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HOLOGRAPHIC SAFETY PRESCRIPTIONS FOR AR-BASED CONSTRUCTION INSPECTIONS

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Abstract

Safety management and monitoring are critical challenges in the Architecture, Engineering, Construction and Operations (AECO) industry, which is characterized by a high incidence of workplace injuries and fatalities, as well as limited process digitization. On-site safety inspections rely on inspectors' expertise and standardized checklists, making the process susceptible to human error and bias. This research aims to introduce a more effective paradigm for safety monitoring, leveraging technologies such as Augmented Reality (AR) and Building Information Modeling (BIM) to enhance the accessibility of safety plans on construction sites and to document the progression of safety equipment layouts faster.

Introduction

The construction sector is historically known to be one of the riskiest sectors in terms of injuries and fatalities. According to INAIL report, in Italy around 40,000 work-related accidents were reported in the construction sector in 2022, including 175 fatalities, which places construction in second place after the manufacturing sector in terms of the number of fatalities reported. The European Council enacted the European Safety Directive 92/57/EEC in 1992. This directive imposes a clear obligation on the client or project supervisor to draw up a Safety and Health Plan (SHP) for each project before construction begins (art.3). SHP comprises a codified set of regulations relating to hazard prevention, encompassing such aspects as the provision of safety equipment and procedures, the implementation of mandatory checks, and the configuration of construction site layout. Such regulations are specific for the specific construction site in question, with the requisite consideration given to the nature of industrial activities that are being conducted on the site and the associated risks (e.g. burial during excavation, falling from a height, drowning, etc.). Compliance of construction site's status and practices with SHP is verified through periodic inspections, carried out by labour inspectors. Since the contents of SHP are not structured according to a time schedule of building phases, consultation can be challenging both for operators (who must implement safety regulations) and for inspectors (who must verify the compliance with SHP) (Semeraro, 2022). Moreover, it is crucial to acknowledge that the construction sector is the least digitalized sector to date (Brilakis et al., 2020). Recent technological advancements, such as Building Information Modelling (BIM), facilitate the three-dimensional visualisation of projects enables the incorporation of pertinent information concerning the project's entities. Nevertheless, the inherent static nature of BIM remains a concern, and the existence of numerous BIM authoring software programs gives rise to challenges related to interoperability and management of processes (Khudhair et al., 2021; Corneli et al., 2023). The implications of scarce digitization also refletcs upon safety management matters. In particular, safety inspections today follow an inefficient process, which heavily relies on manual data collection via checklists derived from templates, resulting in not very site-specific procedures and delays in safety management decision-making (Rey et al., 2021). In addition to that, labour inspectorates cannot have an inspector on each construction site to continuously force compliance with the laws and regulations (Dias, 2009). Given the limited human resources, it is mandatory to implement new methodologies for accelerating and enhancing the precision of the preparation, data gathering and decision making of site inspections. The present research explores the possibilities offered by digital tools such as BIM, AR and cloud platforms for data management to propose a new and more efficient paradigm for the operational management of safety monitoring.

Literature review

Drawbacks related to actual safety inspections methods

The on-site inspection process is comprised of three macro-phases: (i) preparation, (ii) execution and (iii) report writing and potential action in the event of non-compliance with the SHP (Dias, 2009). These macro-phases are further delineated into sub-phases, as illustrated in Figure 1. According to (Dias, 2009), inspection visits to construction sites by labour inspectors should take a proactive approach and use a systematic process. Proactive monitoring involves regular inspections to ensure that safety conditions are based on goals and planning, and that barriers and control measures are working adequately. This is in contrast to a reactive approach, which acts on the basis of data related to accidents that have already occurred (Dias, 2009; Rey et al., 2022). Frequent and efficient inspections have proved to be effective in terms of improving workplace conditions (Lin et. al, 2014; Rey et al., 2022). However, as previously mentioned in the introduction, the process of site safety monitoring relies heavily on manual data collection and the experience of inspectors, resulting in a low degree of standardisation (Rey et al., 2021). This forces safety specialists to mostly rely on their experience to check the overall site surroundings and identify the most alarming issues, resulting in human errors and bias (Lin et al., 2014).

