounting for 21.5% in the same years [1]. These accidents encompass a variety of risks, including being struck by heavy equipment and other vehicles like excavators, dump trucks, and various types of cranes.

Among the most common accidents associated with struck-by incidents are those occurring during lifting operations, where workers find themselves within the hazardous workspace where harmful contact with the equipment or its parts can occur [4]. Hoisting operations are indispensable in construction projects, with cranes frequently maneuvering loads near and above workers in crowded areas that may overlap with multiple ground crews [5]. Between 2011 and 2017, the US Bureau of Labor Statistics recorded 297 crane-related fatalities, with more than half involving pedestrian workers struck by moving crane parts or falling objects [2]. In recent years, there has been a steady rise in lifting operations both on construction sites and off-site, driven partly by the construction industry's increasing use of prefabricated elements and modular building components. Given the weights and sizes of such elements, lifting becomes necessary at various stages of the construction supply chain and assembly process.

Considering this, Fard et al. delved into 125 accidents related to modular and prefabricated building components, finding that 62% of these accidents occurred on construction sites, primarily during installation tasks [6]. Similarly, the Norwegian Labor Inspection Authority analyzed accidents related to prefabricated elements, examining 21 cases and identifying that in over 50% of these incidents, workers were situated within hazard zones [7].

The complexity of conducting safe crane operations underscores the importance of clear and comprehensive communication between the crane operator and the pedestrian workers. Pedestrian workers must remain vigilant about their surroundings, including the presence of loads, and must ensure they stay clear of danger zones to avoid potential accidents involving falling loads or crane components.

Challenges in crane operations communication

Effective communication is crucial for safe crane operations. As mentioned before, human error is the cause for most of the crane accidents, implying that proper training of crane operators and signalers is essential [3]. Typically, hoisting involves a crew where a signaler communicates with the crane operator, who executes commands using a remote control

or controls on the crane itself. Depending on the crane type, the operator may be situated in a cabin or on the ground, facing limited visibility and relying on communication with the pedestrian workers so that successful hoisting operations are possible.

Typically, the rigger or signaler would use hand gestures to share commands with the crane operator, but limitations exist. Fig. 1 shows a selection of commonly used signals. They enable effective communication irrespective of the construction noises and language barrier between the workers [8]. There are standard hand signals for operations such as crane rigging. However, misinterpretation of these predefined hand signals by the operator of the cranes may cause severe accidents [9]. Additionally, these hand gestures require a direct line of sight between the crane operator and the riggers. However, in highly dynamic environments like construction sites, occlusion occurs frequently, hindering effective communication. Automatic recognition and interpretation of hand gestures may potentially assist in effective communication between the signaler and the operator.

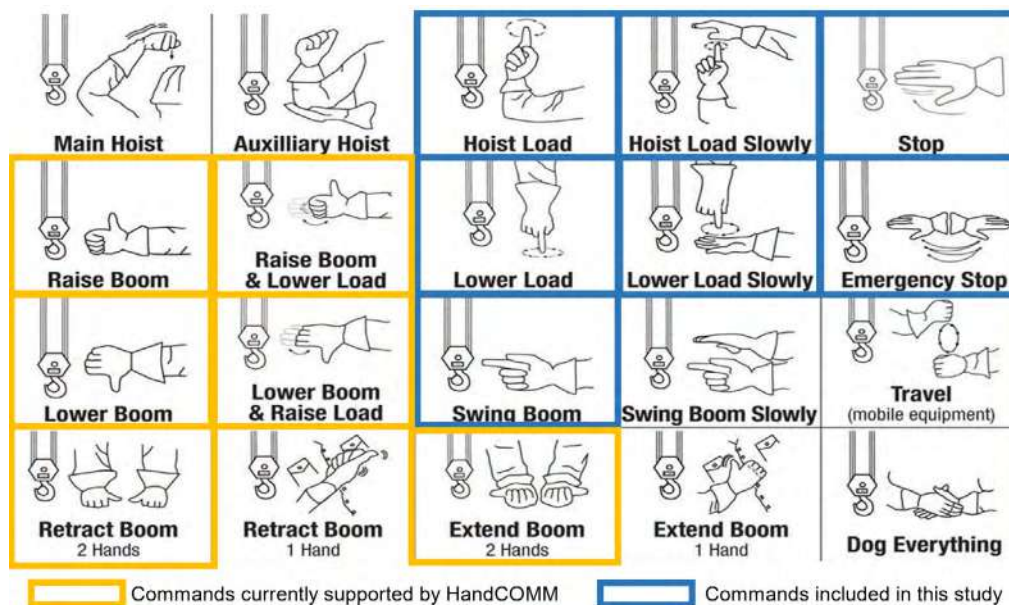


Fig. 1: Hand gestures commonly used in tower and mobile crane operations.

