This project has received funding from the European's Union Horizon 2020 research innovation programme under Grant Agreement No. 957258

Architecture for Scalable, Self-*, human-centric, Intelligent, Secure, and Tactile next generation IoT

ASSIST-IoT Technical Report #7

Exploiting Mixed Reality in a Next-Generation IoT ecosystem of a construction site

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Submitted to: ACM MMSys 2022, Athlone, Ireland (14-17 June 2022)

Exploiting Mixed Reality in a Next-Generation IoT ecosystem of a construction site

Occupation Safety and Health monitoring

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ABSTRACT

Ensuring smart safety of workers in large construction sites calls for centralized ecosystems, supported transversely by security, privacy, and trust enablers, to facilitate data sharing and protect the growing attack surface. At the same time, human-centricity and interaction with IoT ecosystems have to be a core part of the process. Mixed Reality (MR) applications allow the execution of context-aware applications with advanced interaction interfaces improving decision making, data gathering, interoperability with other services, accessibility, and real-time data sharing. We leverage the advanced features of MR interfaces and interoperability with IoT systems to contribute towards a more usable, functional, and perceptive human-centric Next Generation ecosystem in large construction plants aiming to contribute to workers' health and safety during inspection processes. In this study, an MR enabler is designed and developed to collect data from various sources of such an ecosystem. The main objectives are to identify workers in large construction sites and their medical and training records, get real-time information regarding their stress and health levels, and alert when dangerous activity is being performed, or a worker reaches an unauthorized location. At the same time, the MR enabler allows the visualization of BIM models, their digital representations and data, as well as the submission of reports. The MR enabler, connected to other components within the Next-Generation IoT ecosystem, will be applied to various construction sites in Poland.

KEYWORDS

Mixed Reality, Health and Safety, Construction, IoT, Next-Generation, BIM

ACM Reference format:

Tina Katika, Fotios K. Konstantinidis, Thomas Papaioannou, Aris Dadoukis, Spyridon Nektarios Bolierakis, Georgios Tsimiklis, Angelos Amditis. 2022. Exploiting Mixed Reality in a Next-Generation IoT ecosystem of a construction site: Occupation Safety and Health monitoring. *ACM, MMSys 2022, 14th-17th June, Sheraton Hotel, Athlone Ireland.*

1 Introduction

According to the European statistics on accident at work (ESAW), the highest incidence of non-fatal accidents at work in the EU was observed in the construction sector, with 2876 accidents per 100.000 employees [1]. Almost one-third of EU fatal accidents at work resulted from losing control of a machine, tool, and transport/handling equipment [2]. The high rates of construction incidences have significant social and economic impacts, led by a loss of lives and profits. Recent review studies connected these incidents to the lack of preventive and proactive measures within the construction plants to identify risks and hazards, lack of risk identification, safety awareness, proper training and education ([3], [4]).

The high numbers of accidents indicate the need to undertake new measures to enable quick, precise, and secure monitoring of hazards at the construction sites, analyze the risk, and provide an appropriate response to the needs.

Modern technologies, manipulating visual elements, have a great potential in various safety-related applications such as training, hazard monitoring, and preconstruction planning, as they can seamlessly integrate with construction and other safety management processes. In particular, mixed reality (MR) technologies have learning capabilities that guarantee predictions of possible dangerous situations based on individual workers' physiological reactions, their behaviors and interactions with other workers, machines and tools, and can potentially demonstrate very promising research direction in accident prevention [5].

The construction industry has already adopted some innovative technologies related to, e.g., worker location tracking or warning signalization; however, Occupational Safety and Health (OSH) performance remains on a low level (e.g., [6]). Nowadays, construction management has significantly advanced towards digitalization, where Building Information Modelling (BIM) not only offers a holistic approach towards asset and building management but also impacts construction safety and health at different stages of the construction [7]. BIM is a digital information management system that offers the methodology to manage design data in a digital format to be used throughout a project's life cycle. In this field, a combination of digital innovations collectively called the Internet of Things (IoT) brings new emergent needs and capabilities that drive the construction industry to adapt, ensuring the availability of information from sensors to improve decision quality as has never been previously possible at such a scale [8]. Therefore, the need for an innovative approach that combines OSH aspects with combined digital innovations and BIM has appeared.

