APPLICATION OF DIMINISHED REALITY FOR CONSTRUCTION SITE SAFETY MANAGEMENT

Alessandra Corneli, Berardo Naticchia, Massimo Vaccarini, Alessandro Carbonari & Francesco Spegni
Department DICEA, Polytechnic University of Marche

ABSTRACT: *Safety management in construction sites has always been one of the most sensitive aspects of the AECO industry and a problematic that recalls the complexity of such a multifactor domain. The high number of work accidents that occur on construction sites is also caused by the fact that not all the information to work safely is always available. For instance, visibility during some maneuvers is a key aspect of safety in operations, and this is often impeded due to the layout of the construction site and working methods, especially in the use of some equipment. The latest approaches in order to overcome complex situations is represented by the Digital Twin paradigm. This approach has among its main criticisms:1) the way of connecting physical reality and its digital replica and 2) the system for exploiting the combination of real-time data and digital applied intelligence for supporting operations on site. This paper proposes a framework for the development of digital twin of the construction site. An application of augmented reality that exploits the concept of diminished reality and workers location detection will improve visibility during critical operations.*

KEYWORDS: *Diminished reality; Augmented Reality; Health and Safety; Building Information Modelling; Digital Twin; Construction Site Management.*

1. INTRODUCTION

Safety in construction has always been a major issue that impacts the industry in terms of efficiency and cost. Construction is in fact one of the most hazardous industries due to its dynamic, temporary, and decentralized nature (Li et al., 2015). Among all economic activities, with the exception of oil, coal, and mineral extraction, the highest shares of serious incidents are recorded precisely in the construction divisions, which record rates above 35 percent. In the five-year period 2014 - 2018, compared to cases that occurred in other sectors, events in construction showed a higher prevalence of risk factors related to the predisposition of work environments (19% vs 12%) and procedures implemented by the injured (40% vs 47%) (Inail, 2022). These statistics focus our attention on two aspects: 1. The worksite is a place that by its conformation and nature carries a high percentage of risk; 2. The proper execution of procedures is a critical aspect that should be worked on to reduce its percentage of risk that is the highest among all (Li et al., 2015).

The traditional approach to safety also referred to as Safety-I (Martins et al., 2022) involves working to reduce the number of adverse events as much as possible. This most often involves using methods to counter or prevent the occurrence of misbehavior (e.g., audible warning systems on machinery) or to limit the effects should they eventually occur (e.g., individual and collective prevention devices). This approach involves having to envision all possible adverse scenarios so as to provide methods to counteract possible adverse outcomes. This is a continuous chase that however struggles to take into account a fundamental aspect that characterizes construction sites: their high complexity (Fang and Wu, 2013). Difficulty in standardization of procedures, complicated production processes, temporary organizational structure, relationships between stakeholders, and variable workplaces are some of the factors that contribute to the deep diversification between construction sites and other industrial production sites (Li et al., 2015). All these factors provide the backdrop for another crucial aspect that is encompassed in the concept of complexity and that is the need to manage the unexpected, which in terms of safety can be translated as dealing with new, variable and real-time risks and hazards.

In this context, the use of new technologies to collect and analyze real-time data from the construction site can be a disruptive innovation (Teizer et al., 2022). A push in this direction is also provided in the Italian context by Law 36/2023, which in Annex I.9, article 12 letter m states: *"In the formulation of information requirements by contracting stations, specific uses, operational methodologies, organizational processes and technological solutions may be defined as objects of evaluation for the purpose of rewarding, with reference to the execution phase of works, to digitally increase health and safety conditions at construction sites."* However, there are still unresolved issues in this regard that prevent widespread and pervasive use of these methods in the real environment. On the one hand, real-time on-site data collection itself encapsulates within it several problems: the sensorization of construction sites (workers, vehicles, materials), methods for collecting images that can be

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exploited to apply artificial intelligence, the possible need to have to provide power in the open environment to IoT devices, and the lack of a unified framework where to channel and integrate the collected data. On the other hand, information derived from analyses, short-term simulations or application of artificial intelligence should increase the knowledge of the stakeholders involved and thus in the interest of safety management they should be made immediately available on site in order for being used by operators, safety managers and site managers. This aspect represents a great complexity because making content usable on site requires finding quick and effective methods of communication both in terms of sending the data and visualizing it at the construction site. Augmented reality is a technology that has great potential in terms of visualization. Indeed, the use of holograms superimposed on the real-world view makes it possible to add an information layer that can show aspects not visible to the human eye or enrich knowledge with information from analysis of previously submitted data. In some cases, however, what is needed is not so much to add a layer of knowledge as to remove something that impedes the view. There is for this purpose a specific class of augmented reality that is called diminished reality (Cheng at al., 2022).

