Leveraging Extended Reality technologies with RFID to enhance on field maintenance of buildings

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Abstract
The combined use of BIM and the advanced visualization provided by Extended Reality technologies can improve productivity in the project management processes in construction. This paper concerns an application of MR for seamless data retrieval from a BIM platform towards field workers in charge of maintenance. For instance, in case a failure of any systems has been claimed, workers must retrieve the information about the localization of components prior to repairing. This step can be facilitated by on field data visualization through MR. As the number of on field repair actions is huge in complex buildings, minimizing the time required for the alignment of virtual models is beneficial. Hence, an approach for model alignment that is based on the use of RFID tags has been developed. The first advantage is that these embedded devices are suitable for reuse at any survey with no need for re-deployment. Secondly, this approach does not require that the virtual model is displayed during the alignment, which makes it suitable for large models.

Keywords: mixed reality, augmented reality, virtual models, alignment, BIM, field work

1 Introduction
An increase in the complexity of all phases of the construction process requires multidisciplinary inputs and enhanced information management and visualization. In this context, BIM is a visualized digital construction information database application for collecting, generating, storing, analyzing and managing information related to the building and construction processes (Prabhakaran A. et al 2020). In order to be economically sustainable, BIM adoption needs an implementation strategy and requires the application of techniques, tools, and technologies that increase the productivity and performance of construction processes. Mixed Reality (MR) offers a revolution in the virtual representation of objects and space through context awareness as well as the incorporation of information beyond 3D geometry. Thanks to this approach, countless opportunities for more effective information visualization and coordination are generated. By

using MR, a construction company can interact with the BIM information model on top of the physical space by either superimposing the different design options within the existing job site conditions or reading additional information which does not exist in the real world (Alizadehsalehi S. et al 2019). This is expected even to lead towards the development of a distributed collaborative environment, where each participant will see the constructed model as overlay to the construction scene from an individual perspective. Manipulations of one participant could be transferred directly to all others, too, thus realizing a cooperatively work scenario (Blank C. et al 2015; El Ammari et al 2019). Such an improved collaboration would determine a lot of benefits in the AEC domain, including the Facility Management (FM) area.

The target of the solution showcased in this paper is to improve the efficiency of the data exchange and facilitate on-field visualization of information in the functions related to operation, maintenance and repair of built assets, that is a very common concern in FM (Cotts et al 2010). It includes both regular maintenance and replacement or changes of building sub-systems and components. In these situations, field workers usually need to focus on the real facility components and locate those ones in need for repairing. Also, they should retrieve additional information with less time-consuming model navigation before checking failures in the system. The easier and quicker these operations are the better the overall process efficiency. As a result of the adoption of MR, service orders can be accomplished directly at the first on field survey. However, some preliminary procedures are required, such as an accurate alignment of virtual models over the physical environment.

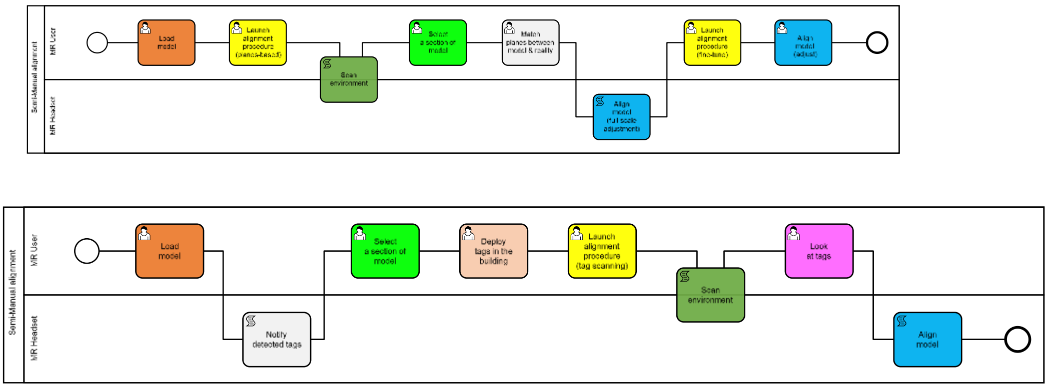
The main research objectives we want to tackle in this paper is how MR can be exploited to support the augmented display of real assets on-field for the purpose of repair in maintenance processes. The second objective concerns an approach for seamless alignment of the virtual model over the real one. As reported in the next section, this is usually performed by means of markers deployed and visible in the asset. In case these markers are affected by building layout changes, they must be rearranged through an additional effort. In order to overcome this drawback, in this paper an alignment approach based on the use of RFID tags and commercial handheld devices is suggested. The tags endure spatial rearrangements of buildings and can be kept embedded over the whole lifecycle.