Several technologies support automated hand gesture recognition, which can be categorized into wearable devices and computer vision-based devices. Computer vision-based gesture recognition methods involve data collection using cameras, offering the advantage of not requiring the worker to wear a glove; however, they are sensitive to occlusion and environmental conditions [10]. Wearable devices include data gloves, inertial sensors, and myoelectric sensors [11]. Data gloves are widely used in virtual environments for gesture recognition, involving processes such as data collection, parameter extraction, and selection [12]. Despite their high recognition accuracy, data gloves are costly, unsuitable for construction sites, and may impede workers from performing manual tasks.

Objectives and research methods

The previous section highlighted that crane operations contribute significantly to construction site accidents. Additionally, it noted the importance of hand gestures for communication signals. However, in environments like high-rise construction sites where visibility is often

limited, hand signals are not always feasible. Despite this, hand signals remain effective due to workers' familiarity with them, and their standardization facilitates collaboration.

This study aims to explore the potential of integrating a smart signaling system into crane operations, addressing communication and visibility challenges. Its primary goal is to gather insights and data that can inform future studies. Therefore, the following research questions were formulated:

RQ1: What are the potential benefits and limitations of using hand gesture recognition systems for communication during crane operations?

RQ2: How can such a system support the crane operator in detecting hazardous situations and issuing warnings based on collected data in a simulated environment?

The objective of this study is to mitigate the risks associated with poor line of sight and communication in crane operations. To achieve this, the authors adopted an exploratory and experimental research approach. The study focuses on integrating a signaling system, HandCOMM, into crane operations. In response to the limitations in existing literature, the authors designed an exploratory system that incorporates HandCOMM into crane lifting operations. To further explore potential valuable data, the study also tracks the hazard exposure of pedestrian workers to crane loads. The system was implemented in an experimental, controlled environment using the Unity game engine in a virtual multiuser setting. This setup tests the functionality of the system, including hand gesture recognition, real-time communication, and exposure detection under simulated conditions. Utilizing synthetic environments is a common approach for the preliminary assessment of developed systems.