Additionally, safety specialists may face challenges in delivering precise regulatory guidance to workers when identifying safety hazards, as relevant safety rules or training materials may not be readily available or easily accessible on-site (Lin et al., 2014). In addition to that, the process of manually re-entering in the final report defect information that has already been documented (in shop drawings or on-site paper records) is inefficient and redundant. This practice not only consumes additional time and resources but also increases the risk of errors such as omissions and inaccuracies in defect data (Park et al., 2013). In order to make a significant improvement in terms of effectiveness of construction safety inspections, we must provide inspectors with simple digital tools capable of supporting multiple steps of inspection phases, highlighted in Fig. 1.

Safety knowledge definition

The AECO sector differs significantly from other sectors due to several distinctive characteristics, starting from the fact that a construction site evolves overtime, as work proceeds. The nature of processes, management practices, organizational structures, working environments, and most of all the behavioural patterns of its workforce, imply a certain degree of unpredictability, hence the definition of construction site as complex system. The inherent complexity of construction site as a system presents significant challenges in establishing standardized practices and advancing toward full digitization (Li et al, 2015; Corneli et al., 2023; Messi et al., 2024; Dobrucali et al., 2024). The utilisation of Building Information Modelling (BIM) has become a prevalent practice within the industry, encompassing the modelling of parametric objects that are embedded with non-geometric data. Interoperability between different BIM software is a crucial issue in construction management. The Industry Foundation Classes (IFC) data schema is currently the most widely used open exchange format, governed by the European standard EN ISO 16739-1 (2024). However, it is important to acknowledge the inherent limitations of BIM when employed in isolation. To effectively represent more dynamic processes, a combination of BIM with other technologies (e.g. AR) is essential (Khudhair et al., 2021).

The AR implementation in the AEC sector

AR enables context-aware visualization of project information. AR integrates virtual objects with real-world imagery in real time using camera input, enabling proactive detection and prevention of construction site issues like omission errors and dimensional deviations. AR has already been used in operator training by simulating project-specific scenarios (Harichandran et al., 2024). A key challenge when dealing with AR is that of spatial registration, which means aligning holograms with the real-world objects, which require the solving of a 6-degree-of-freedom (6-DoF) pose estimation problem (Messi et al., 2024). AR devices typically use onboard sensors (e.g., cameras, IMUs) to align holograms within a local reference system. In order to achieve a more precise localisation, which is also referenced to the global reference system (WGS-84), a hybrid Real-Time Kinematic (RTK), Global Navigation Satellite System (GNSS) and Simultaneous localization and mapping (SLAM) Outdoor Augmented Reality System, was able to maintain a high accuracy tracking also in wide and unprepared scenarios (Ling et al., 2019). The limitations when using GNSS for localization and tracking are related to the lack or loss of signal that occurs in indoor scenarios or urban canyons (Ling et al., 2019). In such cases, it is possible to rely on image-based registration methods. HF-Net is a hierarchical localization approach that relies on computer vision algorithms capable of extracting and matching visual features from point clouds or images in order to obtain accurate positioning (Sarlin et al., 2019; Sarlin et al., 2022). However, this approach tends to exhibit limitations in performance when applied to scenarios characterized by monotonous patterns or a limited number of reference points, which can hinder accurate detection and assessment. By means of an AR cloud platform integrating two high precision GNSS/inertial-based and image-based registration engines and an engine switcher, it is possible to seamlessly align BIM models, images, and point clouds within a unified geospatial context. This integration compensates for the loss of GNSS signal, ensuring accurate spatial positioning even in environments where satellite-based localization is unreliable (Messi et al., 2024). Despite advancements in digital tools implementation, there is still no unified system for managing site safety that allows safety information to be automatically extracted and visually linked to the specific real world elements requiring verification.