2 Literature Review

Extended Reality (XR) technologies have enormous potential to improve AEC efficiency and productivity. XR is a collective term which groups the whole spectrum of experiences between virtual environments and the real world, that is from Virtual Reality (VR), through Augmented Reality (AR), and finally to Mixed Reality (MR). In a VR environment, the participant-observer is totally immersed in, and able to interact with, a completely synthetic world (Milgram et al 1994). In both AR and MR, instead, virtuality and reality are combined, but in a different degree in the one and the other. AR is characterized by digital contents superimposed on the users' real surroundings, whereas MR totally integrates them, so that users can interact with both digital and real contents, and these elements too can interact (Flavián et al 2019).

Examples of collaboration enhanced by XR are reported by several research studies. In (Muhammad et al 2019), the authors explore the applicability of VR technology for improving communication between the different actors (e.g., construction manager, site engineer, jobsite layout planner, contractor, etc.) involved in the construction jobsite organization. In (Riexinger et al 2018), the authors focus on MR solutions for inspection tasks, carried out by workers and stakeholders both individually as well as in collaboration with others. In (El Ammari et al 2014), the authors propose an MR-based framework to support collaboration between on-site and back-office personnel during inspection tasks for facilities maintenance. Addressing the activities involved within the Facility Management (FM) poses many challenges (Ibrahim et al 2017). To cite a few, retrieving on-site data, managing work orders, localizing components and accomplishing maintenance works are just some of the many issues to be addressed by facility managers. In order to successfully apply XR technologies in the field of FM, the full integration between reality and virtuality, which characterizes MR, is required. In fact, an MR headset with its capability of overlaying virtual and real world represents a powerful tool for the direct visualization of on-site information and then overlaying it on the object undergoing maintenance work (Naticchia et al 2020). The users’ perception of the real environment can be improved by showing information that users cannot directly acquire otherwise (Wang et al 2004). In this way, field workers will visualize maintenance data and repair requests even on-site, allowing them to interact with the virtual models and real assets. Currently, the technological developments that can truly generate pure mixed realities are the holographic devices Microsoft HoloLens and Magic Leap, which integrate virtual and real objects in a real-time display.