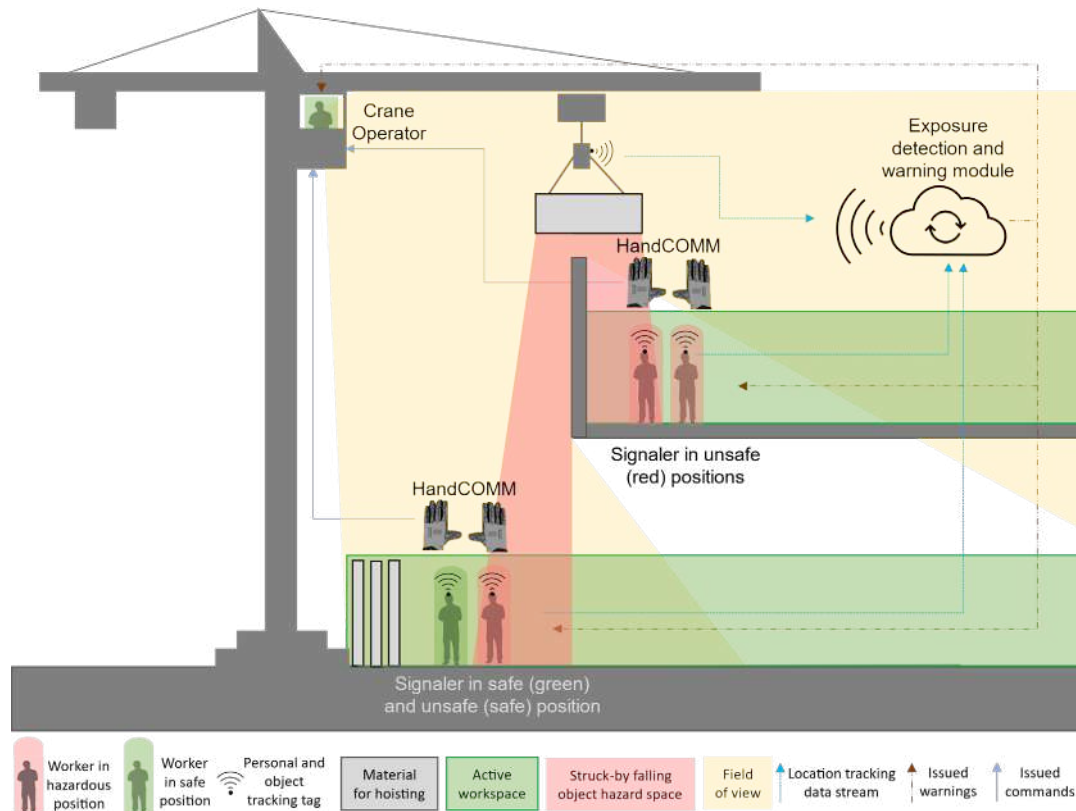


Fig. 2: The proposed system in the context of one potential use case.

Smart signalling system

The proposed system includes two modules (see Fig. 2). The first module facilitates the communication between the crane operator and the signal. This module is called HandCOMM and is comprised of two parts. The smart gloves worn by the signalers and a base station in the operator's cabin are equipped with a screen and a speaker. The second module tracks the crane loads and the pedestrian workers on the ground. With the locations available, the module can detect proximities and issue warnings to the workforce when hazardous exposure is detected. The following sections delve into the details.

HandCOMM

The HandCOMM technology illustrated in Fig. 3 consists of two primary components: two glove modules and a display module. The system configuration includes a total of two glove modules, each featuring three flex sensors to accurately gauge the bending of the thumb, index finger, and middle finger. These modules are also equipped with motion tracking devices optimized for low power consumption, cost-effectiveness, and high performance, comprising a 3-axis gyroscope and a 3-axis accelerometer to precisely measure glove rotation and movement. Additionally, each glove integrates a processing unit for hand gesture recognition, along with a radio signal transmitter to transmit signals corresponding to the detected hand gestures.

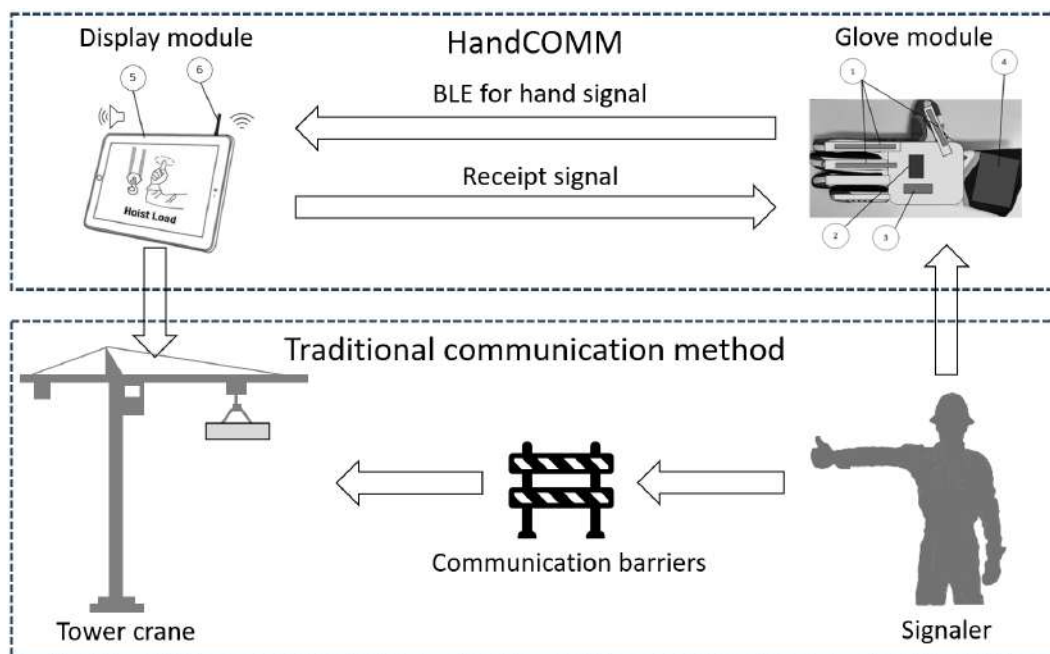


Fig. 3: The HandCOMM module illustrated on the top overcomes communication barriers from traditional communication methods.

