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--- ACCEPTED VERSION ---

A Collaborative Augmented Reality Annotation Tool for the Inspection of Prefabricated Buildings

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Abstract: The inspection of prefabricated buildings involves different stages and tasks such as the collection of measurements, the visual inspection of components and the written annotation of defects. Traditionally, inspectors have documented the process, the kind of defects and the proposed correction measures in paper format, hindering the collaboration with other experts (either simultaneously or asynchronously) and the collection of other types of annotations (e.g. images, 3D elements). In this paper, we present an AR tool designed to aid inspectors during this process. The tool has many benefits, as it allows simultaneously performing a collaborative inspection, taking multitype and geolocated annotations, their monitoring and edition, and performing in situ augmented visualizations. The quantitative and qualitative user evaluation carried out with our tool in a real environment (including usability and satisfaction evaluations) shows the relevance that such a technology might bring to the field and prove that our tool is usable and fulfils most of the inspectors' expectations.

Keywords: Augmented Reality; Annotations; Collaborative interaction; Prefabricated buildings; Inspection.

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1. INTRODUCTION

Prefabricated buildings are composed of factory-made units and modules that, once completed, are transported and assembled on-site to form a complete building. To ensure a minimum deviation between the designed and the built modules, inspection campaigns are carried out at different stages: first, on the individual units (e.g. panels), then, on the modules assembled in the factory and, finally, on the on-site complete building. Ensuring a minimum deviation between the designed and built modules is of utmost relevance in order to keep the energy efficiency of these kinds of buildings, among other reasons. Because of that, the inspection of prefabricated buildings is a relevant and demanding task, requiring the involvement of an expert or a group of experts (inspectors, technicians, workers) who need to work in collaboration. Some of the tasks carried out during the inspection process are the collection of measurements (e.g. distances, densities, angles), the visual examination of different components, the written annotation of possible defects, etc. During the process, the inspector decides about the defects, their importance, their intensity and their extent [39]. In order to finish an inspection, all the defects must be corrected, which can take a great deal of time (depending on the nature of the defect) and therefore, an inspection process might last several days and possibly involve different inspectors. Traditionally, the inspection process has been documented with paper support and photographs, where the tasks carried out during the inspection (e.g. measurements), the defects found and the correcting measures are annotated and documented by the inspector(s). Once finished, the annotations are manually uploaded to a dedicated managing software, at the office. Thus, the documentation of defects and their digital recording have been, traditionally, two different processes.

However, nowadays there are a variety of new technologies that can be integrated in the inspection of prefabricated buildings, allowing the on-factory and on-site digital documentation and interactive managing of defects. We argue that Augmented Reality (AR) can aid in the inspection process by allowing a real-time visual comparison of the designed and constructed building, the enhanced documentation via different types of annotations (e.g. text, images) and the online collaboration of different inspectors (simultaneously or in different periods of time), while allowing the inspector(s) to freely navigate through the real environment. Although there are some works integrating the AR technology in the construction sector, the types of annotations and the collaborative issues that this technology can bring to the field are not sufficiently exploited, to the best of our knowledge.

In this paper, we present an AR-based tool for the inspection of prefabricated buildings, which was developed in the scope of the SIRAE (*Sistema de Realidad Aumentada para la Auto-Inspección de Edificios Energéticamente Eficientes* – Augmented Reality System for the Automatic Inspection of Energy-efficient Buildings) project [2]. The project aims at detecting the quality and energy efficiency deviations between the designed and constructed buildings, focusing on prefabricated ones. To that end, we have developed a solution for automating the process and documenting the inspection of prefabricated buildings. In the project, two different tools were developed: (1) a tool that embeds the traditional inspection process while giving new functionalities to the inspectors based on digital documentation (text, images and 3D clouds of points) and AR visualizations, which was previously explained in [35]; and (2) an AR-based tool to inspect modules, for which an initial design was outlined in [16]. In the current paper, we present in detail the AR-based tool, and also give the results of a user evaluation in a real environment, after a complete module was assembled.

The novelty of our AR-based tool in comparison to other existing solutions is that it simultaneously allows: (1) a collaborative inspection of buildings (different inspectors, both in situ and asynchronously); (2) different types of annotations (texts, strokes, images, 3D models); (3) geolocated annotations (related to the virtual model of the designed modules); (4) the monitoring and edition of registered annotations; and (5) the in situ visualisation of both the designed and the actual state of the building by means of the AR technology.

The rest of the paper is structured as follows. In Section 2, we deal with the related work, paying special attention to annotations. In Section 3, we explain our AR-tool in detail, addressing its design and technological and implementation issues. Section 4 provides the quantitative and qualitative results of an evaluation carried out with users testing our technology in a real environment. Finally, the conclusion section summarizes our main findings.

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2. Related work

In this section, we focus on the use of the AR technology for tasks related to the inspection of processes in the construction sector. First, we offer a brief description of this technology and the advantages it can offer. Second, we offer a literature review of the AR technology for inspection processes. Finally, we focus our attention in the construction sector.

2.1. Definition and Advantages of AR

AR is a computer-based technology by which virtual data can be added to the user's perception of the real world. It is a transversal technology since it is applicable to multiple scenarios and in multiple areas of knowledge, including education/teaching [26, 42, 46], medicine/health [6, 9, 27], engineering [11, 32], entertainment and cultural heritage [20, 37, 40], tourism [29, 31], etc.

The term AR was coined for the first time by Caudell and Mizell [10] to describe a screen used by aircraft electricians that mixed virtual graphics with the physical environment. At that time, the definition of AR was linked to specific types of displays (Head-Mounted Displays, HMD), since they were the only ones in which this technology had been tested. It was a little bit later when AR applications were developed for other types of displays, so its definition was extended and dissociated from the visualization technology. Today, AR is referred as the technology that simultaneously combines real and virtual information, which are registered in a 3D space, and is interactive in real-time [3].