In order to fill the gaps regarding nowadays safety monitoring procedures and tools addressed in this section, this research aims to answer the following research question:

RQ What data architecture allows for the description and query of safety regulations to be followed on construction sites, enabling their consultation through AR?

Methodology

AR-based safety monitoring framework

The proposed method is founded on the results of (Messi et al., 2024). In response to the RQ identified in the previous section, and in order to enhance the effectiveness of on-site safety inspections in terms of accuracy and speed of performance, the intention is to upload a geo-referenced IFC file of safety equipment (e.g. scaffolding, mobile scaffolding, fencing, monoblocs, etc.) to an AR cloud platform. This file originates from the IFC export of a model created using BIM authoring software. Within this model are elements we conventionally decided to refer as 'Safety Boxes' (Figure 2). Safety Boxes serve both as placeholders and containers for displaying safety checks in AR during the inspections, associated with the various elements that compose safety equipment. The modeling of Safety Boxes will be discussed in detail in the subsequent sections. The model and the information it contains will be used as the basis for creating a two-way flow of information from the site to the cloud platform and vice-versa, enabling two key applications:

1. The possibility to automatically extract and visualize through AR the information regarding the safety requirements contained in the IFC file.
2. The automatic creation of a database of geolocated images aligned to the BIM model, which can be very supportive in reducing the report redaction time. Moreover, the images database can be consulted at any time during the evolution of the construction site.

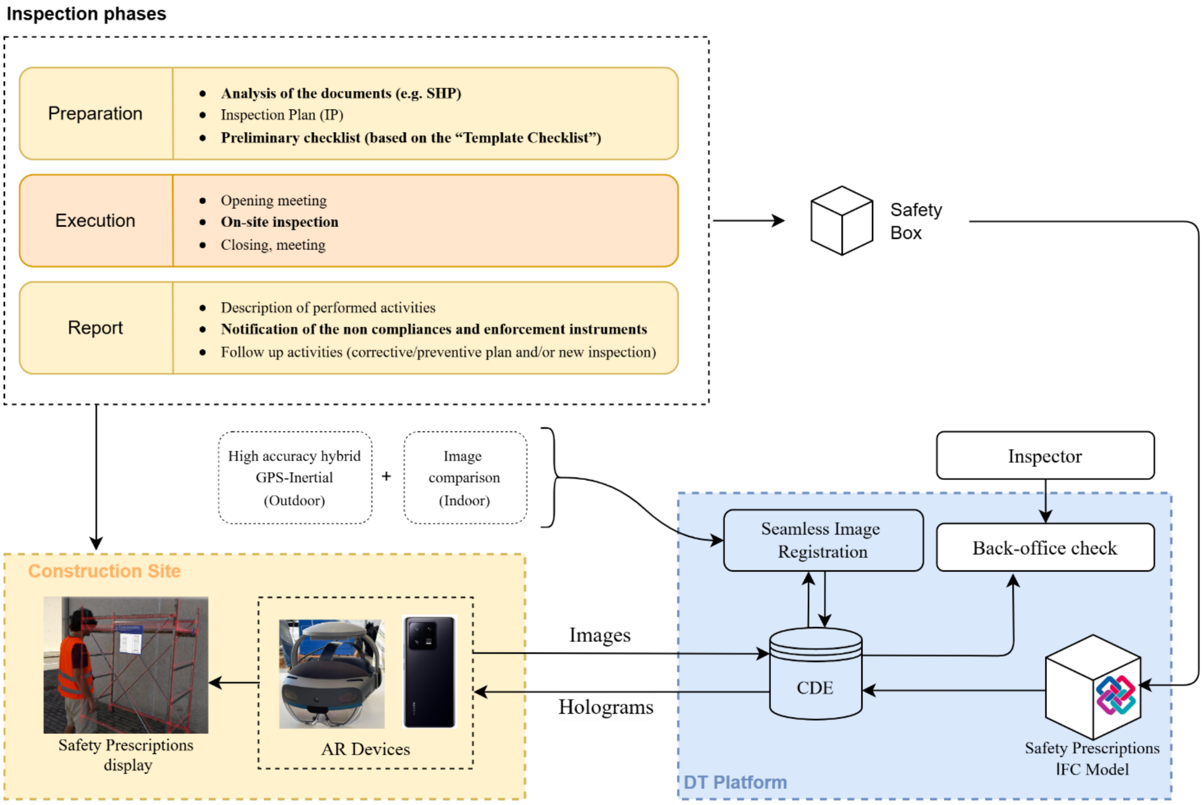

Figure 1: System architecture.

