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A Practical Deployment of Tactile IoT: 3D Models and Mixed Reality to Increase Safety at Construction Sites

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Abstract

This chapter elaborates on the usage of mixed reality equipment (Microsoft HoloLens 2) and software (enablers based on the ASSIST-IoT project) for improving the safety and health of blue-collar workers at a construction site. Building upon a proven methodology and architecture, the chapter summarizes the introduction of network technologies and techniques as well as other mechanisms (such as ultra-wideband communication) that allow Tactile Internet principles to be realized in the proposed scenario.

The user interface of the mixed reality device and an engagement study are described, along with future validation and demonstration activities assessing the appropriateness of the proposed system, both at the laboratory and a construction site located in Poland.

Keywords: Mixed reality, Internet of Things, Tactile Internet, edge–cloud continuum, construction safety, ultra-wideband, semantic integration.

14.1 Introduction

In the year 2020, a record number of fatal accidents at work accompanying construction activities was reported [6]. According to the EUROSTAT, the majority of these activities took place at construction sites, making it one of the most dangerous work environments. Unpredictable weather conditions, changing environment, demanding work activities, as well as increasing involvement of subcontractors observed recently in the construction sector are undoubtedly the factors influencing workers' safety. These factors are particularly hard to manage in a traditional–collective way, on an occasional basis. The emergence of Tactile Internet technologies makes it possible to create better support systems for the management of occupational risks, particularly in workplaces where environmental conditions are subject to dynamic changes that can have serious consequences for human health and life [24].

The deployment of Tactile Internet technologies for occupational safety and health (OSH) management significantly contributes to a paradigm shift from traditional methods of carrying out collective risk assessment for specific groups of workers to assessment methods, which allow to determine the level of risk individually for each worker. Moreover, the existing periodical risk assessment approaches can be replaced by continuous monitoring of hazards in the working environment in real time [23]. Finally, the introduction of properly adjusted prevention measures has become possible, thanks to early warning OSH systems based on immersive and Tactile Internet technologies.

Immersive technologies, such as mixed reality (MR), allow their users to efficiently interpret physical and digital information while understanding their spatial relations. MR keeps the end-users engaged in an environment enriched with related digital content without disconnecting and isolating them from their surroundings. At the same time, MR offers a unique opportunity to enhance safety communication in construction as it enables a human-centric approach through better interaction of the end-users with the IoT environment [13].

Head mounted devices (HMDs) and particularly the recent development of lightweight, commercially available Microsoft HoloLens 2 bring three-dimensional (3D) models out of the screen and provide users with the ability to engage and interact with data and media more intuitively while experiencing and understanding designs and structures [22]. HoloLens 2 is a powerful HMD that can substitute a computer, a screen, and a keyboard while boasting more processing power than an average laptop and can be used anytime, anywhere. In various setups, it demonstrated its ability to protect its end-users from external factors that may impact their health and safety [19]. MR has the capacity to bring 3D data to life by putting information in front of users' eyes without changing or adjusting the data format. This way, project management and delivery methods become more efficient, less costly, and less time-consuming, and the communication and collaboration among parties are also improved [2].

In the face of networking needs, there are challenges in transmitting real-time information from edge devices to MR devices [14]. In terms of Tactile Internet, which is the main pillar in the development of the proposed architecture, a set of tools are used to reduce the latency, guaranteeing extremely low round-trip delays with excellent availability, reliability, and security for human–machine and interaction-centric real-time applications. Those tools are mainly deployed in the data management layer, which manages all operations associated with data collecting, delivery, and processing to perform essential data-related services.

The stringent requirements of Tactile Internet systems drive the need for deploying the services in a distributed manner, and on the edge (as close to the data and the user as possible). The complexity of hand-crafting and managing such deployments quickly becomes overwhelming, and thus dedicated tools for service management and orchestration are needed [7], [8].