The purpose of this research is to apply the concept of diminished reality to construction sites in order to support operations with regard to risks related to operator safety. The proposed framework and the first experiments developed involved moving loads with a crane work scenario, including work at height, where the operator of the vehicle has a not fully unobstructed view. The application of see-through diminished reality allows the crane operator to visualize any worker placed in the vicinity of the load through the use of a depth camera and artificial intelligence. Innovations of the proposed system include: 1. Visualization by the operator not only of the relative position between workers and load but also of the orientation of the workers' bodies. This information makes it possible to understand whether the worker is aware that he or she is near a moving load or whether there is a risk of catching the worker by surprise (in case it is shown that the subject is with his or her back to the load). 2. An automatic procedure that transforms the visualization from solid to wireframe of objects that are opposed between the machine operator and human figures detected by the depth camera. In this way through a two-way line of communication and interaction between the actual construction site and a digital representation of it, a Digital Twin (DT) type approach will be achieved in which data obtained are processed and sent back, after the necessary analysis, directly to the site real time use. The system proposed in this article makes more sense at large, complex construction sites where the expected safety costs are higher and therefore allow for the implementation of new technologies.

2. LITERATURE REVIEW

The use of innovative technologies such as virtual (VR), augmented (AR) and mixed reality (MR) in the construction industry has found different levels of application due to the differences between them. Applications using augmented and mixed reality have long since found their use in construction sites. Chalhoub et al., 2018 proposed a method for electrical system component's location visualization on site using mixed reality and head-mounted displays. A similar way of exploiting MR is proposed in recent times also by Dallasega et al. (2023) for MEP components installations in general. A number of applications of AR and MR in construction sites still refers to way for showing design information or building components specifications in a more straightforward and easy understanding way (Carbonari et al., 2022; Yoon et al, 2022; Sabzevar et al, 2023; Pendersen et al, 2020; Um et al., 2023).

As far as worksite safety is concerned, however, most applications focus on the possibilities of leveraging these technologies for operator training. Boschè et al. (2015) proposed a novel MR system uniquely targeted for the training of construction trade workers. One of the aims of this paper was to enable trainees to experience construction site conditions, particularly being at height, in different settings. Anyway, the majority of these applications makes use of VR or Augmented virtuality (Wolf et al, 2022) which means that the operator is transported completely into the virtual world to carry out serious game-like experiences but without testing in the real world or with operations carried out live. Jelonek et al. (2022) developed a VR application for training operators in the use of cutting equipment on site introducing in the serious game procedures to follow in order to be sure that all the involved personnel is following all safety prescriptions. Wolf et al. (2022) developed a serious game for inspector job simulation in a complete virtual environment. Speiser and Teizer (2023) tried to move forward introducing the concept of digital twin for construction safety training in order to link various data sources to generate a Virtual Training Environment (VTE) automatically. However, few applications are yet attempting to bring these technologies on site to provide real-time assistance. Nguyen et al. (2022) started to work on skeleton recognition for action recognition on site but they have not developed an AR visualization on site yet. Eiris Pereira et al. (2019) combined training and augmented reality but directly on site for reporting situations with danger of falling from height.

One aspect that is still underemphasized in the construction world is that sometimes it can be very useful that information is taken away rather than added, and in this sense the application that should be considered is that of Diminished Reality (DR) (Mann et al., 2002). While AR and MR superimpose virtual objects on the real world to enhance reality by placing new objects among real objects or extending real objects with virtual objects (Mori et al.,2017), DR deliberately removes parts of a real-world scene or replaces them with computer generated information (Mann & Fung, 2001) and it can be considered a subtype of AR. Based on computer vision techniques, unwanted image elements are detected and replaced by other image elements, creating an overall plausible and consistent impression for the viewer. The idea in diminished reality is to virtually remove something from the view. There can be identified different techniques for diminished reality implementation. In one kind of approach the object to be removed needs to be detected and the corresponding image area needs to be filled in with a texture that seems to belong to the background. In image processing terms, this kind of filling-in operation is called image inpainting (Siltanen, 2017). Another approach discusses a way of representing occluding objects as semi-transparent. This visualization technique is called AR X-ray vision, see-through vision, or ghosted views. Semi-transparent representation is useful for seeing through car interiors and walls (Mori et al., 2017). In automotive settings, a number of see-through displays have been incorporated. In Samsung's Safety Truck, for example, live video images were displayed on the back of the truck, effectively granting trailing drivers the ability to 'see through' the truck.