Positioned strategically on the back side of the glove, as shown in Fig. 3, are essential components ensuring the efficient operation of the processing unit, motion tracking device, and radio signal transmitter. A battery storage unit (3) on the backside provides power to the system, while a flexible solar panel (4) supplies power to the flex sensors, motion tracking device, processing unit, and radio signal transmitter. Power distribution is regulated by the battery storage unit (3) to ensure seamless functionality.

The display module, depicted in Fig. 3, is integral to the operator's cabin signalman communication assist system, conveying vital information to the crane operator efficiently. It comprises a display monitor (5) for visual representation and a radio transceiver (6) for seamless communication gloves. Bidirectional communication between the display module and gloves ensures the real-time exchange of essential data. Additionally, the display module includes an audible source to announce hand signals based on received radio signals and allows the selection of preferred language for display and announcements.

During a blind lift scenario, where visual contact is lacking, the glove module worn by the signalman plays a central role. It recognizes hand gestures using a specific algorithm and transmits corresponding radio signals to the display module. In the operator's cabin, the display module receives Bluetooth signals, audibly announces corresponding hand signals, and displays them on its screen, ensuring swift and accurate responses from the crane operator. Additionally, a receipt Bluetooth signal confirms the successful transmission and reception of mobile crane hand signals.

Exposure detection and warning module

The pedestrian workers often do not realize that they are under suspended loads. Incidents relating to crane operations occur frequently, as mentioned before. The Exposure Detection and Warning (EDW) module of the proposed framework detects workers who are exposed to suspended crane loads. The workers can either be workers involved in the hoisting process (riggers, signalers, crane operators) or pedestrian workers performing independent tasks. To facilitate this functionality, two variables are required: The location of the workers and the spatial description of the hazardous area.

Safety monitoring in construction involves tracking the status and movement of workers, materials, and equipment to detect safety incidents in both static and dynamic environments before they turn into accidents [13]. Real-time location tracking is crucial for monitoring safety, allowing for spatial and temporal analysis to identify violations of safety rules or conflicts between resources. Various tracking systems, both active and passive, have been utilized in different construction scenarios. For instance, Costin and Teizer employed passive Radio Frequency Identification (RFID) to locate workers indoors [14], while Cheng et al. utilized ultra-wideband tracking to visualize worker positions in construction models [15]. Global Positioning Systems (GPS) are commonly used for outdoor tracking on construction sites [16,17]. Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS), an advancement of GPS, offers higher accuracy by correcting the signal using static sensors [18]. Another approach represents the use of computer vision, where locations can be determined using camera footage [19].

In our proposed system, location tracking occurs directly in the virtual environment. There is no need for a sensor system. The advantage is that no noise or signal issues occur. On the other hand, it represents a limitation of this study as the feasibility of the system in a real-world scenario is not assessed. Nevertheless, the above-mentioned research demonstrates several applicable pathways.

The hazardous area can be described as a cone-shaped spatial object. Similarly to the tracking technologies described for tracking the workers, a sensor attached to the crane loads or computer vision algorithms can determine the position of the hook. Then, the hazardous space can be described as a space under the crane load. Fig. 2 illustrates an example of such a scenario. The transporter material creates a hazardous space below the load. Determining the geometry in a real-world scenario may require the dimensions of the load. Additionally, the swing motions would influence the exact shape of this space. In this study, the shape is considered to be constant.

Once the exposure has been detected, a warning must be forwarded to the workers. Research shows different results about sending warnings. Besides runtime issues due to latency, there are concerns that sending warnings may lead to undesired behavior, which could cause incidents where no incidents happened without the alert. Another issue with alerts is so-called alert fatigue, where workers no longer react to alerts as they occur too frequently. Despite the known issues, our system includes a warning module. Further research must investigate how this feedback is transferred most effectively, and filtering should occur based on other indicators. In this research, however, the warning is always forwarded to the pedestrian worker and crane operator once an exposure is detected. This warning is forwarded visually as research shows that workers react faster to visual feedback. In practice, however, this would imply that the workers must wear smart glasses. In the virtual environment, issuing this warning is facilitated through a warning on the screens.