The multi-modal information about the construction site must be collected from a variety of sensors in real time. One key challenge here is personnel and asset tracking inside and outside buildings. To this end, ultra-wideband (UWB) tags and anchors can be used to provide live location data, with low power consumption. The collected highly heterogeneous data must be integrated by the IoT system. This problem of data integration has long been recognized as a key challenge in implementing IoT platforms [9]. The different parts of a system can be maintained by different, independent stakeholders, which rules out an "authoritative" approach to integration – in which a single, central body decides upon all schemas and protocols. Thus, solutions are needed to manage the inherently decentralized landscape of data formats and schemas.

Therefore, the aim of this chapter is the introduction of network technologies and techniques as well as other mechanisms (such as semantic data integration, ultra-wideband communication) that allow Tactile Internet principles to be realized in the construction environment, following the objectives:

- using mixed reality equipment and edge-based software for improving the health and safety of workers;
- employing state-of-the-art network technologies at a construction site based on Tactile Internet needs;
- solving the data integration problem with modern approaches to streaming semantic annotation and translation;
- tracking workers and assets in real-time using ultra-wideband communication;
- deploying the solution in an edge-cloud context with the use of the ASSIST-IoT reference architecture.

14.2 Solution Architecture

To address the challenges outlined above, a solution was devised, based on the ASSIST-IoT reference architecture for next-generation IoT. Figure 14.1 presents the overall solution architecture. ASSIST-IoT deployments consist of encapsulated enablers (sets of microservices, jointly providing functionalities to the system) and other custom components. The enablers and custom components are deployed in a virtualized (Kubernetes) environment [7] and orchestrated via a novel MANO-based custom software delivered by the project [8].

The proposed system aims to provide the OSH manager with digital tools that facilitate performing inspections and alert the manager of unusual or dangerous situations. Through the MR enabler (using a head mounted device – HMD), the OSH inspector obtains contextual visual data about activities that occur at their location or dangerous events from the construction area. The MR enabler is integrated with the Tactile Dashboard, the Semantic Repository, the Long Term Storage, and the Edge Data Broker enablers.

The Tactile Dashboard enabler displays data in real time using user-friendly and interactive visuals, providing the capability to configure the MR enabler in each scenario. The Semantic Repository serves as a nexus for data models used on the construction site. This includes storing 3D and BIM models of the site. The function of the Long Term Storage enabler (LTSE) is to provide safe and robust storage for other enablers and store important data such as workers' medical and training records. Lastly, the Edge Data Broker provides a common point for IoT devices and services to broadcast their data in a streaming manner. The integration between the MR enabler and the Edge Data Broker enables other components to easily transfer messages to the MR enabler by publishing data to a particular topic to which the MR is subscribed.