With advanced immersive technologies, particularly the recent development of lightweight, commercially available Microsoft HoloLens 2, MR offers a unique opportunity to enhance safety communication in construction. Such novel interfaces offer human-centric interaction through better interaction of their end-users with the IoT environment. MR provides the advancement of introducing the human effort and decision, if and when needed, in the loop of every critical decision. Thereafter, the MR end-users can receive and provide tactile, real-time, and visual feedback as well as data capable of identifying essential improvements, preventions, and triggers in long-, short-term, or real-time. MR allows reliable data gathering to extract information and perform analytics through reporting functions. Decision-making is improved as human flexibility, creativity and expertise, interact with IoT platforms and devices.

Despite the potential of MR, its use and performance in real site scenarios, where the health and safety of construction workers is one of the highest priorities, is scientifically unknown. Therefore, the aim of this study is to assess the feasibility of applying MR to improving safety management and communication on construction sites from an industry perspective following three objectives:

1. Integration of MR to a Next-Generation IoT ecosystem of a large construction site.
2. Real-time and near-real-time feed of information.
3. Visualization of BIM models, alerts, dangerous zones, and other risk factors.

The paper is structured as follows. First, we discuss related work and highlight limitations of the current health and safety processes in construction plants. Next, we provide the methodology applied to the design and development of the MR enabler. Connectivity to the entire Next-Generation IoT ecosystem of the construction site, as well as the MR enabler system design are included in the same section. We conclude our paper by presenting the use case that the MR enabler will be applied and the selected workflow of information, along with an evaluation of the progress and limitations.

2 Related Work

Construction plants are dynamic and complex and involve a large number of processes while offering employment to many workers in various fields. Construction work often involves long working hours without sufficient breaks under unfavorable weather conditions for many workers. Safety management is often employed to improve safety policies, processes, and practices while regulating construction activities and controlling the risks and hazards [9]. Visualization technologies (such as virtual and mixed reality, BIM, and CAD designs), are often linked to safety management. In particular, augmented and mixed reality have been applied to various projects and proposed to research studies the past decade, as the MR interfaces become readily available, user friendly and accessible [5]. Researchers have proposed mobile AR solutions not only for managing a construction project (e.g., [10]), but also for maintenance procedures (e.g., [11]) as well as safety and visualization (e.g., [12]).

Regarding the devices that are designed to offer endless MR capabilities, the head-mounted devices have gained traction in the past decade in construction management, maintenance, and safety, as they provide several benefits compared to hand-held devices [13]. Newly developed interfaces offer head tracking fidelity, high visual resolution, user mobility, hand and eye tracking fidelity, a number of input modes, adaptability of input. At the same time, such devices have high-resolution displays, advanced sensors, audio and speech recognition, and spatial mapping while being able to connect over network and Bluetooth to other devices. Their small size and weight make them suitable to fit under the construction gear, ensuring the end-user's safety. In the past decade, MR has attracted growing research interests within the Architecture, Engineering and Construction (AEC) community ([14], [15], [16]). MR has also been proposed in the field of construction operations where timely and accurate decisions affect machine operations and, therefore, the safety of the operator. Besides, MR interfaces have been exploited to simulate risky construction workplaces to extract valuable information regarding risk-taking behaviors and safety interventions [4].

Despite the technological advantages of MR and the several proposed efforts, Hang et al. l., [13], in their recent review in the field of MR in architecture and construction, demonstrated that the industry lacks applications able to provide the appropriate features to the end-users. The key features consist of adjusting a BIM model in size, repositioning models and items, providing real-time sharing of information, and determining real-time geographical location. Other limitations and the lack of required features in the already available MR applications have been demonstrated in the critical review on construction safety by Li et al., [4]. Their analysis concluded that an effective MR solution for the safety management at a construction site should include the alerts to create information-rich experience, be able to achieve high interoperability between MR systems and other ICT tools in a site to display and information retrieval of construction safety, be able to respond immediately to workers during incidents, identify potential risks, connect to a complete project-level human-computer interaction environment, and be able to offer automatic evaluation process and method.