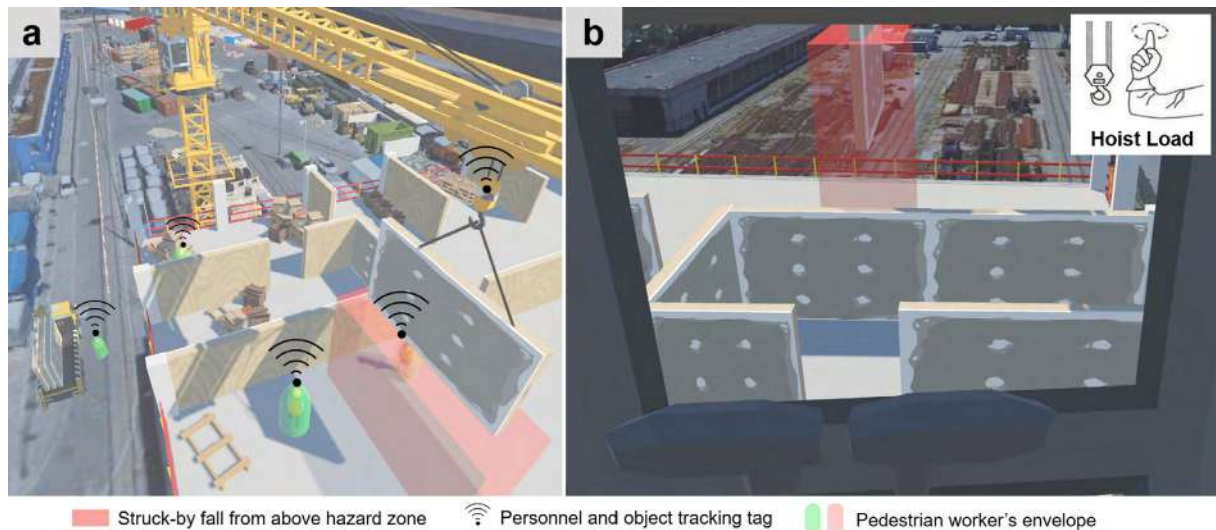


Fig. 4: The virtual learning environment for hoisting tasks.

Implementation in a virtual environment

The defined system has been implemented in a virtual environment using the game engine Unity (see Fig. 4). Unity has been demonstrated as a successful tool in construction research for safety training [20,21], monitoring [22], or simulations [23]. The virtual environment represents a situation where a crew performs hoisting of prefabricated elements.

Hoisting process

A truck arrives at the construction site delivering four prefabricated Cross-Laminated Timber (CLT) elements. At this point, the process illustrated in Fig. 5 starts. The crane operator moves the hoist to the truck so that the pedestrian worker on the ground (Rigger X) can connect the first element to the crane. During this step, the riggers indicate the motions to the crane operator. Once the hoist is in the right position, Rigger X connects the first element to the hoist. Then, the crane operator moves the object to the designated position. During this process, the pedestrian worker on the building (Rigger Y) communicates with the crane operator. The rigger is equipped with a HandCOMM glove, as occlusion may forbid clear sight. In fact, in the virtual environment, the only signal is the HandCOMM signal, as the virtual environment does not support animating the avatars themselves. Once the final position is

reached, Rigger Y gives the signal to stop the hoisting. Once they are sure the crane operator understood, they can detach the element. In the last step, Rigger Y indicates that the hoist is detached so that the crane operator can continue with the next element. The complete process is repeated three times until all four elements are moved.

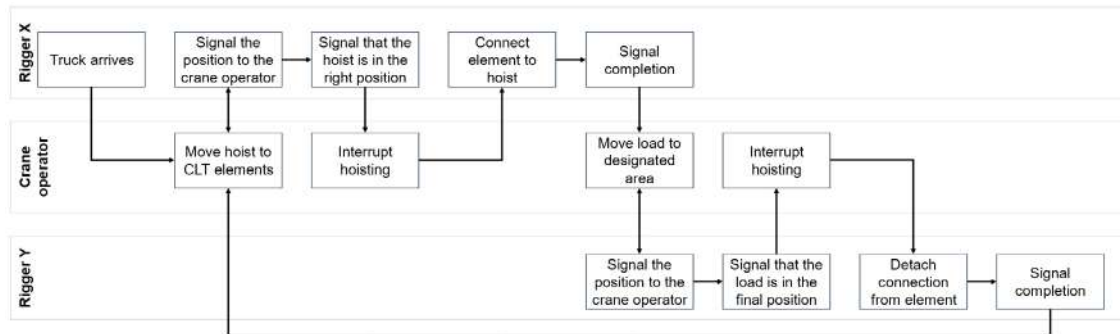


Fig. 5: Sequential description of a hoisting operation performed in the multiuser learning environment.