In another order of ideas, it is also possible to highlight various "potential" aspects or abilities that the AR technology provides in comparison to other technologies [5] and that are relevant for collaborative applications, i.e., applications where different users can simultaneously participate in an AR experience, as it is the case of SIRAE: (1) a seamless interaction between virtual and real environments; (2) the ability to enhance reality; (3) the presence of spatial cues for remote and face-to-face collaboration; (4) the support of a tangible interface; and (5) the ability to move smoothly between reality and virtuality.

The ability to provide interactive annotations is another relevant issue in AR, and can be very useful to aid in inspection processes. An AR annotation can be defined as virtual information that describes in some way a real object and that is linked to it [44]. The "real object" must be understood in a broad way, since it can be a part of an object, a set of them, a place or even a semantic area instead of a single physical object. Through virtual annotations anchored geographically to the real world, it is possible to communicate information about the elements of that environment so that they become a fundamental part of collaborative systems. Therefore, it could be said that an AR annotation must have at least two components to be considered as such: a spatially dependent component that links the annotation to the real object and another spatially independent component that contains the virtual information. In fact, an annotation in AR is characterized by being attached to a location, that is: the user who creates or visualizes it and the annotated object are co-located and the annotations are represented directly in this real object [23]. Some questions are essential when considering the development of an AR application that uses annotations, such as anchoring, location, content, structure, presentation, interactivity or persistence.

Finally, it can be pointed out that, although different stimuli (e.g. visual, sonic, tangible) can be included in AR applications, most of these applications deal with visual stimuli by merging virtual objects with images of the real world, which are computationally generated in real-time. The image of the real world usually comes from a camera stream and it is visualized on a screen merged with the virtual information. Nevertheless, other displays can also be used to show only the virtual information, while users see the real world through the display (e.g. see-through displays) or projected on them (e.g. AR mirrors [36]). On the other hand, AR systems based on smartphones or tablets (also called handheld AR systems) represent nowadays the most common setup, making the AR paradigm almost ubiquitous. In SIRAE, we make use of tablets in order to show the AR scene.

2.2. AR technology for inspection

The aforementioned characteristics of the AR technology make it suitable for the inspection/supervision of works in a variety of areas and environments. In the last years, different solutions have arisen, mainly for repair, assembly and maintenance, demonstrating in several cases the advantages of using this technology in comparison with the usual way of performing these operations. For example, in [24], the benefits of AR for maintenance and repair operations are studied, with a case study for military mechanics that perform routine maintenance tasks inside a turret of armoured vehicles. The study showed that AR allows mechanics to locate tasks more quickly and, in some cases, they required fewer head movements. In addition, the mechanics found the AR paradigm intuitive and satisfactory for the realization of the tested tasks. In [18] an application of AR for the motor industry is presented, allowing the assisted maintenance of parts of a vehicle, among others. The system is based on SLAM (Simultaneous Location And Mapping) techniques to allow the 3D registration in real time, and the visualization is done through a mobile device. In [43] an AR platform is presented for the training of operators in industrial assembly and maintenance skills. For visualization, they use a mobile device and the system offers haptic feedback using vibra-tactile bracelets that can apply vibration stimuli to the arm, forearm and wrist.

More recently, [47] presents a context-dependent AR system to assist in industrial maintenance tasks. In this system the operator uses a pair of AR glasses for the visualization, being these connected to a portable computer that is loaded in a backpack. For the 3D registration, ARToolKit libraries are used [25]. In [13] the development of an AR application that assists the operator, through instructions, in maintenance work is provided. In this case, the visualization of the augmented environment is done on a large screen, rather than through the use of mobile devices, which is usually the most common case. On the other hand, in [14] a work is presented, which focuses on the use of AR technology to show cognitive help in the work environment. A series of recommendations are offered when designing applications of this type, among which it is important to keep the instructions as simple as possible or that the visual content must be shown in the precise place where the operation should be carried out. Finally, it is worth mentioning the work provided in [34], where a systematic review of AR applications for maintenance is carried out, also highlighting the next development trends of this technology for that purpose, among them, hardware, recognition and human-machine interaction.

The use of AR annotations in collaborative and remote assistance applications for conducting inspections, maintenance and repairs is being studied in recent years. In [17] we can find an example of how a local user and a remote user communicate through geolocated AR annotations to perform teleassistance operations. After conducting a study with 60 users with the task of repairing a car, they conclude that their system is much more effective than a traditional videoconference or systems with fixed annotations (without geolocation). More recently, in [48] a remote user can place world-stabilized text, image and stroke annotations in the scene in order to help the local user in their maintenance tasks. With a similar purpose, [15] propose a solution that combines different types of user immersion in a collaborative system that allows navigation, pointing out objects and taking annotations.

2.3. AR technology in the construction sector

AR technology is being integrated in the construction sector by using mobile devices, such as smartphones or tablets. These devices are lightweight, integrate at least one camera and are provided with other sensors, such as accelerometers, making them suitable for AR applications. The integration of robust AR applications in construction areas is nevertheless not trivial, as the environmental conditions can be particularly harsh (dust, changing light conditions, electromagnetic noise, etc.). Therefore, factories, construction sites and other similar environments represent a challenge for the use of AR applications. An example of the use of AR in a complex hostile environment is presented in [1] to aid improving the supervision and maintenance tasks in the Large Hadron Collider at CERN, Genova. In this work, a gamma camera is used to capture the emitted radiation and show it for workers on top of visible images.