It is therefore apparent from the literature that MR interfaces have the potential to simplify complex processes in construction planning, architectural design, and provision of high-fidelity procedures for health and safety monitoring purposes, enabling the integration of construction processes and bridging the communication gaps between project design, development, implementation, and maintenance. At the same time, limitations and other bottlenecks in introducing MR to improve the health and safety in a construction site need to be addressed and improved.

3 Methodology

In this study, Microsoft HoloLens 2 was selected to develop the MR solution to monitor and improve the health and safety of construction workers and minimize their exposure to risk factors. The MR solution, thereafter, MR enabler, is designed to fit the Next-Generation IoT ecosystem of a large construction site, aiming to provide a safety net to each individual present at the sites and their surrounding area. The MR enabler will be mainly utilized by

the Occupational Safety and Health (OSH) inspectors aiming to contribute to the overall health and safety management.
The enabler proposed focuses on human-centric safety aspects and involves connected wearables and real-time monitoring of relevant health and safety information while emphasizing personal data protection and user-friendliness. The enabler offers timely information upon risk identification and contributes to the evaluation process. The current practice aims at minimizing intrusiveness that causes distraction from ordinary activities and contributes to the distribution of real-time information.

3.1 The Next Generation IoT Architecture

The MR enabler is part of a large Next-Generation IoT ecosystem that will be applied to large construction plants. To further define the overall conceptual architecture, we utilized a multidimensional, conceptual approach and divided the overall ecosystem into separated architectural layers depending on their functionalities (Figure 1).

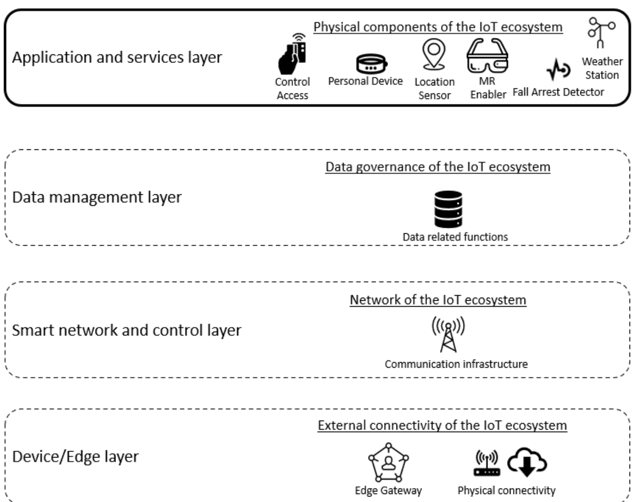

Figure 1: The four layers of the conceptual architecture of the Next Generation IoT ecosystem. The MR enabler is part of the first layer regarding the applications and services.

The main architectural layers of the Next-Generation IoT architecture are the *device and edge*, the *smart network and control*, the *data management*, and *application and services*. The MR enabler interacts with all layers. The *device and edge* layer describes the collection of functions that can be logically appointed to physical components of IoT, including the smart devices, sensors and actuators, wearables, edge nodes, as well as network hardware, such as hubs, switches, and routers. Thus, the MR enabler, consisting of wearables, is part of this overall layer. The *smart network and control* layer manages virtual and wireless aspects of network connectivity, handling technologies that deliver software-related and virtualized networks. The MR enabler relies heavily on connectivity to the other IoT components to retrieve necessary information in a timely manner. The *data management* layer handles all functions in which data are acquired, delivered, and processed to provide key data-related functions. The MR enabler receives and publishes data to the OSH inspector stored in long-term storage, and also comes in real-time or near-real-time format from various sources. The *device and edge* layer contains the physical and tangible components of the interconnected ecosystem and handles external physical connectivity.