Technical implementation of the multiuser features

The virtual environment includes three workers: A crane operator and two riggers. While the previous paragraphs overviewed the tasks and process of the hoist operations, the following paragraphs describe the technical implementation of facilitating these features in Unity.

Fig. 6 illustrates the technical setup. Each role is controlled by humans using computers and represented by avatars in virtuality. For each role, a separate computer is used to visualize the virtual environment from their viewpoint. The three computers communicate through the Unity system Photon. Each object in the training scene has a PhotonView assigned so that possible changes in their states are shared with all other computers.

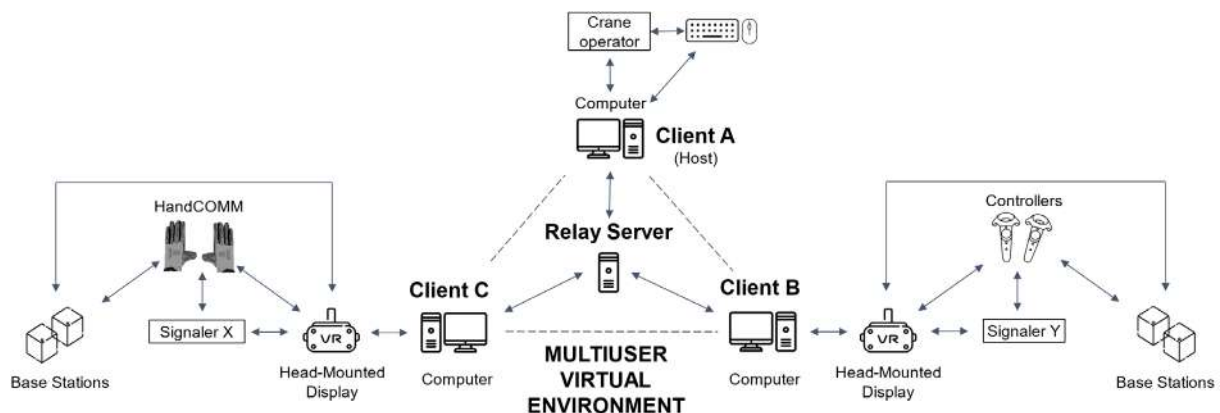


Fig. 6: Experimental setup of the augmented virtual reality hardware and communication.

The crane operator observes the scene from the perspective of the operator's cabin, which is visualized on a monitor. Commands can be entered using a keyboard, and the view angle can be adjusted using a mouse. The operator sees the highlighted hazard zone and the protective envelopes of the workers to estimate their safety (see Fig. 4b). Moreover, the operator visually processes the commands detected from HandCOMM.

The riggers wear a Head-Mounted Display (HMD) and use controllers to navigate the scene. One rigger additionally wears the HandCOMM gloves, which send the detected signals directly to the crane operator. The other rigger must send the signals using a keyboard, as only one pair of gloves is available. The HandCOMM base device is connected to Signaler X's computer using a USB connection. The two gloves send signals using Bluetooth communication. Once a command is detected, the code for the command is sent to the COM port where the device connects. The Unity environment reads these signals from the COM port and visualizes the corresponding icon from the crane operator's point of view.

Exposure detection and proactive warning

The virtual environment in Unity detects the workers' exposure to the suspended loads. Facilitating this feature includes an extension to an existing approach by the authors where hazardous zones are represented as geometric representations in virtual environments [24,25]. In this particular case, a hazard zone in the shape of a trapezoidal prism is added to the crane hook (see Fig. 7). While the angle of the cone should consider the parameters such as velocity and dynamically adjust the size of it, we assume a constant angle of five degrees as proposed in previous research [26].