Other works are focused on aiding the inspectors in the assessment of building quality and their documentation by means of AR tools. In [38], a mobile AR application is shown, which is designed for industrial building environments, and that enables comparing as-planned documentation with the factory that was actually built by overlaying 3D information on top of images. In addition, the user could immediately annotate the observed artefacts in the AR overlay view using a stylus. The work described in [21] brings a method based on an energy performance AR environment that deals with the automated analysis and visualization of deviations between buildings' actual and simulated energy performances. In [30] a mobile defect management AR application is presented that enables workers and managers to automatically detect dimension errors and omissions on the jobsite. In [28] a mobile AR application is presented for Building Information Models (BIM) registration,

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where positioning in real-time is achieved by means of a Kinect sensor. The use of BIMs is increasing in the architecture, engineering and construction industries and a tighter coupling with tools based on AR concepts are being studied in different research. Some examples are [22, 45], which incorporate AR annotations in their systems in order to facilitate the work of users. In [19], an AR-aided inspecting system for construction sites is proposed and tested. Real world appears in the background with the construction plans superimposed, allowing users to inspect all the visible elements of a given building, to guarantee that these elements are built in the correct place and orientation and to add annotations as the building process is completed. Finally, in [12] a work is presented that allows on-site acoustic inspections, where the measurement data is post-processed and converted into a three-dimensional numerical model of the acoustic indicators, which is integrated afterwards into an AR application.

Although the AR technology can bring many benefits for the inspection of buildings, we have not found a dedicated solution for the inspection of prefabricated buildings that takes into account a variety of annotations and the consideration of multiple inspectors. In this sense, our tool is novel, as it combines the advantages of a collaborative system with the versatility of editable, multitype and geolocalized annotations. Moreover, all this is embedded in an AR environment that allows simultaneously visualizing both a 3D model of the prefabricated module (previously designed) and the actual module as it has been built.

3. Material and methods

In this section, we detail the operation and functionalities of the AR-based tool as well as the software and hardware used to implement it. Figure 1 shows how the different components of the system, which are explained in the following subsections, interrelate. In the central part of the figure, we can see the hardware with which the operators inspect the prefabricated modules and the type of annotations that they can take. With these devices and the related software, it is possible to georeference the inspectors. All the information taken by the application is stored in a database and can be consulted and modified thanks to a REST service, as we can see in the right part of Figure 1. The left part of the image represents the interface of the AR application, with the annotations and the virtual model of the prefabricated module superimposed on the real world.

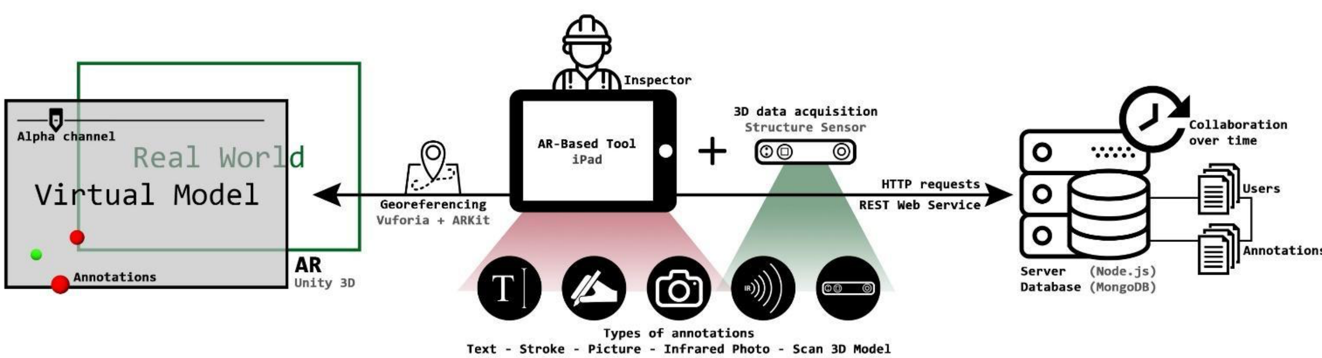

Fig. 1. Scheme of the different components of the system

3.1. Description of the System

The inspection tool based on AR annotations that we present in this work has been developed with Unity3D, a cross-platform game engine [41]. Our AR application allows to establish a spatial relationship between the virtual information and the elements of the real world during the inspection of prefabricated buildings. With this purpose, the inspectors need to carry an iPad equipped with an Occipital's Structure Sensor [33] and with our AR-based tool installed. This hardware is suitable to support the needs of the SIRAE project, as explained in [35]. In addition, there are two previous requirements for our application to work. On the one hand, it is necessary to load into the system the 3D model of the prefabricated module that is going to be inspected. This is straightforward to achieve, since precisely the goal of these inspections is to identify the

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deviations between what it was designed and what it has been built, so such a 3D model is available in the majority of cases. On the other hand, it is necessary to have some AR markers placed in the prefabricated module in order to perform an initial alignment of the virtual model and the real world, as explained next.

Once an inspector is physically located in the prefabricated module that needs to be reviewed, he or she uses the AR application to superimpose the predesigned 3D model of the module on the real world. When the operator focuses on an AR marker with the camera of the mobile device, the two worlds are aligned, so he or she is able to move around the augmented module in order to inspect it. When a defect is detected during the inspection, the worker indicates the point in the virtual model that he or she wants to highlight and takes an annotation. Locations with annotations are virtually represented as small spheres. In subsequent inspections, this virtual information, which has a spatial relationship with a specific location of the prefabricated module, can be consulted by other operators in order to add new information or to mark it as corrected when the problem has been solved.