The MR Enabler located in the *application and service* layer uses the Edge Data Broker (located in the *data management* layer) to receive real-time information and alerts (Figure 2). Considering that the Edge Data Broker is the "common middle point" in which the IoT devices of the construction plant continuously publish their data, it allows the subscribers (such as the user of the MR enabler) to consume them based on their needs. Due to scriptable features, data can be analyzed on the fly, and the publishers receive alarms or special events that are enabled by predefined conditions. This condition-based intelligent functionality is why the MR enabler primarily relies on the Edge Data Broker to collect the required data for its functionality. Their smooth integration enables edge-based filtering and decentralized data-consuming policies that significantly reduce the data traffic. In case of required communication with other components and devices (e.g., MR devices, Gateway, IoT devices), this is enabled through the smart network and control layer.

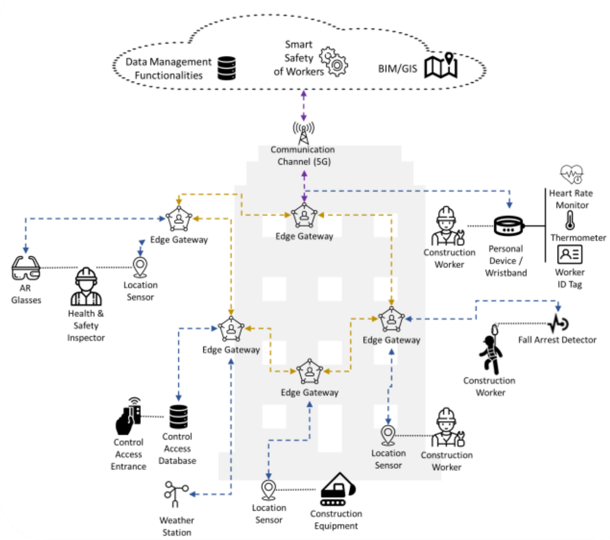

Figure 2: Graphic representation of the Health & Safety inspection support. The MR enabler consumes data from the Edge Data Broker. The data are either generated by IoT devices or transmitted from the cloud where other IoT intelligent functionalities have been deployed. The blue dashed lines represent the wireless communication between the gateway and the IoT devices. The interconnection among the pods of the Edge Data Broker is shown with yellow dashed lines. The gateways are communicating with the rest of the IoT

Architecture using the local telecommunications infrastructures.

3.2 MR enabler system design

The MR enabler is a 2-part solution, as shown in Figure 3. A web interface allows the creation of a configuration layer defining how and where the MR application must connect to communicate with the other components/layers of the Next-Generation IoT ecosystem installed to a construction site. Upon successful connection to the Edge Data broker, the MR enabler starts receiving data and translates it in a format suitable for visualization through the head-mounted MR devices (Microsoft Hololens 2). Data, from long-term storage or real-time data streams, are requested according to its relevance to the user at a specific time and location (such as the BIM models or the physiological parameters). To display the data and information via the MR device, the authorization and access rights of the end-user are taken into account. The MR enabler not only allows user interaction with virtual elements to complete tasks such as generating Health and Safety reports and inspecting information related to construction site workers but also allows the user to manipulate the 3D model rendered in order to provide better understating of the information linked to it.

As shown in Figure 4, the OSH inspector assesses their authorization and localization status through the glasses. They also access the BIM models and the dangerous zones, acquire the necessary information regarding the construction workers, and receive alerts on various risks and hazards, and finally do reports. The MR interface is designed to be user-friendly and accessible, while extra caution has been granted to ensure that it fits under the protective gear in a non-invasive way.