The very first approaches to DR aimed to lower the saturation of some areas to force an observer to face other regions and virtual objects overwrote undesirable real objects to hide the real information (Mann, 1994). After that this technique was used for different purposes: to remove a person from Google Street View pictures to protect his or her privacy, to remove a person in a video, to remove a vehicle in front of the driver, to remove a baseball catcher to visualize the view of the pitcher from a view behind the catcher, and to generate a panoramic stroboscopic image (Mori et al, 2017). In the case of see through applications one of the methods to provide the current state of the hidden area in the main view is the same as that used by Zokai et al. (2003) that used two additional cameras as hidden background observers to erase from the main view pipes in a factory. Mori et al. (2017) constructed light fields with a real time multi-camera system and removed a viewer's hand from the perspective to visualize the viewer's workspace occluded by his or her own hand. Queguiner et al. (2018) presented a diminished reality application running live on consumer mobile devices. In their pre-observation-based approach, the clean 3D scene, free of undesired objects, is scanned beforehand and reconstructed as a high-resolution textured 3D model. Many see-through DR literature tends to investigate more computationally efficient approaches focusing on compensating real–virtual boundary in screen space. Thereafter, semi-transparent or wireframe representation is performed to improve user depth perception. These representation methods will be useful for avoiding the danger of a collision with the diminished objects. In this regard, Peereboom et al., 2023 presented a system that exploits DR for avoiding collisions between pedestrians and cars caused by poor visibility, such as occlusion by a parked vehicle. In one of the solutions, they proposed the occluding vehicle has been made semi-transparent. Still recently, Cheng et al. (2022) proposed a study on users' perception of diminished reality and its possible applications.

However, the concept of DR is still little exploited in construction although Klinker, Stricker and Reiners (2001) develop the first examples of diminished reality in the field of construction with two very significant examples: in the first one TV antennas located on a hill are removed from the view within which the work that will replace them is later placed so that it can be visualized in its chosen location. In the second case given as an example, the installations below a wall are shown in the form of holograms.

This research aims at exploiting the concept of diminished reality for construction sites operations efficiency and safety. The innovation of the system proposed lays in the combination of skeleton recognition, which provide operators position and field of view, and the automatic procedure that detect obstacles and made them visualized as a wire frame model. The integration of different technologies for onsite application is also another key aspect.

3. DR FOR CONSTRUCTION SITE SAFETY MANAGEMENT SUPPORT

The system proposed in this research is a diminished reality application for supporting safety management at construction sites. The development focused on a specific case and that is load handling by crane. In the case of cranes maneuvered from the ground, but not only, there are situations in which visibility can be reduced: work at height in which the support is not clearly visible, maneuvers on the construction site in which the placement of material takes place beyond already built constructions. For this reason, a viewer that supports the operations coordinator in visualizing possible hazardous situations can assume great value (Fig. 1). To this end, we focused in this work on visualizing workers in locations hidden from view.

It was decided to proceed with localization and visualization through depth camera with a twofold advantage: on the one hand, this instrument returns the skeleton that allows us to understand how the worker is placed and oriented; on the other hand, the fact that only the skeleton is communicated removes a number of privacy issues. In this system then it was planned to also instrument moving loads, with sensors (UWB inside and RTK outside) in order to be able to communicate this data to the operations coordinator as well. Finally, the developed application involves the transformation of the obstacle object visualization from solid to wireframe. Such a system finds its application not only in the highlighted case but also in many other site operations such as demolitions where knowing what lies beyond certain elements could be crucial.

Fig. 1: Diminished reality for construction site.

4. METHODOLOGY

The methodology followed in this research for improving the safety of workers in construction sites through the exploitation of DR is shortly described in Figure 2.

The first step is setting up a localization framework covering the entire construction site. Such framework should be a *real-time system* capable of attaching spatial coordinates to any entity, object or person, moving around in the construction site. The specific technology employed for this step can vary depending on several aspects, e.g. whether the construction site is outdoor or indoor, or whether we are considering an existing facility to be recommissioned or instead a new building or infrastructure to be built. For complex scenarios, multiple technologies may coexist at the same time to localize objects and people in different areas of the overall construction site. In such a case a problem arises of allowing a seamless integration of different localization systems to provide a homogenous notion of localization on the construction site. The core idea behind the localization framework is to support the detection of safety hazards so as to prevent incidents.

A second step of the methodology is the setup of a heterogeneous network of sensors continuously monitoring the activities in the construction site. The sensor network may employ very different devices both for their technological characteristics and for the kind of data collected (e.g. temperature sensors, cameras, NFC tags, etc.). The basic requirement for each sensor in our methodology is that it must be able to attach a precise timestamp and a precise set of coordinates relative to the localization framework set up. This would witness when and where the information was sensed in the construction site.

A third step is the setup of a DT Platform integrating several sources of information operating on and off the construction site. For instance, interpolating information coming from the construction design together with data collected by the network of sensors the platform can provide the most updated "picture" of the building or infrastructure being realized. The DT Platform is also responsible for managing and harmonizing the several data models used to express the information coming from the different (internal and external) sources, e.g. by using linked data or ontology-based semantic data integration procedures.