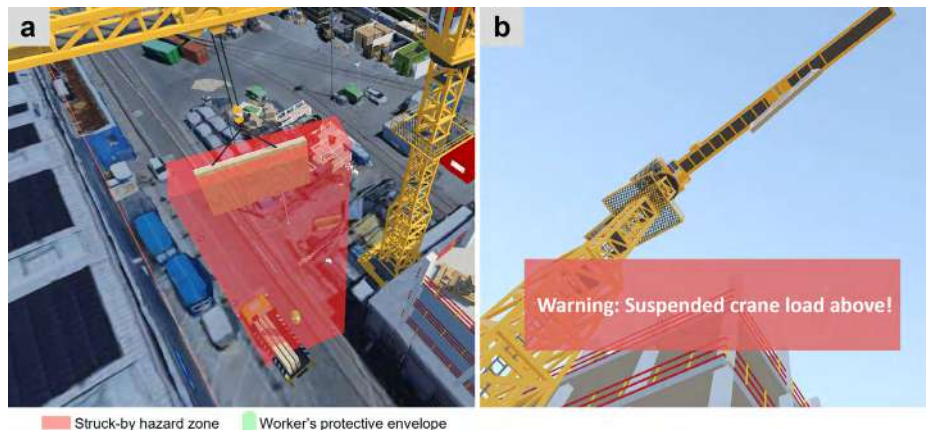


Fig. 7: (a) The pedestrian worker is exposed to a crane load and detected using the collision detection method, and (b) the worker is visually informed.

The VTE also adds protective envelopes to the endangered workers. Both elements, the protective zone of the worker and the hazardous zone connected to the hook, are hidden from the agents in the training scene (see Fig. 7b). And yet, the protective envelope and the hazardous zones exist as objects in the background to facilitate collision detection. Unity provides this functionality with the `OnTriggerEnter` and `OnTriggerExit` methods. These functions represent events that are triggered once the objects collide. Upon collision, the pedestrian worker receives a visual warning, as shown in Fig. 7b. While further research is required on who and how such feedback should be communicated, this approach uses visual alerting as research indicates quicker response to such feedback compared to audio alerts. The authors are aware that forwarding visual alerts in practice requires overcoming several constraints; however, smart glasses or augmented reality-enabled displays could facilitate these warnings effectively.

The virtual environment supports additional data collection functionalities. Throughout the virtual experience, the environment constantly tracks the distance of each worker from the hazardous zone. Unity provides a built-in method to determine the shortest distance between a point and a trapezoidal prism. The distance is logged with a frequency of 1Hz

and then stored in a *.json file for further processing. Besides, the environment also logs the timestamps and type of each command that was detected by the glove. Last, the commands performed by the crane operators are logged. Having this information available allows us to assess the efficiency of the communication based on two indicators: (1) the total number of correct and wrong operations directly after receiving the command and (2) the time elapsed between sending the signal and the crane operator to react.

Results and discussion

The objective of this research was to explore the possibilities of integrating a smart signaling system into crane operations. For that reason, the capabilities of a hand gesture recognition system were investigated. In the second step, the potential of collecting data to provide nuanced insight into communication skills and hazard exposure was investigated. Both approaches apply a qualitative approach to evaluate the proposed system. The following results must be considered preliminary as further tests with more participants are needed.

Hand gesture recognition overcomes occlusion issues. As demonstrated in the use case, the system does not require sight between the crane operator and the signaller. Yet, there are several limitations that require further investigation. First, HandCOMM is not entirely reliable. The technology requires further fine-tuning so that the signals are evaluated correctly by the sensors on the device. Second, an evaluation must be conducted, addressing whether the sensors mounted to the glove may hinder the workers from performing their tasks.

The system can provide valuable insight into the communication skills of a work crew. Fig. 8 visualizes the collected data from the system in the virtual setting. The system constantly tracks the trainees, from sending signals to executing a task. Using this data, we can assess how effectively the workers communicate if the crane operator follows the indicated signals by the workers on the ground. Looking at the recorded graph in Fig. 8b, we can see that the crane operator was not always following the signals sent by the signaller. Fig. 8b also allows us to quantify the response time.