The AR tool integrates an alpha channel that operates on the virtual model of the prefabricated module. The level of transparency can be adjusted at any time, which allows visualising a completely real world, a purely virtual world or intermediate transitions between both. In this regard, the application provides a slider at the top of the screen. Moving it from left to right, the inspectors can see the transition from a purely virtual world to a completely real world, as can be seen in Figure 2. This functionality is crucial to compare the real elements with their virtual counterparts and thus detect the possible geometric deviations existing in the prefabricated modules. Transparency is not applied to the spheres that represent the annotations because, although they are virtual elements, they must always be visible during the inspection, no matter if the inspector is visualising a real or a virtual environment.

(a) (b) (c)

Fig. 2. Examples of alpha channel, where: (a) alpha channel at 0%, where only the real world is visualized; (b) alpha channel approximately at 50%, which shows a mixed world between the real and the virtual; (c) alpha channel at 100%, which shows the virtual world

The indoor positioning needed for the correct operation of the AR application is obtained using the Vuforia and ARKit libraries. These libraries allow developing AR applications with navigation based on image recognition. Thanks to Vuforia, the application captures the different AR markers distributed through the prefabricated modules in order to use them as reference and thus be able to align the virtual model with the real world. Once the initial alignment is done, ARKit relies on the analysis of the image and the orientation of the mobile device to know the location of the point of view of the user and obtain his or her positioning relative to the AR markers. In this way, inspectors can move around the prefabricated module without losing the alignment of the 3D model with respect to the real environment. Each time the system detects an AR marker, it corrects the spatial alignment, achieving a more accurate positioning. The amount of markers needed and the minimum distance between them depends on the environment: the fewer textures there are, the more probability of tracking error there is and the more markers are necessary. These variables make it difficult to determine a priori how often it is necessary to revisit an AR marker in order to realign the real and the virtual worlds. In the user tests carried out, explained in

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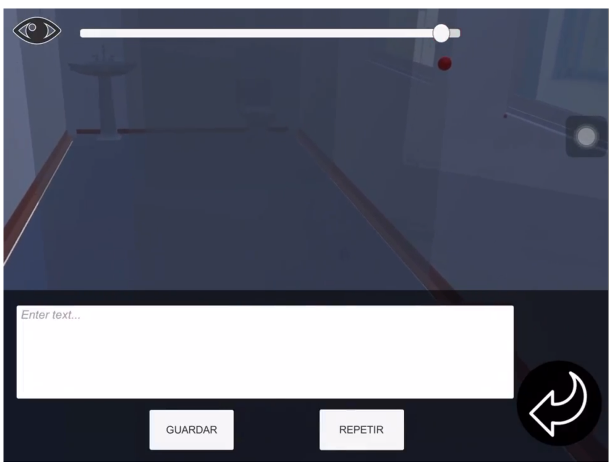
section 4, it was observed that users could inspect each individual module for approximately 5 minutes before appreciating that the virtual information was not correctly aligned with the real world and that it was necessary to revisit an AR marker.

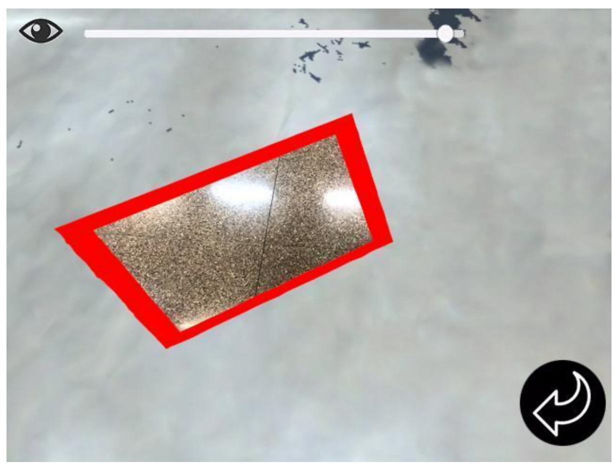
3.2. Annotations

Our AR tool allows to perform five types of annotations: write a text, take an RGB image (acquired with the iPad), take an infrared image (acquired with the Structure Sensor), scan a 3D model and draw lines. All of them are spatially linked to the real world automatically, out of the text-type. This is because the other annotations have a direct spatial relationship with the real world, while the text-type ones involve additional information to the inspected objects. To create a text-type annotation, the inspector must first select on the screen of the mobile device the point of the 3D model that he or she wants to annotate. Then, a text box opens, in which he or she can enter the desired text, as we can see in Figure 3a. When a photographic annotation is taken, either normal or infrared, a small sphere is linked to the real world through the coordinates where it was taken. Later, the picture can be viewed in two ways: in a traditional image gallery or projected on the virtual model, as can be seen in Figure 3b. For this second modality, the necessary deformations are applied to obtain a perspective that corresponds to the current user's point of view.

In addition, inspectors can scan part of the real world to build a 3D model of the part of the prefabricated module that they want to convert into an annotation. To do this, the application captures a cloud of points, converts it into a 3D model and links it to the coordinates where the scan was made. In Figure 3c, we can see an example of a scanning process. Finally, if the user chooses to make a stroke-type annotation, he or she can draw on the scene using his or her finger as a pencil. This allows the inspectors to highlight the errors detected in the module by means of circles or arrows, for instance. In Figure 3d, we show a user taking a stroke-type annotation.