One essential requirement to use MR technology for on-site FM purposes is the correct alignment of the virtual BIM model, so that it perfectly matches with its physical counterpart (Huang et al 2020). Some applications (e.g., SketchUp Viewer, Trimble Connect) support model alignment functions. Model alignment can be carried out manually, but it takes a considerable amount of time and effort, and often results in inaccurate outcomes. Also, a virtual BIM model can be aligned to its real counterpart by retrieving the observer’s position from QR codes scanning. Such method can be implemented by exploiting AR engines (e.g., Vuforia SDK) for precisely and quickly localizing image targets in space. The QR-code-based method requires a QR code label model component to be inserted in the BIM model first, and then the same QR code label needs to be printed and affixed at the same location in the physical space. After scanning the affixed QR code label with the MR device, the model can immediately be aligned (Huang et al 2020). A commercial solution that supports both the above-mentioned alignment methods is, for example, Trimble XR10 for Hololens (Trimble Inc 2019). A distinction must be done between indoor and outdoor applications: whereas the first one cannot rely on GPS signal, the second one can apply GPS-rtk technology. In the case of indoor applications, two approaches for aligning virtual models through MR, i.e. the manual and the markers-based one, are depicted in Figure 1. The former method (Figure 1a) consists in aligning any two surfaces in the model with the corresponding ones in the reality. Then, a manual scaling and rotation of a cube for fine-tuning is required (Trimble Inc 2020a). This method produces a rough but acceptable alignment in case the entire model can be loaded for supporting the manual tuning by visually comparing reality and virtuality. The marker-based alignment method (Figure 1b) consists in aligning the BIM model on the basis of the user position, retrieved by scanning a real and visible marker having its virtual replica (Trimble Inc 2020b) and provided that the visual markers’ positions be verified before each scanning. This method ensures a pretty good model alignment.



a)

b)

Figure 1. Workflows describing the existing approaches for aligning virtual models through MR: (a) manual alignment and (b) markers-based alignment.

In this paper, a new approach for the alignment of virtual BIM models over reality is suggested. The workflow generated by this new method is then compared with the workflows of the approaches mentioned by existing literature, in order to clarify the advantages in terms of efficiency. The suggested solution is based on the use of embedded RFID tags, which can be kept embedded in building components, irrespective of building layout evolution, replacement of minor building components and systems due to regular maintenance. As compared with the manual alignment method, the new method can be applied even in case virtual elements have not their physical and stable counterpart in the real world. As compared with the marker-based, the new method is less demanding, because it does not require that QR code labels are preliminarily affixed in the building and made visible prior to every survey.

3 Methods

3.1 Motivations for improving the alignment method

The alignment of virtual models over the real environment is a practice usually performed by means of manual alignment or markers. In the case of manual alignment, it is accomplished once that any component of the virtual model (e.g. the intersection between two walls) matches with the corresponding component in the physical world. Sometimes this is hard to achieve for several reasons. The first one is that the model must first be uploaded and visually roughly overlapped over the physical entities, which is hard in case of large and complex buildings. The second reason is that the reference component selected in the virtual model must be visible also in the real building, which could not be possible in case construction is in progress or in case it has been hidden by another (even temporary) component. On the other end, the use of visible markers asks for their deployment around the environment and the preliminary positioning of their corresponding virtual entities in the virtual model. This is usually done prior to every survey, as they could be lost over time due to layout changes or bad maintenance. For this reason, in this paper we check the possibility of using RFID tags to determine the workers' absolute position and relative location from building components. In addition, we propose an architecture that integrates mixed reality devices within a BIM platform, from which virtual models are retrieved. For the purpose of our paper, Microsoft Hololens was used as the MR tool.

3.2 Enhancing the workflow by means of on-field alignment using RFID tags

As mentioned in section 2, MR technology can support on-field integration of reality and virtuality. But its application is conditioned upon the full-scale alignment of the virtual BIM model. The approach for model alignment reported in this paper realizes the workflow depicted in Figure 2. RFID tags and a handheld device (e.g., a smartphone) are integrated. The model alignment procedure is based on reading RFID tags which have been previously embedded in the building (e.g. during construction works execution or in the first on-site survey). The first two tasks in Figure 2 relative to the deployment of tags are performed just once. This improves any future alignment process both in terms of efficiency and quality of results.