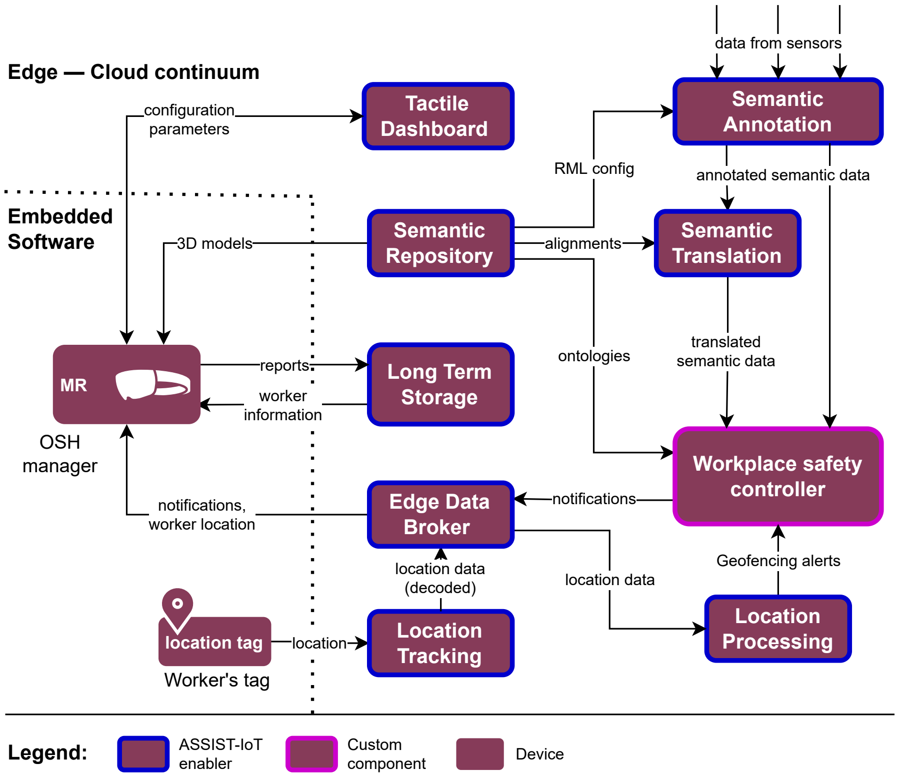

Figure 14.1 Overall architecture of the solution.

The MR enabler depends heavily on the Edge Data Broker to gather essential data for its operation.

The "central" component responsible for processing most of the logic is the workplace safety controller. It aggregates incoming streams of data and performs live operations on them. For example, it is tasked with detecting UV over-exposure of workers. To determine the total exposure of a worker, the information about the worker's location must be aggregated with live weather data and the BIM model of the construction site to determine the amount of shade in a given area. When the workplace safety controller detects abnormally high UV exposure, it emits a notification to the MR enabler so as to inform the OSH manager of the situation. Geofencing boundaries and other types of safety hazards are monitored in a similar manner as well.

The proposed solution faces a number of architectural challenges. The most significant are: the Tactile Internet aspect (low-latency interfaces with immediate feedback); data integration (integrating heterogenous data sources and services); and, finally, the mixed reality interface. These three key aspects are discussed in detail in the following subsections.

14.2.1 Tactile internet aspect

Tactile Internet (TI) is one of the latest advent technologies that play a major role in next-generation IoT (NG-IoT) environments. An NG-IoT deployment is characterized by including all traditional IoT capabilities (devices discovery, data connection, visualization of monitored information, etc.) besides adding new traits such as 5G, AI-based functions, edge/fog computing, and software-defined networking/network function virtualization (among other technologies), considering Tactile Internet as one of the key objectives. All of the previous can be achieved only by modular architectures that use reliable, fast underlying networks to support very low latencies. An application is considered to be *tactile* when it allows a seamless sensation of touch (resolution of 1000 Hz). In general terms, according to European Commission-promoted initiatives, it is crucial to include TI's strict limitations in the architectural decisions of any forthcoming IoT/distributed systems reference architectures [5].

Formally, according to the International Telecommunication Union Standardization Sector (ITU-T), Tactile Internet is defined as *extremely low latency, in combination with high availability, reliability, and security*. In practical terms, it means enabling haptic human–machine interaction, opening up the establishment of use cases like heavy machinery handling, remote surgery, or, as in this case, ultra-real-time awareness of construction workers' status. The authors of this work consider, drawing from the experience gained in the ASSIST-IoT project, that TI must be understood as a system that (i) successfully carries haptic data (in this work, from sensors, BIM models, and MR glasses) by (ii) relying on communication (leveraging, among others, UWB) meeting the requirements of (a) low latency, (b) high reliability, and (c) high data throughput.

In this regard, for what concerns the proposed deployment, communication latency poses a critical obstacle. This is a usual barrier whenever adopting IoT systems in many applications [26], [27]. High latency can even make the technology entirely unfeasible for a given application. In the past decade, a variety of communication protocols and standards were established and implemented by the community to tackle this issue. These protocols emphasize the need for giving special attention to the quality of service (QoS) and quality of experience (QoE) for various applications [17]. In order to ensure low latency (that will facilitate designing Tactile Internet scenarios), it is realized to place computation closer to the user (where tactile data is generated). In technical topological terms, this means shifting the processing workload to the edge of the network.