(a)



(b)

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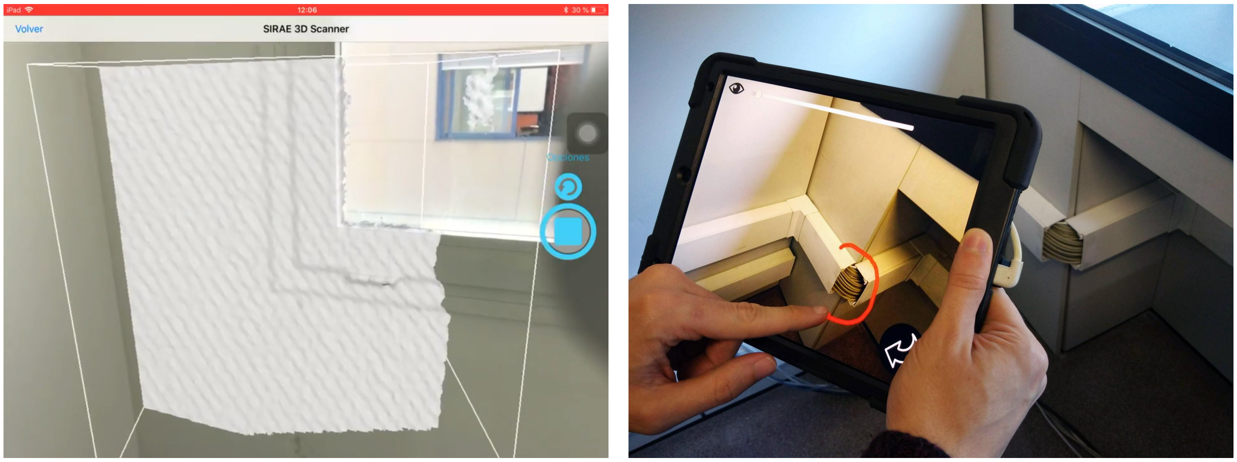
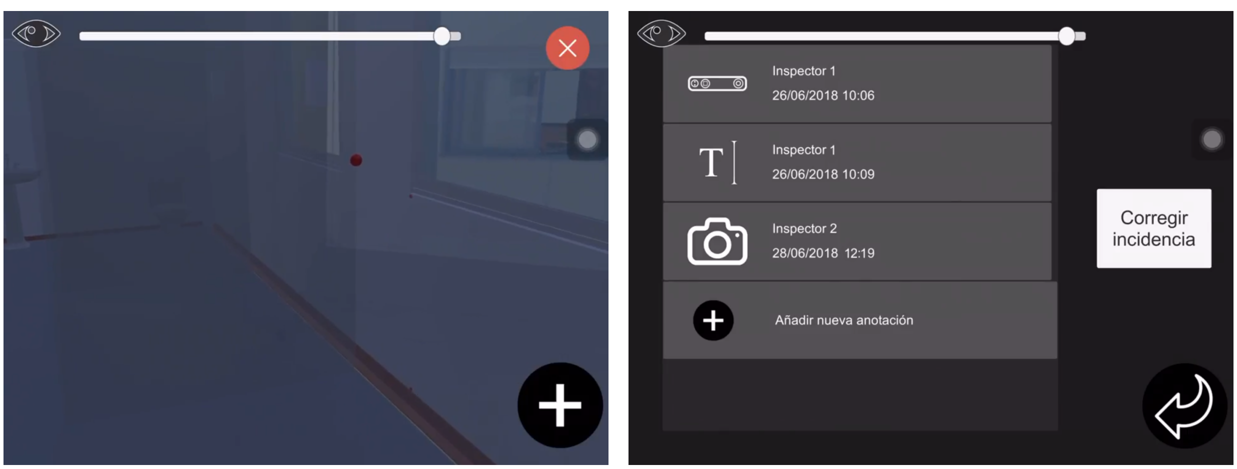


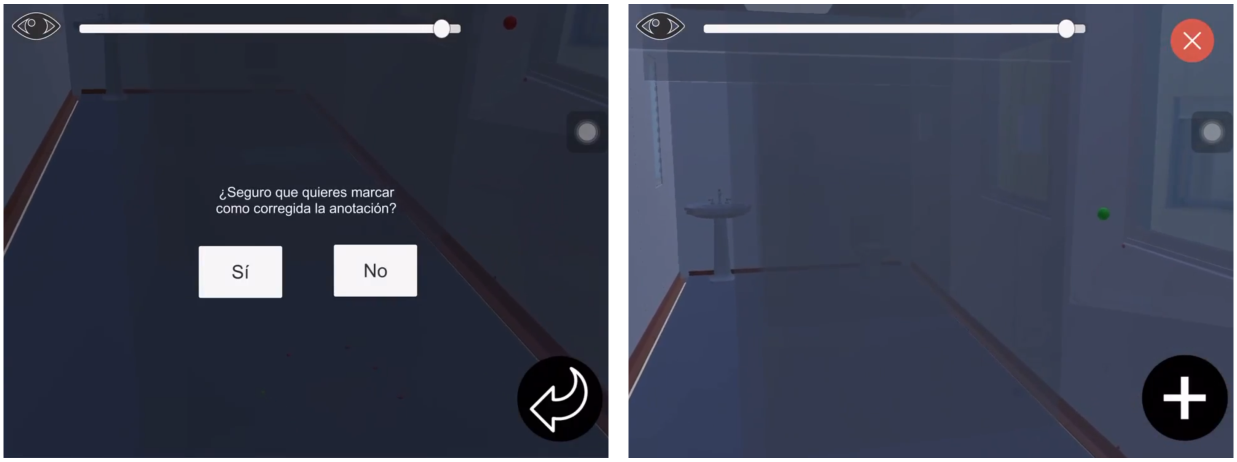
(c) (d)

Fig. 3. Examples of different types of annotations: (a) interface to create a text annotation; (b) projection on the floor of a photographic annotation; (c) scanning the corner of a window to generate its 3D model; (d) creation of a stroke-type annotation

When an annotation has been created and saved by an inspector, he or she can modify or delete it. In addition, other operators can view it and add new information in subsequent inspections of the prefabricated module. This allows a collaboration over time between the different workers who review the module. Usually, an annotation is taken to indicate a defect detected in a prefabricated module. When the defect is solved, the annotation must be modified and marked as "corrected". With this purpose, annotations are represented by small red spheres and, once corrected, they become green. In Figure 4, we can see the process of correcting an annotation. The application provides the possibility to hide annotations already corrected to improve the interaction with other spheres.