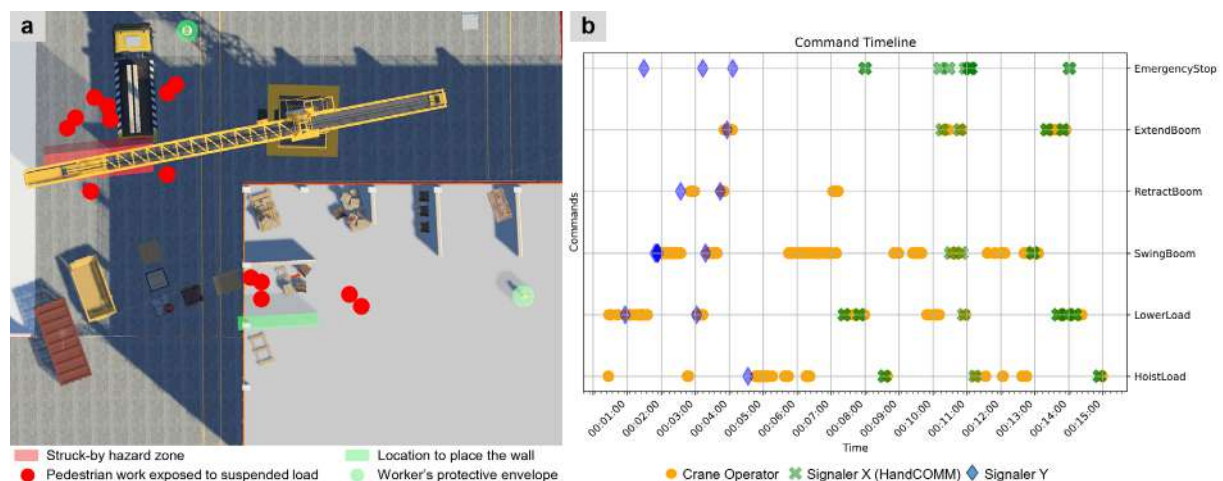


Fig. 8: (a) The EDW module detects when workers are exposed to the crane load and stores the location of such events during the training, while (b) the signalers share hand signals with the crane operator. The chart indicates when the crane operator follows the shared signals.

Looking at the recorded graph in Fig. 8, we can see that the crane operator was not always following the signals sent by the signaler. In fact, three times, they chose to do other things. The second insight from this is that we can see the response time. On average, the crane operator lost 4.5 seconds from receiving the signal to performing the action.

The system effectively detects the workers under the crane load. In the case study, the signalers were exposed to the crane load, as indicated in Fig. 8a. Signaler X was exposed five times, and Signaler Y was exposed nine times. This information can be valuable in estimating workers' hazard awareness. The feedback has been forwarded visually (as illustrated in Fig. 7) to the workers. Future research could investigate how workers respond to the warnings. In practical applications, Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) technology may be capable of providing the necessary data to detect such exposure. Therefore, conducting a real-world case study is essential for further evaluation of the system. Alternatively, the system's accuracy could be assessed without real-world testing by integrating recorded RTK-GNSS data into a virtual environment. This method is similar to previous studies where RTK-GNSS data was used to simulate the interactions between forklift and pedestrian workers [21]. By incorporating such data, the simulated environment closely mirrors real-world conditions, allowing for more informed conclusions based on the collected data.

To sum up, the explorative study indicates that the system can provide valuable insights that have not been available before. The quantification of communication skills can indicate workers' collaboration skills. The exposure detection tracking can help to identify which workers require further training in hazard awareness or which crane operators may risk too many operations over the workers. Lastly, the virtual framework also allows us to determine the distance between the crane load and the workers. Yet, all these parameters need to be tested in specific scenarios in virtual and real-world settings.

Conclusion

In this research, we have presented a comprehensive system designed to enhance communication during crane operations in construction settings. The proposed system integrates two modules: the HandCOMM for facilitating communication between crane operators and signalpersons and the EDW module for detecting and warning pedestrian workers of hazardous situations. Through the utilization of smart technologies and innovative methodologies, our system addresses critical challenges such as communication barriers and pedestrian worker safety beneath crane loads.

The implementation of the HandCOMM module demonstrates its effectiveness in enabling unbroken communication between signalpersons and crane operators, particularly in scenarios where visual contact is hindered. By leveraging glove-based gesture recognition and real-time transmission of signals, the HandCOMM module enhances communication accuracy and efficiency, thereby reducing the risk of misinterpretation and associated accidents. Furthermore, the EDW module showcases support in identifying and alerting pedestrian workers to potential hazards posed by suspended crane loads. Through real-time tracking and proximity detection, the system provides timely warnings, thereby mitigating the risk of struck-by incidents.

While our research presents promising results in a virtual environment, several limitations and areas for improvement remain. Future research should focus on refining the reliability and usability of the HandCOMM technology, as well as validating the system's performance in specific scenarios in the virtual environment and real-world construction settings. Additionally, efforts should be directed toward integrating advanced tracking technologies, such as RTK-GNSS, to enhance the accuracy and reliability of pedestrian worker detection.

Overall, our research contributes to the advancement of safety practices in the construction industry by introducing innovative solutions to mitigate risks associated with crane operations. By leveraging smart technologies and virtual environments, our system lays the foundation for safer and more efficient crane operations, ultimately promoting the safety of workers and productivity in construction projects.

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