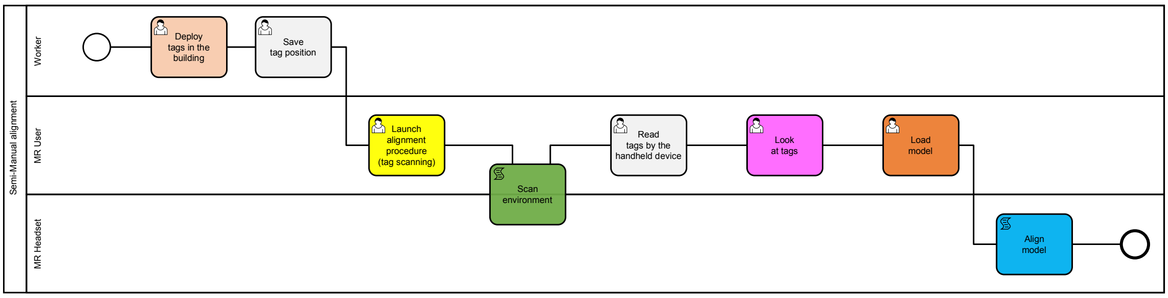


Figure 2. Workflow describing a novel approach which integrates RFID tags and a handheld device in the alignment of virtual models through MR.

As a result of a comparison between the two workflows depicted in Figure 1 and the one depicted in Figure 2, several benefits are determined by the new method. Indeed and thanks to the use of RFID tags embedded in building components, the first two tasks of the first lane of the workflow depicted in Figure 2 must be performed just once, e.g. during the first on-field survey in the building. On any next on field surveys, only the remaining tasks in the second and third lanes must be performed. On the contrary, in the workflow in Figure 1b every task must be performed at any survey. This is due to the evidence that visual markers represent objects that are affixed on the internal surfaces of building components and that can be easily removed during the lifecycle of a building. Even more evident is the benefit of the RFID-based alignment procedure against the manual one. In this case, the adoption of RFID tags overtakes the need for having the virtual counterpart of a real element always visible.

3.3 Architecture of the platform

The layered architecture of our WeBIM platform (PRIN 2017) is a CDE solution compliant with “BIM according to the ISO 19650 series” and enables the development of a federated information model (BS EN ISO 19650-1). It is supposed to manage information during asset management and project delivery in the several information models, including AIM to support asset management activities. XR technologies make all the information stored within a CDE (e.g., model, non-graphical data, documentation) available on-field for workers during maintenance practices. It is made of a bottom storage layer, web applications at the top and a set of web-services in between, i.e. the middleware. The storage layer contains information structured either as files or NoSQL databases that in the current version is realized by means of ArangoDB, a state-of-the-art graph database. Data about tags are stored within the same devices deployed throughout the building, hence realizing a geotagging of the space. The application layer contains several Apps. Among them, those ones involved in this application are the GUIs “Handheld device”, “MR headset” and “model management”. The first one is optimized for NFC enabled devices such as smartphones and is used to scan RFID tags, receive data and visualize them as markers. The second one is developed for the MR headset Microsoft Hololens™, and allows on field workers to select projects and other options to manage holograms and related information during their navigation on-field. Also, the UI “model management” is used to upload and view models. The middleware contains services that communicate via Rest APIs to ensure seamless integration among the several layers. These services have been developed in Node-RED visual programming environment, thanks to the flexibility and reusability it provides in the management of information flows. The service “tag reading & notification” performs the association between tags, their WGS84 coordinates and the BIM models in the storage layer. The “ifc to gltf conversion” service generates the geometry and textures from ifc files. Model versioning and splitting is managed through metadata, whenever it might be necessary. The “ifc to rdf” conversion translates models for the sake of more efficient queries. Projects are stored in the GraphDB of the WeBIM platform along with models and views, as depicted in Figure 3. A model is the base entity of the platform and is a structured data stored in the GraphDB. It can be generated from files and it may be linked to other files. The geometric information associated with an IFC file is a model linked to it and to the corresponding gltf/glb file. A view is represented by a document and a collection of edges that links together different models or other resources of the project. Other “engines” are available to perform specific simulations and inferences in support of the several Apps.