(a) (b)



(c) (d)

Fig. 4. Example of how an inspector corrects an annotation, where: (a) the annotation is not corrected and it is represented as a small red sphere; (b) by clicking on the sphere, a panel with all the information of the annotation (history of editions) and the button "Correct incidence" is displayed; (c) window to confirm that it is desired to mark the annotation as corrected; (d) corrected annotation, represented by a small green sphere

A single sphere represents a combination of annotations for a single location, which are acquired throughout the successive revisions made during an inspection. For instance, Inspector 1 can take a text-type annotation indicating that a wall is defective and then scan the wall to document the defect through a 3D model. Both annotations are anchored to a single point of the virtual model of the prefabricated module by means of a red sphere. Once the error is corrected, Inspector 2 can take an image linked to the same annotation to document that the problem in the wall has been already fixed. Figure 4b depicts the panel showing the annotation history with all this information. To achieve this, it is necessary to store the history of editions of each annotation. With this objective, a REST web service has been developed. The server has been implemented with Node.js and a MongoDB database. The AR application makes HTTP requests to this server to store and retrieve all the information related to the annotations. Thus, the database stores, for each annotation, the following information: the type, the user who created it, the date and time of creation, the initial content, the point of view from which it was taken, whether it has been corrected or not and each one of the modifications that it has suffered over time, with its corresponding content, point of view, user, date and time.

In our work, we have paid attention to other details such as the occlusion of the spheres that indicate the location of the annotations. Occlusion in AR applications consists in the ability to hide virtual objects behind the real ones in order to achieve a perfect integration between the real and the virtual worlds. As we said before, the spheres are not affected by the alpha channel, so they are always visible even when the transparency level is 100%. Therefore, a proper occlusion with the real elements of the scene should be calculated. Since a 3D model of the prefabricated module is available, it is possible to use it as a phantom object in order to perform the occlusion of the spheres correctly, as we can see in Figure 5.

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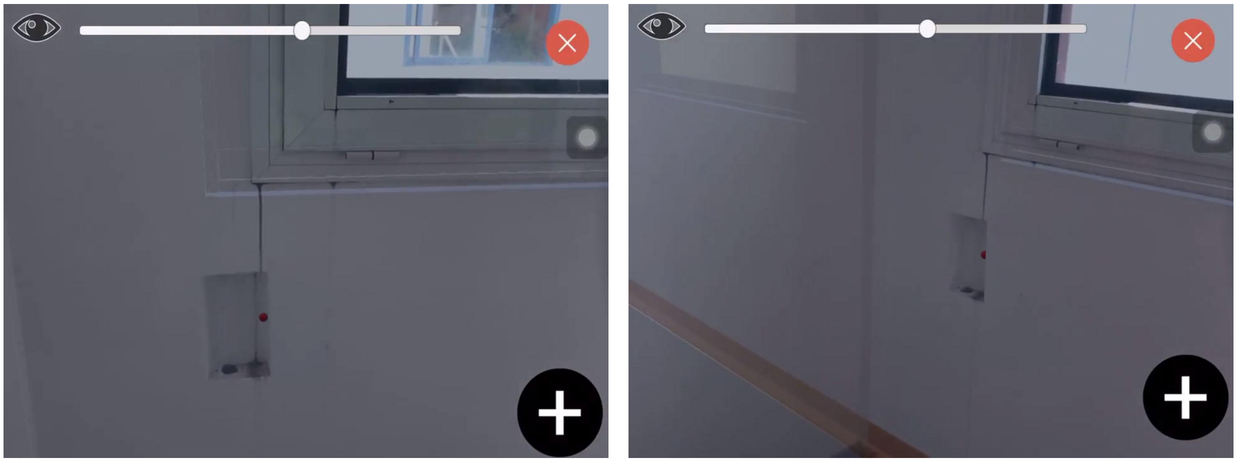

(a) (b)

Fig. 5. Example of partial occlusion of a sphere using the 3D model of the prefabricated module as a phantom object. In (a) and in (b) the same sphere is shown from two different points of view

4. Evaluation and Results

The validation of the system in a real environment was carried out in a factory of prefabricated buildings located in Seville (Spain). A module was selected to that end which was completely assembled next to the factory, thus simulating a real constructive environment. The module has a plant dimension of 11.4 x 3.4 m, being composed of five small rooms, as indicated in Figure 6. A total of four AR markers were placed in the rooms, as indicated in Figure 6, to a height of 1.6 m. The room to the right-most part of this figure was not considered for the tests, and thus a marker was not placed there.

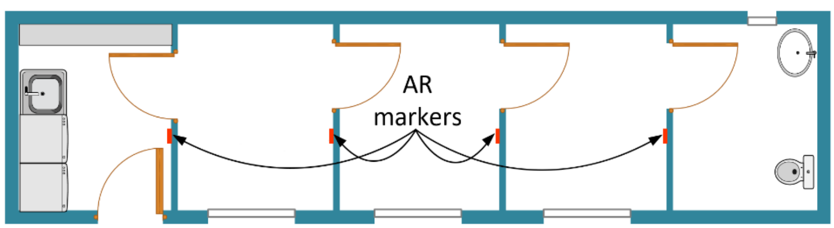

Fig. 6. Plan view of the module used for the validation of the system with the indication of the AR markers' location. As it can be seen, only the four left-most rooms are used for the tests and are provided with AR markers.