Several architectures and works [16] have proposed to follow a primary–secondary approach relying on edge computing. This is achieved via reducing connectivity to a few links and by setting up a primary gateway node (at the edge) to connect secondary devices to the network. Using this architecture (inspired by IEEE 1918.1), information is encoded, optimizing data transmission, and the security and privacy are clearly enhanced.

To support such needs as well as to comply with the latter requirement exposed above, the Edge Data Broker enabler (EDBE) was developed, whose filtering and ruling capabilities reduce the number of transmitted messages, while the quality of service (QoS) is adapted based on the use case requirements. These scriptable capabilities allow data to be routed and processed in real time, with the specific pipelines being triggered by predetermined criteria. Their seamless integration allows for edge-based filtering and decentralized data-consuming strategies, which cuts network traffic and latency dramatically, fulfilling the requirements of Tactile Internet. Following those design principles, human–machine collaboration is enabled in applications such as Construction 4.0 [20], Industry 4.0, virtual reality, and augmented reality [15].

Several enablers and components in the proposed deployment connect to EDBE via the MQTT protocol. For the needs of semantic integration (described in detail in the following subsection), the Semantic Annotation and Semantic Translation enablers communicate in a streaming manner. Here, EDBE ensures that the data is routed locally to the nearest available consumer, minimizing latencies. To address the needs of processing geospatial data, the Location Tracking enabler produces streams of location data from each tracked asset. The Location Processing enabler is then able to run complex geospatial queries on the gathered data. Finally, the workplace safety controller component aggregates streaming MQTT data from various sources and emits the necessary notifications and alerts.

An experimental feature, currently being investigated in the hopes of further lowering the latencies, is the novel Jelly RDF streaming protocol [27]. It is meant to provide high-performance, low-latency streaming of semantic data between the semantic enablers and the workplace safety controller.

14.2.2 Data integration

The challenge of integrating data from heterogenous sources is well-addressed by ASSIST-IoT enablers in the data management plane: the Semantic Annotation enabler, Semantic Translation enabler, and the Semantic Repository enabler. This technological stack provides a robust set of tools for addressing data integration using ontologies and Semantic Web technologies [1]. Here, the Semantic Annotation enabler annotates non-semantic streaming data using RML mappings [4], giving it explicit meaning. The Semantic Translation enabler in turn translates the semantic data to allow the consumers to understand the meaning of data represented using different ontologies [10]. The semantic translation and annotation processes are applied to data gathered from sensors present on the construction site.

The final piece of the data integration solution is the Semantic Repository enabler, which serves as a "nexus" for all schemas, ontologies, and other data models used in the deployment. The repository offers robust versioning and metadata support, allowing all other components to stay synchronized with each other, with regard to the used data models. In this use case, the repository stores (among others) ontologies used by the workplace safety controller, RML configuration files for semantic annotation, alignment definitions for semantic translation, the BIM model of the constructed building, and the 3D models of the building displayed to the users.

14.2.3 Mixed reality interface

The MR enabler is a standalone native application that is deployed on a head mounted device (Microsoft HoloLens 2) to monitor the worksite and notify the OSH manager about incidents or undesirable behavior. It visualizes information from the BIM model, including construction components and dangerous zones. The MR enabler collects, curates, and then displays the required information related to the construction site and the workers.

Upon establishing a connection to the Edge Data Broker, the MR enabler starts receiving data to visualize. The data, from long-term storage or real-time data streams, is requested according to its relevance to the user at a specific time and location. When displaying the data and other content, the authorization and access rights of the end-user are taken into account. More specifically:

- Blue-collar worker's ID, medical and training data, are retrieved from the Long Term Storage enabler for the OSH manager to verify their compliance with the expiration dates. Alerts and notifications from localization services ensure that construction workers move around areas that are safe and where they are authorized and trained.