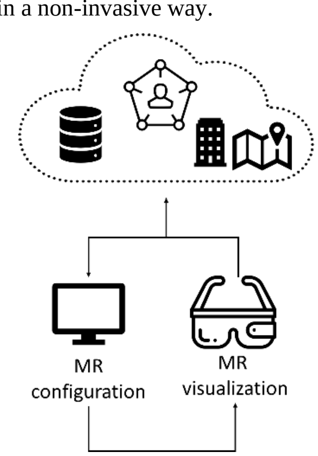

Figure 3: The three interactive components of the MR enabler: data input from various sources bringing the necessary information related to health and safety (storage, cloud, real-time etc.), data configuration through the MR configuration interface and visualization and customization of content through the MR device.

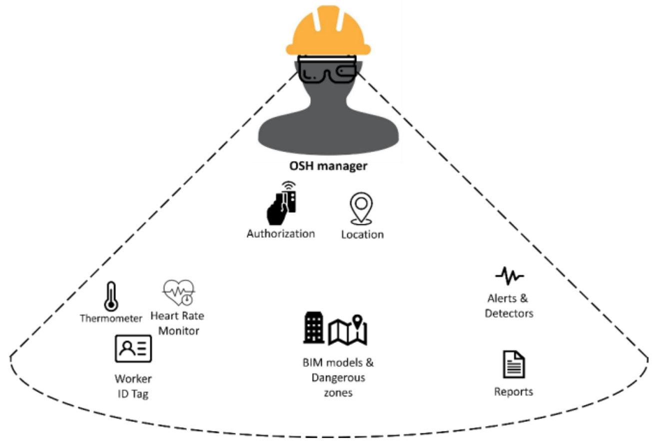

Figure 4: A mock-up of the MR Health and Safety inspection application; along with the features and applications available for the end-users (OSH inspectors).

3.3 Connection of the MR enabler to the IoT ecosystem

In the construction deployment, the MR enabler is a standalone native application that is being deployed on a head mounted device to monitor and protect the construction workers' health and safety and notify the OSH inspector about incidents or undesirable behavior in the construction site. At the same time, the MR enabler visualizes information from the BIM model, including construction components and dangerous zones. The MR enabler collects, curates, and then displays the required information regarding the construction site and the workers. More specifically:

- The physiological parameters of the construction workers are being monitored in real-time using wearable sensors to ensure that their health and safety are protected at all times while at the construction site. Critical information, such as health abnormalities, reaches the MR enabler through the Edge Data Broker.
- Edge processing units locally assess the worker's fatigue and stress levels through federated learning schemas without transmitting sensitive information to a central location unless a serious incident occurs. The information reaches the MR enabler through the Edge Data Broker.
- Measurements and information related to the worker's identity, training, and medical expiration dates, as well as their assigned activity for the day, are collected, and then the information reaches the MR enabler from the Long-Term Storage.
- Environmental conditions are also taken into account, such as ambient temperature and UV radiation. Sensors in the construction plant are responsible for recording the data, and the information reaches the MR enabler through the Edge Data Broker.
- The construction workers' location within the construction site is monitored so that first responders can

be sent in case of an emergency. The information reaches the MR enabler through the Edge Data Broker.

- Geofencing services are also supported to ensure that construction workers move around areas where they are authorized and trained. The information reaches the MR enabler through the Edge Data Broker.
- Interactions between construction workers and construction plant are continuously monitored as the system. The system is able to detect when a construction worker operates in the construction plant or when getting to a dangerous zone. Then the information reaches the MR enabler through the Edge Data Broker.
- The main gate to the construction site, and other secondary access points (gates and doors), are controlled. Authorized construction workers and vehicles (e.g., excavators) are permitted to enter and through the Edge Data Broker information reaches the MR enabler.
- A fall arrest detector is attached to the construction worker when they are working at height, such as at an aerial lift. An activation detector identifies fall events alerting stakeholders rapidly and through the Edge Data Broker alerts the user of the MR enabler.

4 The Use Case

The aforementioned data and information are continuously generated at a large construction plant following the IoT ecosystem process. In such a plant, the construction workers are equipped with personal edge devices, while vehicles, such as trucks, are equipped with localization devices. An access control unit is mounted at the entrance, controlling the authorized access to the construction plant. A weather monitoring station is also installed to monitor UV radiation. As presented in Figure 2, the various systems are interconnected through gateways where pods of the distributed Edge Data Broker are deployed. To demonstrate and validate our solutions and interoperability of the MR enabler, a construction plant located in Poland, following the above-mentioned processes, will enable our performance and evaluate the proposed workflow.