The AR tool was tested by a total of eleven people with ages ranging from 28 to 56 years old. There were five women and six men. Half of the participants (six out of eleven) reported to have very little or no experience using AR systems. All of them were inspectors with previous experience in the inspection process. In Figure 7 it can be seen an inspector using our application.

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Fig. 7. An inspector testing our AR-based tool in a real environment

Before the inspection took place, the tool was explained individually to all participants. They were then asked to do the following tasks:

A. To initiate the tool by introducing the project reference, their inspector's id and the date.
B. To do an initial alignment of the real and virtual worlds.
C. To use at least once the alpha channel during the inspection.
D. To revisit at least one annotation made by another inspector.
E. To make at least two annotations of different nature on at least one place.
F. To revisit at least one of their own annotations.
G. To delete at least one annotation.

The first two indications, A and B, needed to be done in the first place. Indication F was only possible after E. The rest of indications could be done in the desired order. A possible sequence could be: A, B, E, C, F, G, D. In order to ensure that they completed all tasks, a person was guiding them during the process.

As a measure of validation, the participants were asked to complete a test of usability, a test of user satisfaction, and were also prompted to give some additional comments on the performed tasks. The outcomes of these tests are reported in the following subsections.

4.1. Usability test

The SUS (System Usability Scale) test was used as a measure of usability [7]. SUS provides a fast and reliable way to measure the usability of a tool. It consists of a 10-item questionnaire with five response options: from strongly agree (5 points) to strongly disagree (1 point). Originally created by John Brooke in 1996, the SUS allows evaluating a wide variety of products and services, including hardware, software, mobile devices, websites and applications. The noted benefits of using SUS include that: it is a very easy scale; it can be used with small samples with reliable results; it can effectively differentiate between usable and unusable systems. The SUS questions are depicted in Table 1. As it can be seen, odd questions are formulated in a positive way, and thus the best possible score would be 5 points, whereas even questions are formulated in a negative way, and therefore for this case the best possible score would be 1 point. The individual scores given by users and the calculated SUS score are shown in Table 2. Additionally, we also provide the average, standard deviation (s.d.) and the minimum (min) and maximum (max) values for each of the questions and the individual SUS score. The values of the SUS score range from 0 to 100, with 100 meaning the best imaginable result. In our case, this score reaches 81.36 points, which can be considered between "good" and "excellent" on the scale of scores provided by the questionnaire and taking into account the fact that a minimum score of 68 would be deemed acceptable for a tool [4, 8]. Note that the SUS score is the average value of the individual SUS scores.

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Table 1
SUS questions

Questions
Q1. I think that I would like to use this system frequently.
Q2. I found the system unnecessarily complex.
Q3. I thought the system was easy to use.
Q4. I think that I would need the support of a technical person to be able to use this system.
Q5. I found the various functions in this system were well integrated.
Q6. I thought there was too much inconsistency in this system.
Q7. I would imagine that the most people would learn to use this system very quickly.
Q8. I found the system very cumbersome to use.
Q9. I felt very confident using the system.
Q10. I needed to learn a lot of things before I could get going with this system.

Table 2
Scores given by users (Ui) in response to the SUS questions (Qi). The last column shows the individual SUS scores, and the last row shows the SUS score.

id	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q9*	*Q10*	*SUS*
U1	5	1	5	2	4	1	5	1	4	2	90.00
U2	4	1	4	3	4	2	4	1	3	1	77.50
U3	3	2	4	1	3	1	4	2	3	1	75.00
U4	4	2	4	2	5	2	4	2	4	2	77.50
U5	4	1	3	1	5	1	5	2	5	1	90.00
U6	4	2	3	1	2	4	4	2	3	1	65.00
U7	5	1	5	1	4	2	5	1	5	1	95.00
U8	4	1	5	4	5	1	4	1	4	2	82.50
U9	5	3	4	2	4	2	4	2	4	2	75.00
U10	5	2	4	2	4	3	4	1	4	2	77.50
U11	5	1	4	1	4	2	5	1	5	2	90.00
average	4.36	1.55	4.09	1.82	4.00	1.91	4.36	1.45	4.00	1.55	**81.36***
s.d.	0.67	0.69	0.70	0.98	0.89	0.94	0.50	0.52	0.77	0.52	8.97
min	3	1	3	1	2	1	4	1	3	1	65.00
max	5	3	5	4	5	4	5	2	5	2	95.00

**** SUS score***

4.2. Satisfaction test

In order to evaluate the user satisfaction in using the SIRAE tool, a few questions were further asked, which are depicted in Table 3. The possible response options are aligned with that of the SUS questionnaire, i.e.: from strongly agree (5 points) to strongly disagree (1 point). However, in this case all questions are formulated in a positive way, meaning that the best possible score to all questions is 5 points. The scores given by users to this questionnaire are shown in Table 4. It is worth mentioning that, in this case, we are not computing a global score in a range scale of 100 points, as this is particular for the SUS score. However, we provide the average, standard deviation (s.d.) and the minimum (min) and maximum (max) values for each of the questions. Additionally, as all questions are formulated in a positive way, we also provide these statistical values for each of the users. It can be seen that, the individual lowest average values are for users U3 and U6, who also give the lowest individual SUS scores (Table 2). In fact, the Pearson correlation coefficient between the individual SUS scores

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(Table 2) and the individual averages (Table 4) is r(9) = 0.58, p = .059. In Table 4, it can be seen that the punctuations that are most repeated for all users correspond to the highest values (4 or 5 points). Regarding the neutral score (3 points), all questions receive one or two neutral votes. Only Q1 receives a vote that can be considered negative (2 points), and the worst value of the scale (1 point) is not chosen by any of the users in any of the questions. It is remarkable that the average values for all the questions are above 4 points, being Q3 the one that receives the highest average value. Based on these results, it can be said that the enquired users are satisfied with the tool, and that they especially appreciate the added value for documenting the geometry of the elements.