- Manipulation of the BIM models, where the OSH manager can manipulate the BIM models to be informed about dangerous zones and evacuations routes.
- Environmental conditions such as ambient temperature and UV radiation are also reaching the MR enabler through the EDBE to ensure that workers function at suitable conditions.

Many functionalities of the MR enabler ensure that the required information is collected, such as location and proximity data, exceeding of the physiological parameters thresholds, weather conditions, personal identification information, training and medical records, building information, alerts, and notifications. At the same time, the MR enabler supports activities that improve the overall health and safety management. More specifically, we have the following:

Connection to the EDBE to consume data. In the case of the MR enabler, it connects wirelessly to an edge gateway device, where the Edge Data Broker is deployed and subscribes to multiple topics in order to be able to consume/produce data that other enablers produce and consume.

Importing of the BIM models through the Semantic Repository. The BIM visualization functionality relies on the loading of the BIM model from Semantic Repository in a way that can be visualized through the MR

Figure 14.2 In this figure, real-time data is visualized to the MR device, which are produced by a worker's wristband.[2]

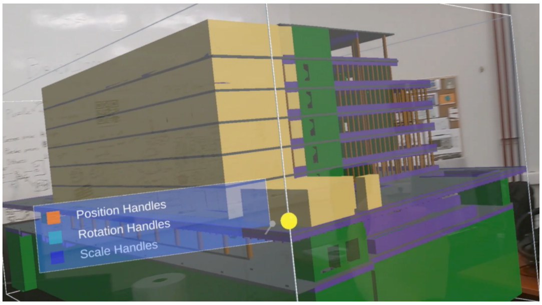

Figure 14.3 The BIM model visualized through the MR glasses upon conversion to the required format through the laboratory facilities.

device. The dangerous zones are included in the model, as presented in Figure 14.3 and updated by the construction site's owner.

Manipulation of BIM. The MR enabler is designed in a way that allows the user to manipulate the 3D model rendered in order to provide a better understanding of the information linked to it, while the manipulation handles are presented in Figure 14.4.

Generation of reports. Using the reporting feature, as it is presented in Figure 14.5, the OSH manager can report unusual or dangerous situations, while the reports are transmitted to the LTSE.

Displaying alerts and notifications. This activity includes the alerts and notifications that the inspector receives in case of a dangerous event within the construction site via the MR device.

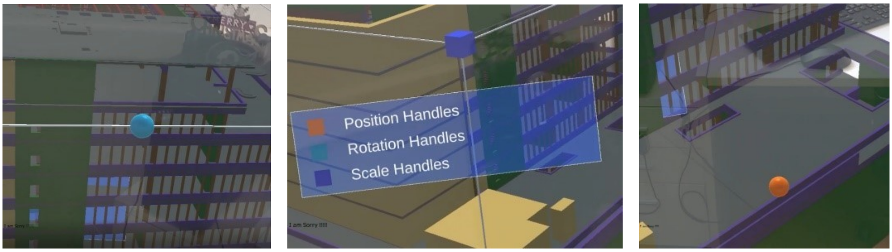

Figure 14.4 The model has handles at the model's corners that enable the user to scale the model. The handles in the center of the BIM edges enable the user to rotate the model in each direction. The user may then move the 3D model freely inside their range.

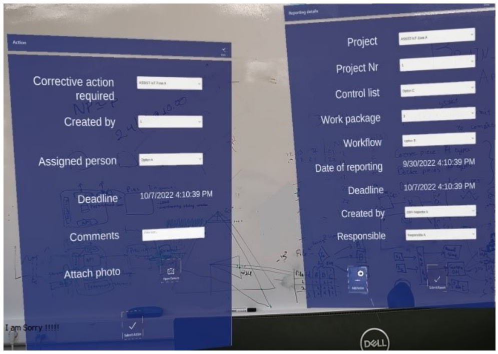

Figure 14.5 The reporting function is visualized, where the OSH inspector can produce a human-centric report when they identify misalignments during the inspection procedure.