System Architecture

The AR platform architecture comprises a cloud-based system and an AR client, integrating services such as data storage, GNSS-based and image-based AR registration engines and an engine switcher. It facilitates data processing, storage, and distribution via a RESTful API. A key feature is its capability to localize and align BIM models, images, and point clouds within a unified geospatial framework based on the WGS-84 standard. This enables bidirectional data exchange (Figure 1), allowing data to be pre-aligned for AR devices or site-captured images to be aligned with BIM models on the platform. Accurate alignment is achieved through absolute world coordinates and 6-Degree-of-Freedom (6-DoF) pose estimation. The GNSS-based registration engine is designed for outdoor environments, utilizing GNSS-RTK and IMU systems to address challenges in dynamic, open and unprepared spaces. The image-based engine, optimized for indoor environments, employs convolutional neural networks (CNNs) to achieve precise localization in the absence of GNSS signals. The engine switcher dynamically transitions between these approaches based on signal and feature availability, ensuring uninterrupted AR functionality. This architecture delivers a robust, marker-less AR system adaptable to both indoor and outdoor applications.

Informative modelling and exporting of safety prescriptions

The method entails the production of safety equipment models during the design phase, containing the aforementioned Safety Boxes, small generic masses containing the requirements for a certain category of

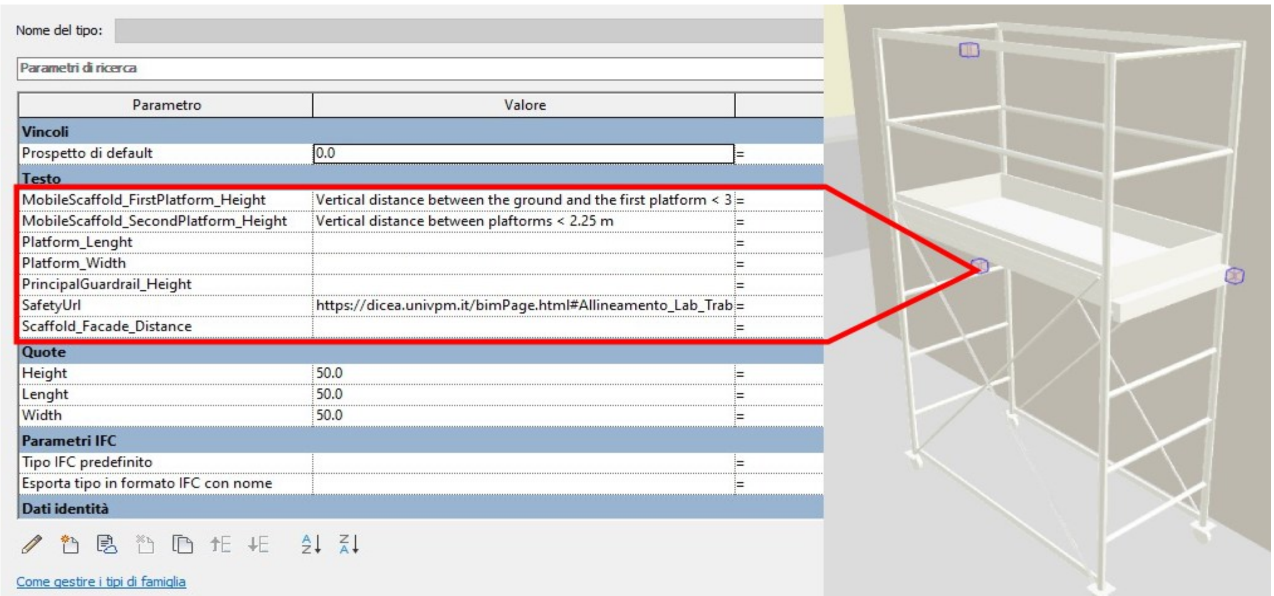

Figure 2: Safety prescriptions contained in 'Safety Boxes'.