3.4 The localization and alignment procedure based on RFID tags

In the WeBIM platform, a tag is represented as the RFID unique permanent identifier (UID) and its absolute position, given as a set of geographical coordinates referenced to the WGS 84 coordinate system. Calibration offset is also stored in the RFID for adjusting its spatial reading offset. We assume that a new model added to a project through the “model management” UI includes the absolute location of a building, its orientation, geometry and a set of tags located inside the building components. A suitable GUI may help the user to add tags to the model by specifying their UIDs, to calculate the absolute position and to set the reading offset with respect to the building reference frame based on the depth at which the RFID is placed inside a building component. RFIDs can be installed either during construction or during the first survey of the built asset performed by the maintenance company. The RFIDs used in this application are compliant with ISO 14443, HF, MIFARE standard. They can be read/written with NFC enabled handheld devices within a 0.04 m range, depending on the geometry of the antenna and on the reader’s configuration. This reduced reading distance allows to precisely localize the tag inside a component. This operation is supported by the handheld device App. As soon as a tag is placed onsite, it is read and matched with its model in the platform, then its absolute coordinates retrieved from the model are written on it together with an eventual reading offset provided as input in the UI. In this way, each tag represents a persistent and absolute geographical reference. RFID tags, in fact, do not fade away nor degrade over time. After the first tag has been placed, the geometry is deployed from the platform to the MR headset App and aligned with the real building for exploring the environment and guiding the operator during the installation of the other tags. The relative coordinates of tags can be displayed over the real asset for the sake of a precise and quick positioning. As long as further tags are installed, the alignment can be refined. The selection of the geometry to be sent to the MR headset is made by filtering the objects of the model based on the location of the last tag.

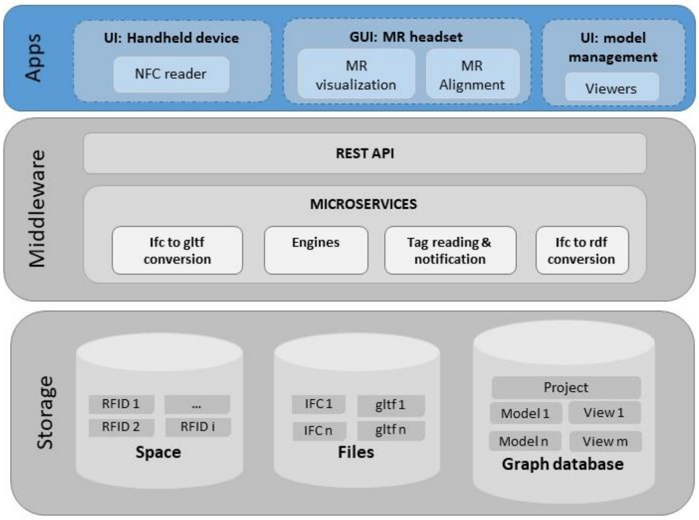


Figure 3. Architecture of the WeBIM platform

Alignment of models with the physical world is made by visually localizing the handheld device that reads the tag and by calculating its relative position w.r.t. the model (Figure 4). The offset between its position in the model and its actual position is used for aligning models over the physical world. In case just one tag has been installed, the model orientation can be adjusted by exploiting the normal of the surface on which the tag is applied; in case at least two tags have been detected, their relative position is exploited for aligning the model around the vertical axis. For the sake of simplicity, but without loss of generality, the model is assumed horizontal since the inertial sensors of the MR headset are usually accurate enough to ensure this. The visual task of detecting the position of the handheld device when reading a tag is performed by showing a target image on the handheld device and by exploiting AR engines (like Vuforia) for precisely and quickly localizing image targets in space.