4.1 The MR enabler Workflow

The main course of data, including location and proximity data, physiological parameter measurements, weather conditions measurements, personal identification information, training and medical records, building information, users' thermal comfort preferences, alerts and notifications, are displayed through the Microsoft Hololens 2. Upon collecting the necessary information, the following steps can be followed from the device's end-user (in our case, the OSH inspector). Figure 5 demonstrates a potential journey of the MR enabler end-user utilizing the main features and functionalities of the software.

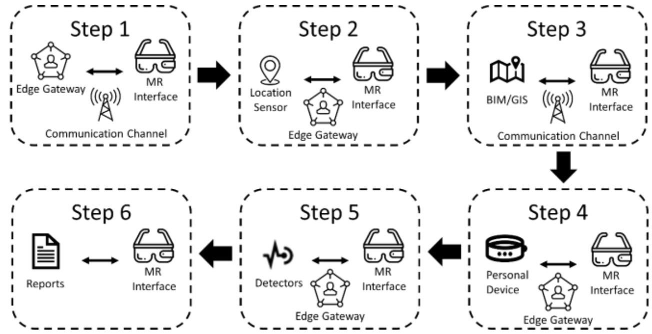

Figure 5: The proposed workflow of the MR enabler addressing main features and functionalities.

1. Step 1: Connection to Edge Data Broker

The edge data broker is a high-performance, distributed MQTT message broker that has the capability to scale horizontally and vertically on edge gateway devices. It can support a large number of clients that consume and produce data through a pub/sub mechanism.

The Edge Data Broker may support devices such as the MR enabler by being deployed on a cluster of edge gateway devices. Each node of the cluster hosts an instance of the Edge data broker, and all those instances communicate with each other. That results in the entire cluster behaving as if it was a single instance of a centralized Broker. Each client connected to any node of the cluster can consume/produce data from clients connected to any other cluster node.

In the case of the MR enabler, it connects wirelessly to an edge gateway device. It subscribes to multiple topics of the Edge Data Broker through the instance that is deployed there. That way, it is able to consume/produce data that other enablers produce and consume.

2. Step 2: Orientation and localization

An essential step of the workflow is to position the MR enabler in the construction plant. Ultra-wideband (UWB) devices placed around the construction building in different positions pinpoint the location of the OSH inspector. The UWB devices offer accuracy for less than 10 cm, immunity to multi-path and interference, range and coverage typically 50 to 70 meters, are very secure, their location service latency is less than 1 millisecond, the scalability is more than thousands of tags, and they require a relatively low infrastructure cost. The UWB devices can find a requested location, using the "time of flight" of each message that has been sent from a transmitter to a receiver. Due to the magnitude of the spectrum they use to transmit messages (hundreds of MHz), they are able to pinpoint a specific location with high accuracy and precision. Interference with other systems using the radio spectrum is prevented because of the low power of the signals that are being transmitted.

3. Step 3: Importing the BIM models

The OSH manager needs access to the BIM model to assess all needed information for the access points, location of red zones, and authorized areas. Developing an MR experience with the 3D BIM model and data can prove a complicated process, as the 3D engines do not support the *.ifc format produced by the initial software. Therefore, converting the IFC model to appropriate formats, like *.dae files, for the model to be appropriately rendered inside the graphics engine and uploading to the MR enabler is necessary to demonstrate elements of the BIM model and other elements of the model. A plugin for the Unity 3D engine is being used, to decode the *.ifc format of the model into:

4. a *.dae file (for the graphical representation of the building), and
5. a prefab (Unity's default object package format) that matches the *.ifc file's extracted info with the corresponding *.dae file.

As soon as the conversion is done, the unity files can be extracted and stored on a file server and then are ready to be downloaded from the MR Enabler on runtime (Figure 6).