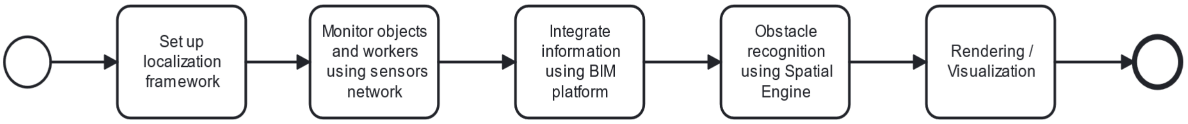

Fig. 2: Methodology for applying Diminished Reality to construction site safety.

Next, a Spatial Engine should be implemented that processes all the spatial information from the BIM models, the persons equipped with DR viewers, the sensors deployed through the site, the vehicles and all the various agents acting within the site. Given the position of a person using a DR viewer, its main role is to determine which agents and BIM objects are of interest for him/her and to provide the corresponding data streaming. Moreover, by exploiting the information stored in the CDE, the Spatial Engine is the place where possible spatial interferences can be detected, forecasted, and notified at run time to the involved agents in order to prevent injuries.

Finally, a DR visualization tool is in charge of rendering holograms mixed with the real objects of the construction site in order to allow the observer to view also those hidden objects that can be involved by the ongoing operations. The obstruction is determined in real-time based on the observer's point of view and the position of the moving objects given by the sensory data: when a BIM object is hit by the ray joining the observer with a moving object, this BIM object is classified as obstructing and it is rendered as wireframes thus making visible the virtual objects behind it that reproduce their invisible real twins.

In the following sections this methodology is applied starting with the indoor localization framework. The sensor network has been set up with a depth camera and two location tags. The former is a special computer camera with two "eyes". By merging the visual information coming from them, it can compute the distance (or depth) of objects and bodies w.r.t. its point of view, when they appear in the picture. The chosen depth camera also provided advanced artificial vision software capable of recognizing the position of core joints in the skeletons. This information can be exploited to know the real-time position and orientation of an individual or of a crew of workers. As a consequence, it is possible to relate this information the one coming from the tag attached to the load lifted by the crane in order to know the exact relative position and the risk of the workers to be hit. A mixed-reality head-mounted display (HMD) is used as visualization tool where the BIM model of the construction site and signals coming from the sensor network (e.g. the position of the workers in the construction site coming from the depth camera, as well as the position of the depth camera itself, and of the crane load) are downloaded from the DT platform together with the spatial simulation results. Also the head-mounted display DR application can download from the DT platform information about the 3D objects that hinders the view of workers and the load when the crane is operating thank to ray-tracing data transmission. The ray-tracing technique uses basic geometry in order to select all the 3D objects (e.g. walls, doors, columns, etc.) that lay in between the user viewpoint and the objects returned as obstructions (i.e. the workers and the crane load) and then the platform sent them back made transparent in a wire frame visualization.

5. SYSTEM ARCHITECTURE

The architecture of the system proposed in this paper is the one depicted in Figure 3. In accordance with what was previously described in the methodology paragraph in this section the specific devices and components of the system will be made explicit. For what concerns the localization of the operators, we chose to use a depth camera and specifically a ZED 2i. This device made possible two things: 1. recognize the skeleton of the workers; 2. place the skeleton in the virtual space once the position of the camera in the real space is known. The ZED 2i camera provides the streaming of the joints of the skeleton, which were set equal to 18 points.