3.5 Experiments setup

3.5.1 The use case presented in this paper

The use case presented in this paper concerns an approach for responding efficiently in case of request of repair of the communication system in one of the sections of the DICEA Department at the Università Politecnica delle Marche (UNIVPM). This part of the department is served by the main switchboard that is located in the middle of the offices and that controls and provides several offices, desktop computers and servers with access to the Web (Figure 5). Both the gateway and the several units of the switchboard are arranged along several rows. In this case, the combined adoption of BIM and mixed reality for the execution of maintenance operations provides several benefits, such as increased efficiency of work order execution to access data and locate the related repair actions, and improved accuracy of data retrieval. Any field worker that is asked to respond to a failure and execute a work order must associate the served office or device with the corresponding switch among all the ones integrated in the switchboard (Figure 5). This task is usually quite time consuming. We assume that a BIM model of the asset has been provided and stored in the WeBIM platform. If this is the case, the field worker wearing Hololens is expected to display the virtual model superimposed over the real asset and automatically associate information about the connection between the device subject to a failure and the corresponding switch in the board. However, the first requirement determined by this approach, is that the field worker is allowed to quickly align the virtual model over the real building and that an accurate enough geometric alignment is pursued. This is dictated by the small size of the units of the switchboard, that still must be clearly discernible.

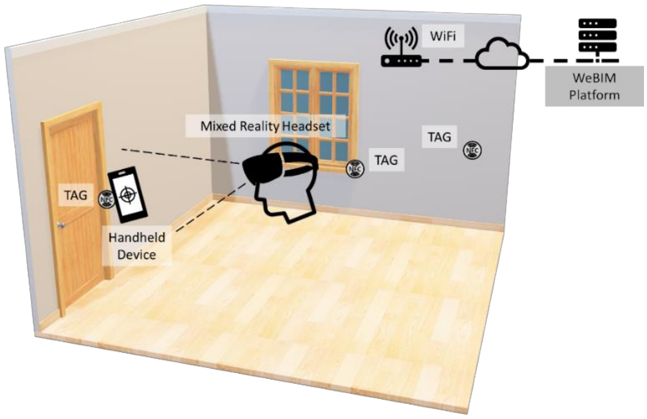


Figure 4. Conceptual schema of the Hololens application that is in charge of the alignment by means of RFID tags