Table 3
Questions to evaluate the overall satisfaction of the AR tool

Questions
Q1. I believe that inspection times can be reduced by using the SIRAE tool.
Q2. The SIRAE tool has allowed me to document the inspection process in a more comfortable way than usual.
Q3. I think that the possibility of documenting the geometry of the elements (3D point clouds) is certainly an added value to the inspection.
Q4. I think the SIRAE tool is suitable for use in a work environment.

Table 4
Scores given by users (Ui) in response to the user satisfaction questions (Qi)

id	*Q1*	*Q2*	*Q3*	*Q4*	*average*	*s.d.*	*min*	*max*
U1	5	5	5	4	4.75	0.50	4	5
U2	3	4	5	5	4.25	0.96	3	5
U3	2	3	4	3	3.00	0.82	2	4
U4	5	4	5	5	4.75	0.50	4	5
U5	5	4	5	5	4.75	0.50	4	5
U6	4	5	3	3	3.75	0.96	3	5
U7	5	3	5	5	4.50	1.00	3	5
U8	4	5	5	4	4.50	0.58	4	5
U9	4	4	5	5	4.50	0.58	4	5
U10	4	4	5	5	4.50	0.58	4	5
U11	5	4	5	5	4.75	0.50	4	5
average	4.18	4.09	4.73	4.45				
s.d.	0.98	0.70	0.65	0.82				
min	2	3	3	3				
max	5	5	5	5				

4.3. Qualitative evaluation

Users were asked if they would also like to highlight any aspect to improve the tool. In the following points, the given answers are shown followed by a brief discussion. We have grouped them according to data, process, hardware or software issues:

- *Data*: Two users point out that it would be interesting to have a summary of the inspection process and be able to deliver it to the clients. One user said that it would be interesting to export the collected data in different formats.
  Regarding the first point, the results are stored in a database, so a form could be built to show the collected data and the comments given by the inspectors during the inspection process. The collected data is stored in standard formats.
- *Process*: Three users found tedious the alignment process between the real and the virtual worlds and the fact that realignment was needed from time to time. One user said that it could be useful to define an inspection protocol.

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Navigation in indoor environments is indeed challenging. In our case, we used a single AR marker per room (recall Figure 6), what seemed not enough for the navigation because the walls were flat and with a homogeneous white colour. Therefore, alignment was required from time to time. On the other hand, an inspection protocol could be defined by the inspectors, and this could be easily integrated in the software solution by giving indications on the next steps to follow. Nevertheless, we think it is best to design the application as generally as possible, so that it could be used with different inspection protocols.

- *Hardware*: One user pointed out that it would be useful to add a thermal camera, and maybe to allow a mapping of this thermal image to the 3D cloud of points. Another complaint was raised about the brightness of the screen, as he or she needed to put it to the maximum to correctly visualize the different elements.
  Collecting images of an additional external camera and storing those images in the database would be easy to accomplish, although thermal cameras are rather expensive. However, in order to allow a mapping from an external camera to the 3D cloud of points, a calibration process would be required. Regarding the screen brightness, it is a limitation of the mobile devices.
- *Software*: Three users complained about the size of the spheres embedding the annotations, saying that they should be bigger. One user pointed out that the initial loading time could be shorter.
  The size of the spheres was corrected after the tests, so they can be better depicted and selected during the inspection process. In any case, they can be easily changed or even configured by the user. The loading time depends on the speed of the connection to the server and the complexity of the virtual elements that are loaded. In this sense, they can be simplified to reduce the loading time.

Regarding the multitype and geolocated annotations of our AR tool, we only received a comment to improve it, the one regarding the size of the spheres (above, in 'software'). On the other hand, we can state that all inspectors were able to successfully deal with all the requested tasks related to annotations (i.e. D, E, F, G). Upon observation of the inspection carried out by all users, we can add that this task was of great interest for them, as they asked us several questions on how to do this and that and wished to complete all tasks.

5. CONCLUSION

In this paper, we have presented the design and the user evaluation of an AR tool aimed to aid inspectors during the inspection process of prefabricated buildings. We have shown the benefits that the tool provides, including collaborative issues and enhanced annotations. Being these aspects fundamental for the documentation of the inspection and for the application of correcting measures, we believe that other existing software solutions do not put enough emphasis on them. On the contrary, our technology allows the multitype (texts, strokes, images, 3D models) and geolocated acquisition of annotations that can be consulted and edited by the person doing the inspection or by other inspectors simultaneously or in different time intervals.

After some user tests carried out at a real scenario, including a usability evaluation by means of a SUS questionnaire and a quantitative and qualitative satisfaction evaluation, we have proved that our tool is usable and fulfils most of the inspectors' expectations, with few improvements left to tackle. As future work, we aim at generalizing our tool so it can be used in other environments requiring inspections, such as those related to industrial processes. As part of this generalization process, a multi-platform solution could be developed in a short period of time thanks to the continuous advances of the ARKit and ARCore libraries. In addition, we intend to integrate virtual indications that aid inspectors fulfilling the process.

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