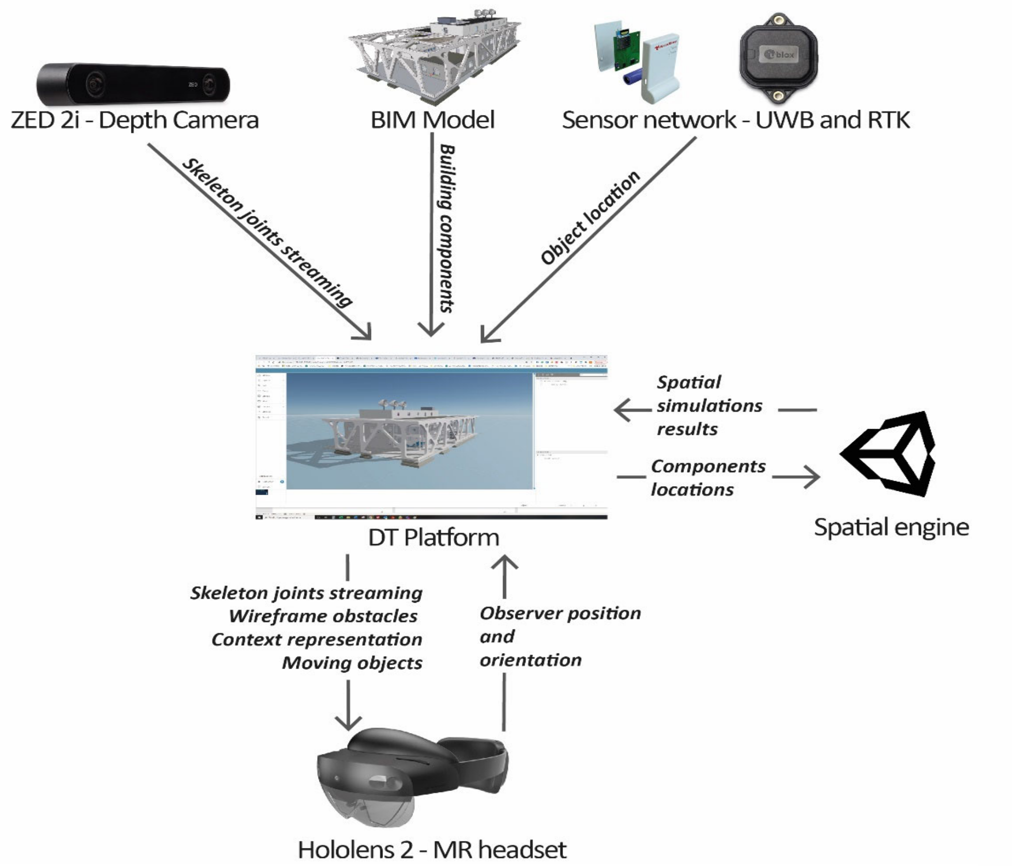

Fig. 3: System architecture and data flow.

For space modelling it can be used a BIM model provided in ifc format. This type of space modelling contributes in modelling the different building components enabling at a later stage to go and select one by one the objects that represent obstacles to workers visualization. In the development here proposed, Autodesk Revit was used for BIM modelling. Moreover, in the case of the construction site where the presence of the elements is dependent on the progress of the work, the combination of ifc files with a timeline also makes it possible to analyse what would be visible and what would not be visible at a precise moment in the construction.

Finally, since not only the workers need to be located but there are other components of the worksite whose location is important to know, a number of sensor networks can be implemented. These vary as needed. In the case taken as an example in this article, two types of sensors were referred to: GPS RTK tags and UWB tags. Although the GPS RTK localization system could not be integrated into the indoor tests reported in section 6, its suitability for outdoor applications is shown by its quite high accuracy reported by technical sheets [Datasheet], which was confirmed by very preliminary trials performed by the authors. But this is going to be used in future research developments. For the purpose of the indoor tests subject of this paper, contextual infrastructure was monitored by means of UWB anchors. In any case, it is worth remarking that both types of sensors can be used to communicate position data.

Moving on to the other components of the system, a platform, resulting from the development of the research project "A Distributed Digital Collaboration Framework for Small and Medium-Sized Engineering and Construction Enterprises" (PRIN 2017), is used. This platform uploads BIM models in ifc format, allowing browsing and querying. The platform then allows the integration of data from a variety of heterogeneous sources (in this case skeleton joints from ZED 2i and location data from sensors) allowing them to be located in space or linked to components (e.g., modeled building objects). In this way it is configured as a real DT platform.

As for the spatial engine, this receives the necessary information and thus the positions of workers and moving objects (provided by UWB or GPS-RTK). The purpose of the spatial engine is to perform real-time processing about spatial interference and then transmit it to the platform, which will also relate it to the components of buildings in space so as to identify objects of obstruction to operator's view.

Finally, the last component of the system is an MR head-mounted display whose use has two purposes. The first is to enable the display of holograms for a diminished reality visualization. The second is to provide the position and orientation of the observer. The Microsoft Hololens used as the MR provider receives the information directly from the platform and thus the visualization of the skeleton joints, the model of the surrounding environment, the positions of moving objects, and objects identified as obstacles and whose representation is then modified by the procedure to change from solid to wireframe. In order to achieve a consistent visualization, the Hololens transmits to the platform the position of the operator with respect to the modelled space and information about the orientation of the head. In this way it is possible to precisely calibrate the sample scenario.

6. DIMINISHED REALITY APPLICATION

The experiment was conducted using a Python application sensing the skeleton information coming from the depth camera ZED 2i through the Python SDK. In this application, the camera acquired two video streams at 30 fps, and once every 3 frames the skeletons information where encoded as JSON objects and published using the MQTT protocol. For debug purposes, the position of workers' skeleton joints where highlighted in a live video stream (Fig. 6 b). This resulted in 10 MQTT messages sent per second. The DT Platform subscribed the topic on the MQTT broker, thus receiving the skeleton signal from the Python application. The DT platform was in charge of sending the skeleton signal as well as the BIM design and the location of the camera, the Head Mounted Display, and the object moved by the crane, to the Spatial Engine. The latter was responsible for detecting in real-time the list of obstacles in the BIM design and passed it to the Head Mounted Display, together with the position of the workers and the crane load w.r.t. the Head Mounted Display.