equipment (e.g. SafetyBox_Scaffold) and exported as IfcBuildingElementProxy. Safety Boxes. From a model geometry perspective, Safety Boxes are modelled as small cubic elements that function as placeholders within the structural framework. The information modelling of safety prescriptions within Safety Boxes involves generating a corresponding text parameter for each prescription relevant to that specific category of elements (Figura 2). The level of geometric detail in safety equipment modelling is determined by the project requirements. In certain cases-precise positioning of the scaffold may necessitate detailed modelling, while in less complex scenarios, it may be sufficient to model solely the footprint of the safety equipment. To expedite the modelling process, different types of Safety Box are defined for each verification (or group of verifications), in which the value fields of parameters not inherent to that specific verification are left blank (Figure 2). Consequently, when the model is exported as an IFC file using a user-defined property set, only parameters with populated value fields containing the safety prescriptions for specific elements will be included in the export. In addition to these prescriptions, each Safety Box type is assigned with an additional text parameter that stores a URL link (SafetyUrl). This link facilitates the retrieval of relevant compliance check visual schemes from a database (), allowing for their projection in AR during on-site inspections, thereby enhancing the verification process. The aforementioned database does not necessarily have to be integrated within the AR platform but can exist as an external resource. However, for the purposes of this research, a database embedded within the AR platform was utilized. The following property set was utilised for exporting safety prescriptions parameters from the BIM model to the IFC file used during the experimentation phases:

Propertyset:

SafetyPrescriptions T IfcBuildingElementProxyType

Scaffold_Facade_Distance	Text
Platform_Width	Text
Platform_Lenght	Text
MobileScaffold_FirstPlatform_Height	Text
MobileScaffold_SecondPlatform_Height	Text
PrincipalGuardrail_Height	Text
SafetyUrl	Text

By interacting with a safety box in AR, an inspector can interrogate the model to obtain highly specific information regarding the compliance of the elements with which it is associated.

Another application of the proposed method regards the creation of a database of images collected by labour inspectors during the inspection activity, with the aim of keeping track of the various layouts and status of the safety equipment over time and supporting the writing of the post-inspection report.

The main characteristics of the proposed system to achieve the research objectives are:

1. Automation of the processes, such as the alignment of images to the model, which minimises the manual actions required to the labour inspectors. (who are not to be considered digital experts).
2. Low equipment costs (e.g. through the possibility of implementing the system not only on AR headsets but also on smartphones and tablets).
3. A high level of accuracy and versatility of the image registration, that we can achieve thanks to the aforementioned technologies (Messi et al., 2024).

Use case and experiments design

Setting of experiments

As a preliminary observation, it is worth noting that 30% of workplace accidents reported in 2022 were caused by crushing incidents due to vertical or horizontal movements against immovable objects, with falls from height accounting for 90% of these cases (INAIL, 2022). Given this strong correlation, the experimental component of this study has been specifically designed to address construction site equipment associated with these risks, with a particular focus on mobile scaffolding. The proposed method was tested by simulating a construction site scenario, positioning a mobile scaffold both indoors and outdoors at the DC3 Laboratory, a warehouse facility of Polytechnic University of Marche.

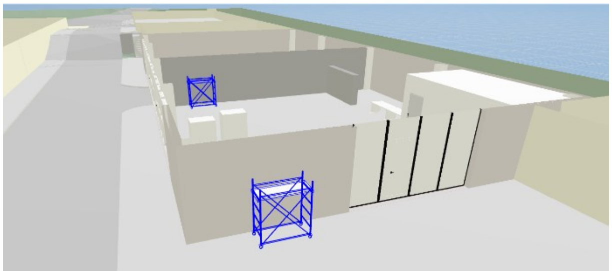

Figure 3: DC3 Laboratory model and mobile scaffolds position.