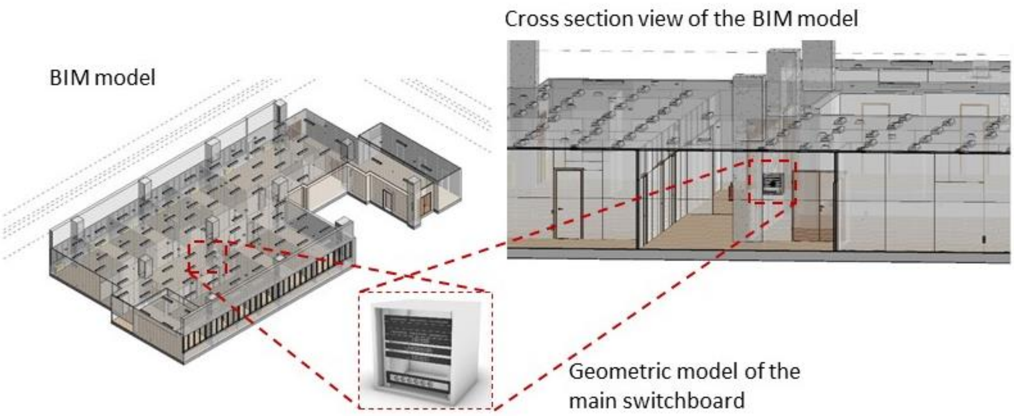


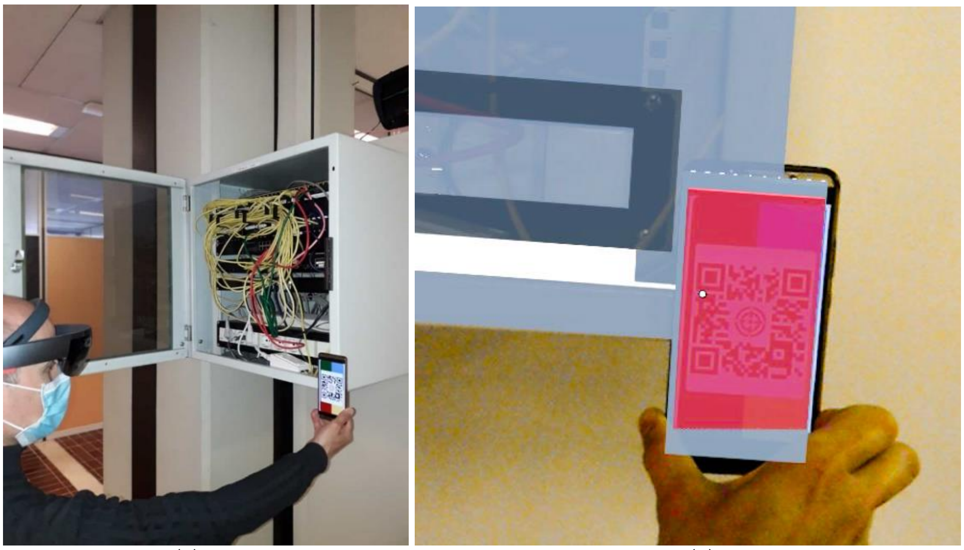
Figure 5. The BIM model of the use case and the main switchboard of the communication system.

3.5.2 Set up of experiments and implementation

In order to validate the effectiveness of this alignment strategy, a serious game App has been developed in C# with Visual Studio 2019 Version 16.7.3 under Unity 2019.4.9f1 environment and compiled for x86 and deployed in Microsoft HoloLens 1.0. The whole app is based on the Microsoft Mixed Reality Toolkit 2.4.0 and Vuforia 9.7.5 for tracking image targets. The target is displayed on the handled device when reading NFC RFIDs. A translation service between IFC files and GLTF files has been developed for automatically generating models suitable for being displayed in a portable device. The GLTF objects are named with the IFC GUIDs so that it is possible to retrieve all the original IFC information by querying WeBIM platform. A web app runs on the smartphone for reading the RFIDs and sending data to the Hololens device.

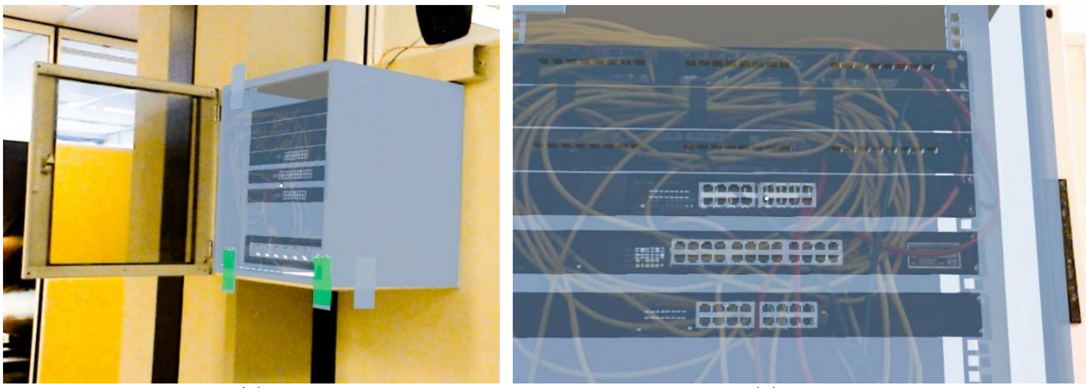
The experimental setup is made of a Microsoft HoloLens 1.0 mixed reality headset that runs the serious game App, an NFC enabled smartphone as handheld device and four Metal MIFARE NFC RFIDs installed in front of the switchboard’s case. When the operator in charge of a survey gets onsite, he wears the headset and runs the MR application. Then, the required first step is reading the first tag in a known position (Figure 6a), which allows the software to infer which model has to be loaded and placed in that position. As a result, the hologram of the switchboard appears overlapped over reality. The user is also allowed to slightly adjust the position of the hologram by moving the smartphone within the reading range of that RFID (Figure 6b). Once accomplished, the user taps the screen of the smartphone for hiding the image target and locking the corresponding tag position in the MR app. With the hologram of the switchboard, also the positions of the other RFIDs that can be used to further align the model. In our case, four RFIDs have been installed on the switchboard at the four front corners, but just two of them (the green rectangles in Figure 7a) have been used to achieved satisfactory accuracy (Figure 7b).