The logic behind the Spatial Engine detects obstacles using ray-casting, a technique implemented by the Spatial Engine which returns a list of objects hit by a hypothetical ray departing from a source position towards a given direction, and having a length bounded by a given maximum value. To reach our aim, we need to use the user's viewpoint as source position of the ray-to-be-casted, next we need to cast a ray on each direction corresponding to each joint of the workers skeletons detected by the depth camera and each object moved by the crane; finally, we must set as maximum length of the casted rays the actual distance between the user and the joints or moved objects.

7. DEVELOPMENT AND CASE STUDY

Feasibility tests of the developed application were carried out in the DC3 laboratory of the DICEA department of the Polytechnic University of Marche. In this case since a crane was not available, the overhead crane carriage inside the laboratory was used to simulate the suspended load in motion. The hook of the bridge crane was instrumented with a UWB position sensor which sends data to the platform (Figure 4). The laboratory is equipped with UWB anchors placed at the corners of the room for precise position sensing.

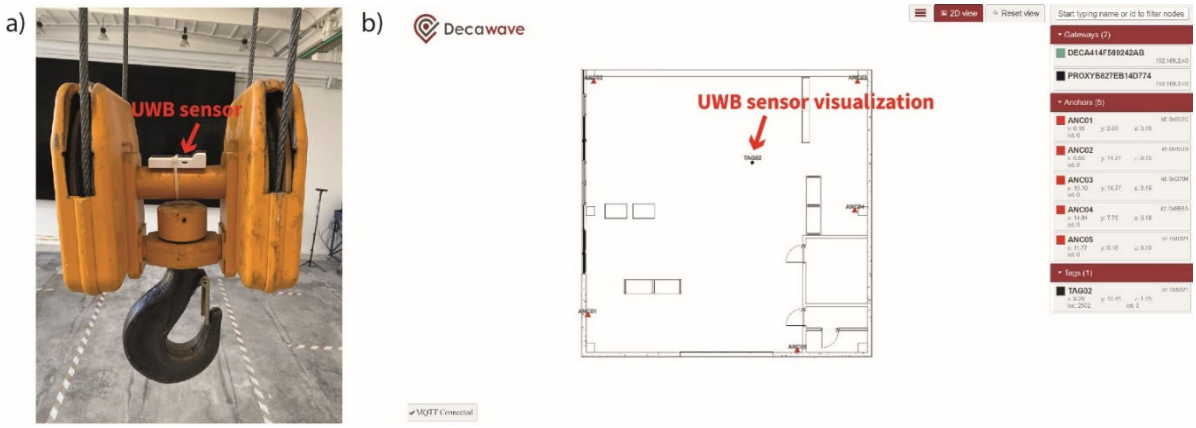

Fig. 4: a) Bridge crane hook instrumented with UWB sensor; b) UWB sensor visualization in the space inside the platform.

Next, the ZED 2i camera was placed as seen in Figures 5 and 6 a). The information that the chamber returns through the recognition of the skeleton joints is as in Figure 6 b). The orientation of the worker is also detected as the blue joints detect the left side of the body while the red joints detect the right side. In this way it is possible to understand which direction the worker is looking at and thus whether in the presence of a moving load he is presumably aware of the presence of the load or whether his being from behind identifies a situation of greater danger as he may not have noticed that something is moving in his vicinity.