The mobile scaffold was modelled on a BIM authoring software by creating a custom model with dimensions based on the actual scaffold used in laboratory tests. This custom model was incorporated into an existing model of the engineering faculty's laboratory (Figure 3). Safety prescriptions correlated to the mobile scaffold were modelled and exported in IFC as described in methodology section. The purpose of the experiments revolves around demonstrating:

- The possibility of effectively embedding safety prescriptions in the IFC model and automatically visualizing them in AR by means of a cloud platform.
- The reliability of the image registration process, by carrying out an accuracy assessment of the quality of the alignment and confronting the results with thresholds established from reliable studies, in particular the LaMAR benchmark (Sarlin et al., 2019, Sarlin et al., 2022).

Spatial registration tests

To assess the accuracy of spatial registration both qualitatively and quantitatively, two types of tests were conducted: (i) a GNSS-based registration test for outdoor scenarios utilizing an augmented reality headset equipped with and RTK receiver, and (ii) an image-based registration test performed using a smartphone, demonstrating the potential for employing more cost-effective and practical equipment in construction site applications. Regarding to (i), no comprehensive or quantitative experiments have been carried out to assess the alignment quality of GNSS-RTK/IMU technology in relation to the photograph's actual positioning. This is due to the fact that GNSS-RTK/IMU technology depends on satellite signals, and a thorough evaluation would necessitate extensive testing that accounts for various environmental factors (e.g., signal strength, RTK antenna proximity, and obstructions such as vegetation or buildings). These tests are planned for future investigations. Concerning (ii), within the designated area for image acquisition, an orthogonal grid with a mesh size of 1x1 m was arranged on the floor. The grid spans 5 meters in width and 4 meters in height, resulting in 20 intersection points with defined coordinates (x, y, z), as illustrated in Figure 4. Six scenarios were defined for the image-based indoor registration test, with the aim of assessing the variations in terms of alignment accuracy as parameters such as the number of photos taken in the mapping phase, the number of points extracted from the images for mapping and matching, or the camera calibration method changed (Table 1).

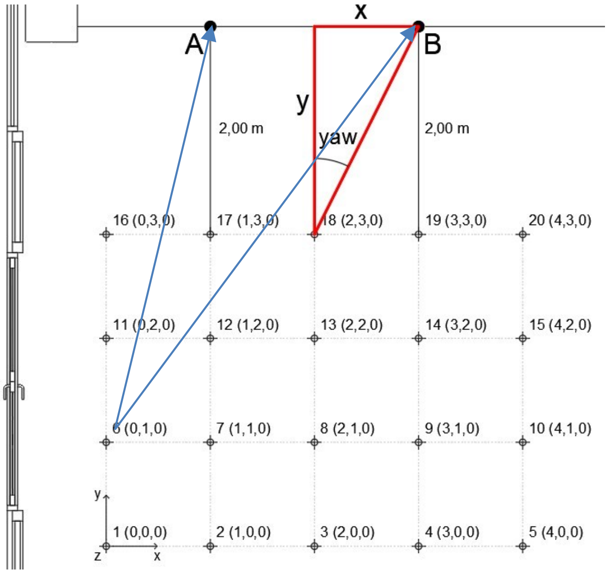

Figure 4: Reference grid.

The photographs were captured using a smartphone mounted on a tripod equipped with a laser pointer and a plumb line. Prior to each capture, the tripod was carefully levelled using its integrated bubble levels to ensure proper alignment. The tripod's position relative to the designated grid point was verified by using the plumb line attached beneath the tripod head, ensuring high-level precision. At each grid point, two photographs were taken: one directed towards Point A and another towards Point B, both of which were arbitrarily selected and kept alignment with these points. As a result, the photographic campaign produced a total of forty images. twenty images were used for mapping the site, whereas the other twenty images were aligned according to the mapping and used throughout the process. The laser pointer mounted on the tripod was used to ensure precision and consistency while gathering the necessary data for evaluating the accuracy of the registration.