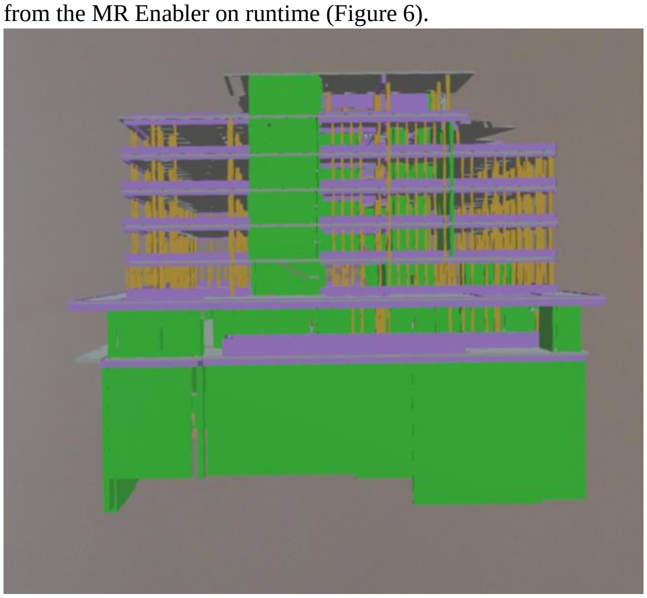

Figure 6: The BIM model visualized through the MR glasses upon conversion to the required format.

6. Step 4: Inspection and recognition of identities

The main elements of a construction site and the most dynamic component of it are the workers. The workers present within site are changing daily, and so do the responsibilities they overtake. Similarly, each worker has their own training, medical, and other historical data. Two solutions are being proposed: one of them utilizing the orientation and localization of the workers and OSH inspector as retrieved from the wearable personal devices, and a second, optional one, scans QR codes attached to the identities of the workers to recognize them through the MR interface.

7. Step 5: Alerts and notifications

Alerts and notifications are generated from various components of the Next-Generation IoT ecosystem. They are used to notify the OSH inspector for incidents such as falling and other accidents, exceedance of permitted physiological and environmental parameters, for unauthorized access, or when approaching dangerous zones. Through the MR interface (as shown in Figure 7) the OSH inspector is notified not only about the type of incident, but also the location and the worker involved.

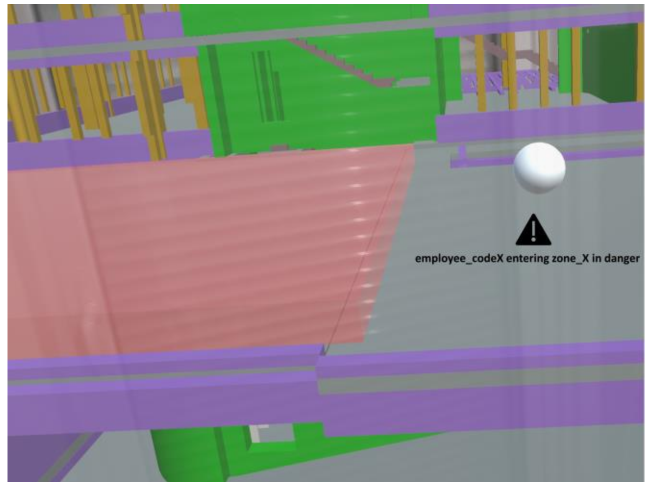

Figure 7: A worker (symbolized with a white ball) is about to enter the dangerous zone at the construction site (red rectangle), and the MR interface notifies the OSH inspector about the type of incident, the ID of the worker, and their location.

8. Step 6: Reporting

During the inspection, one of the primary responsibilities of the OSH inspector is to report unusual or dangerous situations to the stakeholders. For example, when a construction worker, who has been assigned to the construction plant, is not equipped with their appropriate personal protective equipment, it should be reported as an incident. Through the MR enabler, the inspector can create an interactive report that includes photos or videos and relevant information such as the worker's identity and location. Figure 8 shows an example of the reporting functionality of the interface.