Once the holograms are aligned over the physical asset, the worker is allowed to display information retrieved from the virtual model over the real entities subject to maintenance/renewal operations. He may even query the model to see which building rooms are served by specific devices and to directly access the configuration/monitoring page of the switchboard by means of hand gestures.



(a) (b)

Figure 6. Third person view of the worker (a) that reads an RFID placed on a corner of the switchboard by using an NFC enabled smartphone. First-person view (b) of the system’s switchboard where a target image is displayed on the smartphone that is localized by the Hololens app (red rectangle) and aligned with the tag on the model (overlapping gray rectangle).



(a) (b)

Figure 7. First-person view (a) of the whole switchboard once aligned by reading two tags (green rectangles) located at the bottom front side of the case. Closeup first-person view (b) of the devices inside the switchboard. Cable connections and other details not present in the model can be seen as overlapped.

4 Findings

As described in the previous section 3.5, the proposed workflow for RFID-based model alignment through MR (see Figure 2) has been put in place assuming, as use case, the first steps of the maintenance process for the main switchboard of the communication system. In fact, integrating MR technology with the WeBIM platform enables a real-time linking of virtual models, overlaid to its physical counterpart thanks to the Hololens, with the corresponding functional model. The operator, standing in front of the main switchboard, can learn what components make the communication system and all related information stored within the CDE. As a consequence, the efficiency of repair and maintenance work orders is expected to be considerably improved.

As can be inferred by Figure 7, maintenance operations require that the virtual components accurately overlap their physical counterpart. In order to make this possible, an accurate and smooth BIM model alignment is required. In Figure 8 the RFID-based model alignment result is shown. As the border of the switchboard is 2 cm wide and the misalignment is approximately as large as half of that border, we can state that the final accuracy is no lower than 2 cm. This slight deviation can be due either to errors in the alignment procedure or to some installation issues (e.g., the real case could be slightly tilted). Figure 7 demonstrates that the proposed method, as opposed for example to the manual one, does not require the loading of the entire BIM model, reducing the related computational effort and speeding up operations. In addition, the RFID-based method works also if the virtual component, assumed as reference, does not have a physical counterpart in the real world. In addition, RFID tags are not required to be visible and can be embedded within building components, keeping their position unvaried over time.

Figure 8. Accuracy assessment. The border of the box is not fully overlapped with its model. This can be due both to errors in the alignment procedure and to some installation issues (e.g., the real box could be not exactly horizontal).

5 Conclusions

In this paper a new approach for virtual BIM model alignment over physical assets through MR has been proposed. This approach exploits the use of RFID tags embedded in the real asset and handheld devices (e.g. smartphones). Among the many advantages provided by this approach we cite the chance of executing the procedure without concurrent displaying of the virtual model, the geotagging of space and the nature of tags as devices permanently embedded in buildings. This approach was integrated in a platform for the management of BIM models and was showcased in an application regarding the execution of a work order in the repairing of a communication switchboard. Future research is needed in order to overcome some limitations that have been highlighted in the paper. The first is that accuracy is still dependent on the positioning of tags and on the relative position between a tag and the NFC reader. The second one is that on-field workers must be given the opportunity to edit and enrich the model while working on-site. The third one is relative to the need for management of non-geometric information.

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