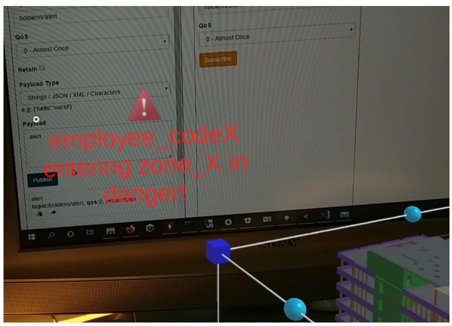

Figure 14.6 The user interface of the various alerts coming from other systems (such as weather station, fatigue monitoring, and location management system about danger zones unauthorized access) is presented.

14.3 Evaluation

To ensure that the developed MR application is user friendly, the visuals and user interface (UI) elements were designed after UI/UX research [12]. As a result, a custom UI was built focusing on an immersive, usable, and familiar user interface environment with a low cognitive load process to improve user engagement and avoid common usability errors. At the same time, the user path was defined upon interviews with construction stakeholders to analyze their needs and the goals of this application. This allowed to define the trail from the very first contact of the health and safety manager with the MR application to their final action. Along with information gathering, prototypes were built to determine the capabilities and complexities of a successful enabler. Both qualitative and quantitative research were performed to gain insights and other analytics that favor the UX design.

Considering the human-centric approach adopted in ASSIST-IoT, the designed mixed reality interface will be also subjected to the evaluation process with end-user participation. Mlekus et al. [21] proved that user experience characteristics significantly affect technology acceptance. Low user acceptance means less frequent use, lower job satisfaction, and performance losses [3], [18], [29]. In order to determine the level of acceptance of MR technology, Rasimah et al. [25] used the metrics of personal innovativeness, perceived enjoyment, perceived ease of use, perceived usefulness, and intention to use. According to their findings, perceived usefulness was the most important factor determining further intention to use MR technology. Therefore, the feedback coming from end-users, being a result of the evaluation process, is recognized to be crucial for the successful deployment of Tactile IoT.

The questionnaire-based methodology for evaluating whether the MR technology can enhance safety-related communication on construction sites was also adopted by Dai et al. [2]. The authors demonstrated a great degree of willingness to adopt MR technology for enhancing safety on construction sites. Advantages of MR over currently used communication methods such as phone calls, walking to people to talk, and video conferencing were highlighted. In particular, instant access to information, context-based perception, and visual interaction were indicated as factors highly contributing to effective communication at the construction site. According to Dai et al. [2], communication with the use of HoloLens was reported as more accurate and efficient than with the use of traditional methods. However, still some issues have been identified as responders indicated, e.g., that it was hard to wear HoloLens and walk at the same time or that the field of view was limited.

Using the technology acceptance model (TAM) and its variations for MR technology evaluation is a known and appreciated method based on collection of responses to questionnaires [11], [28]. However, in the literature also some limitations of this method are indicated, which are particularly related to subjective means of evaluation, including interpersonal influence. Therefore, evaluation methodology assumed both laboratory and field trials including subjective and objective assessment of user experience and technology acceptance. In terms of objective assessment, special focus will be paid to the analysis of the influence of provided MR interfaces on psychophysical load with the use of biofeedback methods. Conclusions from both the subjective and objective assessment will be a basis for further MR interface improvement.

14.4 Conclusions and Future Work

The proposed approach for ensuring the health and safety of construction workers presents a significant paradigm shift in how this problem is addressed in practice. In modern, demanding, and dynamic work environments, it is no longer sufficient to perform periodical risk assessment studies – instead, the safety of the site must be monitored in real time. This would be unattainable without the use of novel technologies, such as the Tactile Internet, mixed reality, and semantic data integration; all combined in a next-generation IoT environment. The proposed solution architecture exemplifies how these abstract approaches can be put to work in a specific use case, using the ASSIST-IoT reference architecture. Moreover, the preliminary evaluation methodology of the solution is presented. In the future, a detailed evaluation of the system will be performed, in the demanding environment of an active construction site.

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