5 Conclusions

The MR enabler proposed in this study is connected to the large and rapidly changing IoT ecosystem of a construction site and aims to do the following:

- Detect abnormalities that are potentially threatening to the health and safety of the construction workers and alert the OSH inspector in a timely manner.
- Track the construction worker's location and motion patterns and avoid unauthorized access or approaching dangerous zones.
- Protect the construction worker from extreme stress or fatigue and reduce thermal discomfort at the construction site.
- Prevent overexposure of the construction workers to UV radiation or other threatening environmental factors.

- Detect construction worker's slips, trips, falls, and immobility and ensure a timely response.

Overall, the MR enabler offers seamless integration to the IoT infrastructure of a construction plant and project and safety management processes. The MR enabler is a user-friendly, accessible, and portable tool that offers the OSH inspector the means to address incidents and life-threatening events, evaluate situations and improve processes as well as the health and safety conditions of the construction workers.

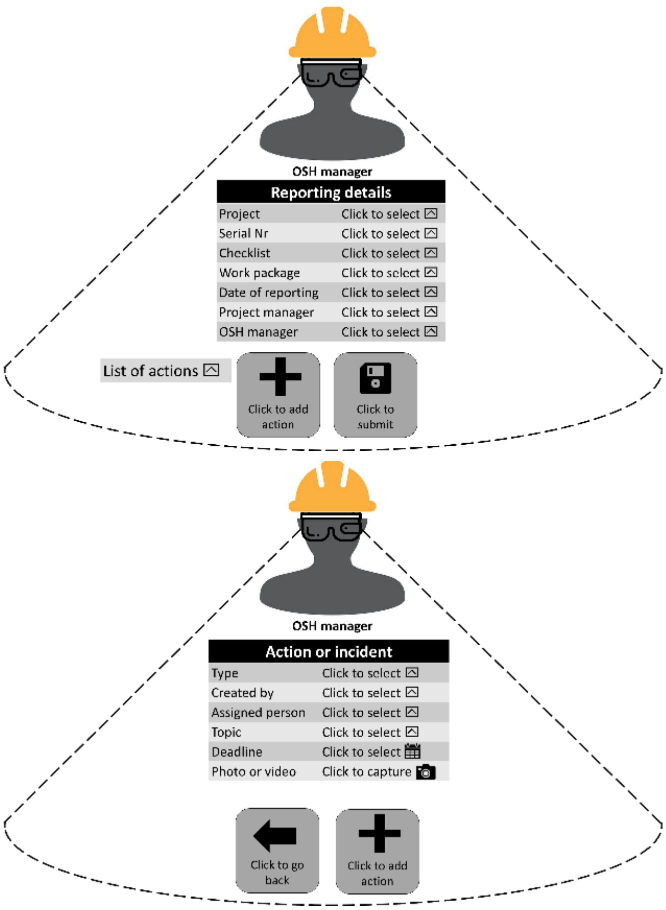

Figure 8: The template for the production of reports through the MR interface. The image at the top shows the template for inserting the general reporting information, and the image at the bottom shows the template for enlisting an action or an incident to the report.

6 Future studies

This study investigated the integration of an MR enabler to a Next-Generation IoT ecosystem. Considering the infancy of MR as an OSH inspector tool, a limited number of applications utilize MR to its fullest potential in this field. Additionally, since not many construction plants have adopted advanced digitalization practices (such as BIM technology and IoT infrastructure), there is a limited number of interested (or well-informed) users. Thorough testing and deployment to the tough conditions of construction sites and exposure to the unpredictive nature of accidents related to these tasks should be the highest priority to achieve the adoption of such modern practices and contribute to a safer construction environment.

ACKNOWLEDGMENTS

This research is based upon work supported by funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 957258 (ASSIST-IoT). Piotr Dymarski and Piotr Klik are acknowledged for providing the BIM models. Anna Dąbrowska is acknowledged for the fruitful discussions during the conceptual phase.

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