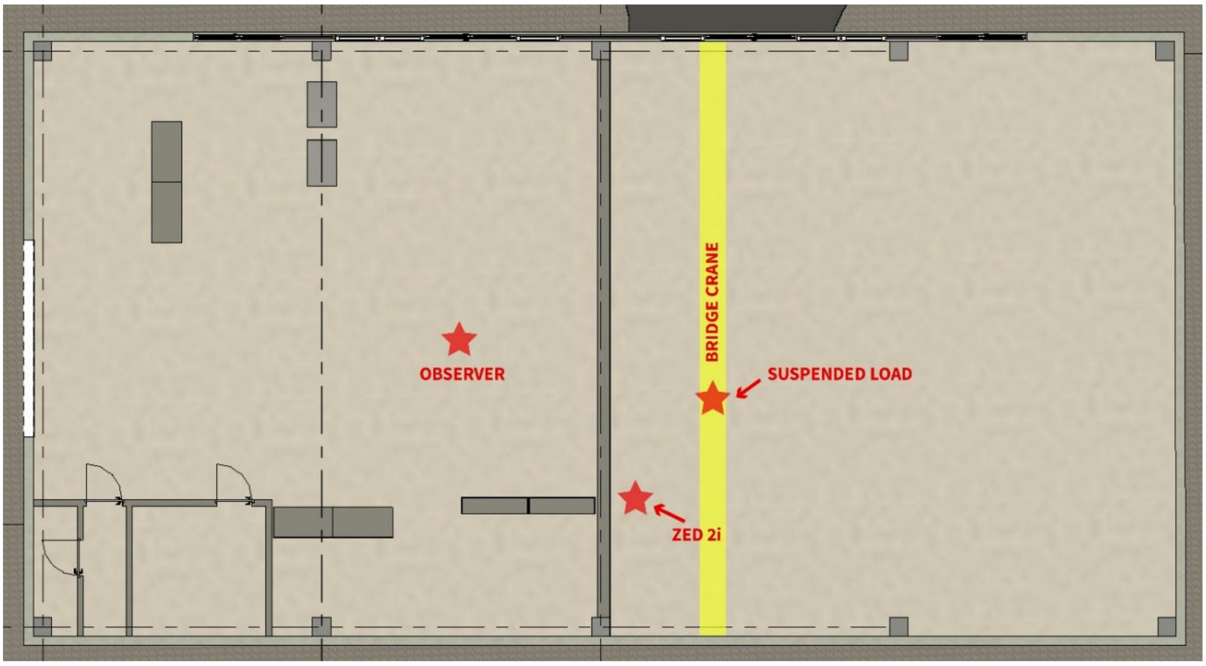

Fig. 5: Components position inside the laboratory.

The test performed reproduced the same conditions shown in Figure 1. The laboratory is placed in a shed divided in half by a wall 3.5 m high, about half of the total height of the structure. Figure 5 shows the location of all components for the experiment in the laboratory. In order to verify the actual operation of the application for the developed diminished reality, the operator wearing the HoloLens stood on the left side in the floor layout of the shed. Looking toward the partition wall (Fig. 7 a)) the HoloLens showed the wall in wireframe visualization and the skeleton points of the operator who was moving around the load on the other side of the room. In this first processing the positioning of the load was not implemented in the hologram visualization although it was present as data in the platform. Again, it is possible to observe the differentiation of blue and red colours for the left and right side of the body respectively which allows the worker observing the scene to understand the orientation of the worker.

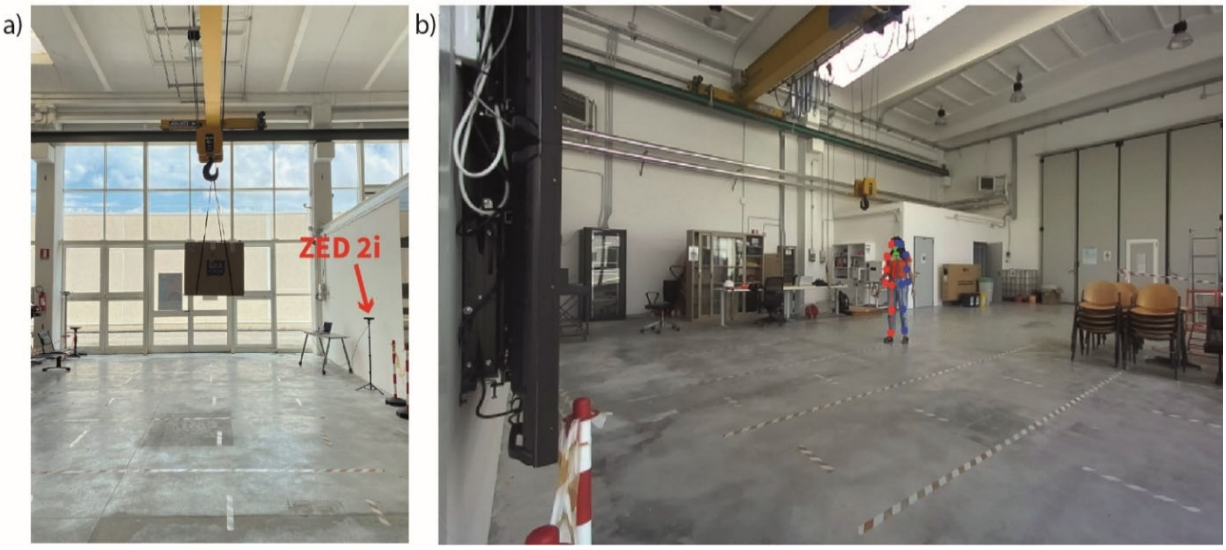

Fig. 6: a) Load position and ZED 2i location; b) Depth camera vision and skeleton joints recognition.

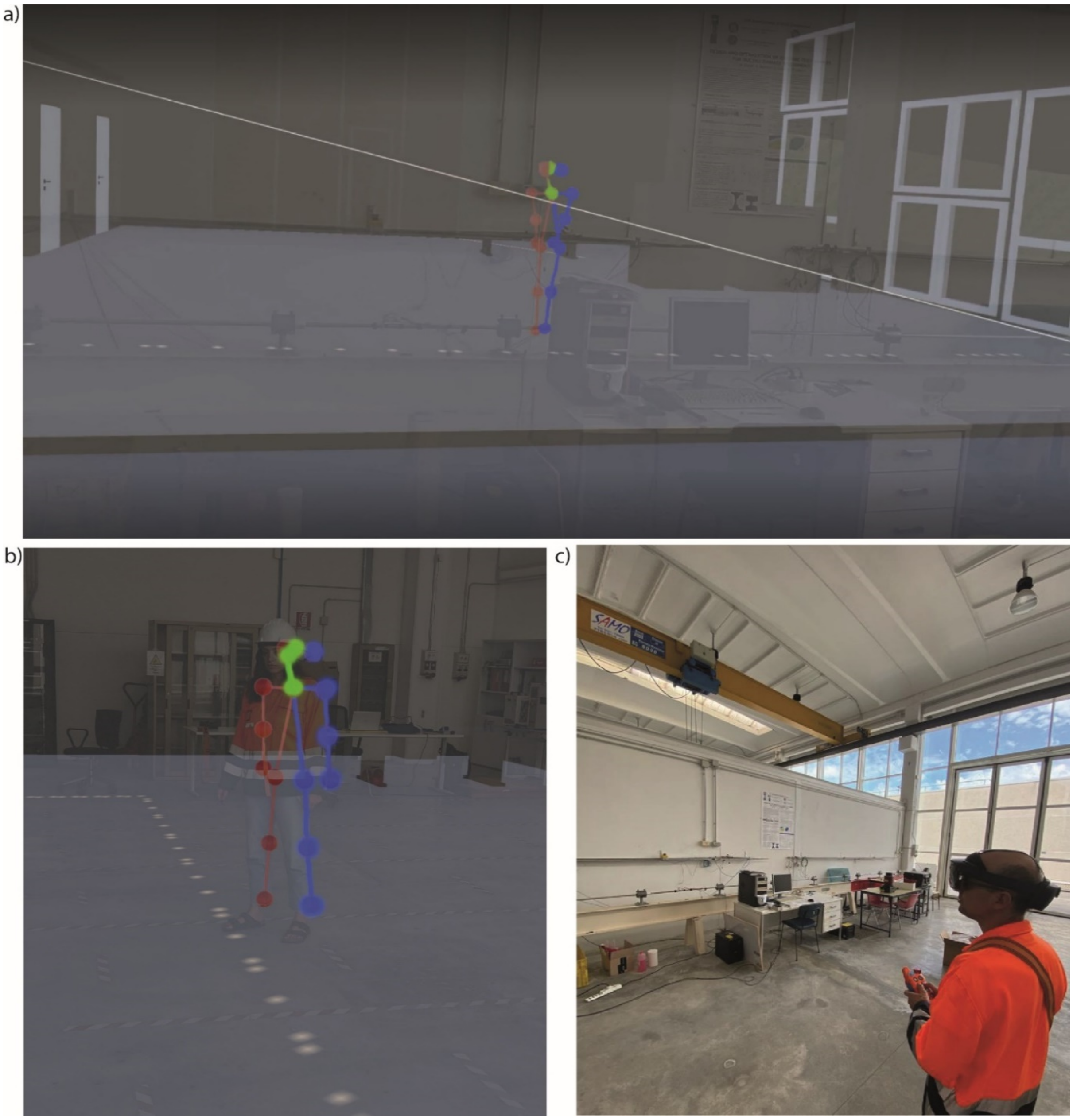

Fig. 7: a) Vision from inside the HoloLens (other side of the wall) ; b) Vision from inside the HoloLens (same side of the worker framed); c) operator with the HoloLens and the bridge-crane remote control (other side of the wall).

8. CONCLUSION

This paper presents an application of diminished reality for safety management support during operations at a construction site. The proposed system involves the use of depth camera and sensors for locating components of interest and implements the development of a DT platform for real-time management. The system thus developed allows for optimization in the number of sensors that can be placed in strategic areas (depth camera) and alternately on moving loads or equipment to be monitored at the stages when they are expected to be utilized. Initial experiments of the application of this development were carried out in the laboratory by reproducing conditions similar to those at a real construction site. The next steps will concern the implementation of the visualization inside the HoloLens of the position of the moving load and tests in outdoor construction sites thus having the possibility to test also the visual rendering of holograms in the open air that could be an obstacle to the optimal visualization for operators.

9. ACKNOWLEDGMENTS

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