Accuracy assessment

The setting of a reference grid allows for confronting the results obtained through the registration process with the real values of position (tvec) and camera orientation (yaw angle). Tvec is a {x,y,z} vector that represents the point in which the image is collected, whereas the yaw angle represents the orientation of the camera on the horizontal plane (Figure 4). After collecting data from the logs generated at the end of the image-based registration process, the error in pose estimation is evaluated by means of the $tvec_{error}$, defined in general as the vector difference between the $tvec_{estimated}$, which we derive from the logs, and the $tvec_{real}$, which we derive due to the reference grid set before the acquisition of the images. The same is valid for calculating yaw_{error}.

Table 1: Indoor image-based registration accuracy assessment scenarios.

Exif-based calibration				High resolution calibration	
DC3_1	DC3_2	DC3_3	DC3_4	DC3_5	DC3_6
300-150 KPTS + 640 PX	300-150 KPTS + 640 PX	5000-5000 KPTS + 1600 PX	5000-5000 KPTS + 1600 PX	300-150 KPTS + 640 PX	300-150 KPTS + 640 PX
10 PICTURES MAPPING	20 PICTURES MAPPING	10 PICTURES MAPPING	20 PICTURES MAPPING	10 PICTURES MAPPING	20 PICTURES MAPPING
Average $tvec_{error}$	Average $tvec_{error}$	Average $tvec_{error}$	Average $tvec_{error}$	Average $tvec_{error}$	Average $tvec_{error}$
Average yaw_{error}	Average yaw_{error}	Average yaw_{error}	Average yaw_{error}	Average yaw_{error}	Average yaw_{error}

$$tvec_{real} = \{x, y, z\}_{grid} \quad (1)$$

$$yaw_{real} = arctan\frac{x}{y} \quad (2)$$

$$tvec_{error} = tvec_{estimated} - tvec_{real} \quad (3)$$

$$yaw_{error} = yaw_{estimated} - yaw_{real} \quad (4)$$

Results and Discussion

Outdoor GNSS-based registration

We report the results of the outdoor image recording carried out using the high accuracy hybrid GNSS-Inertial system. On a visual/qualitative level, we can verify the goodness of the alignment with respect to the state of affairs in Figure 5.

Figure 5: GNSS-based registration result.

To verify that the image has indeed been successfully registered, we inspect the EXIF metadata of the image. We note that under the 'Image Description' field, the geographical coordinates of the point of capture, the accuracy of the localization (14 mm) and the pose {qx, qy, qz, qw} have been saved in JSON correctly (Figure 6).

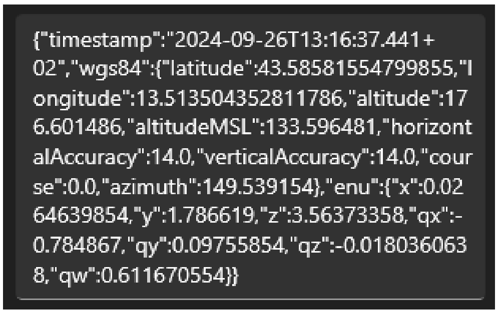
{"timestamp":"2024-09-26T13:16:37.441+02","wgs84":{"latitude":43.58581554799855,"longitude":13.513504352811786,"altitude":176.601486,"altitudeMSL":133.596481,"horizontalAccuracy":14.0,"verticalAccuracy":14.0,"course":0.0,"azimuth":149.539154},"enu":{"x":0.0264639854,"y":1.786619,"z":3.56373358,"qx":-0.784867,"qy":0.09755854,"qz":-0.0180360638,"qw":0.611670554}}

Figure 6: GNSS-based registration result.

Thanks to the EXIF metadata associated with the images stored in the platform database, it is possible to retrieve them at a later stage, already aligned with the model. This tool proves to be particularly useful in those cases in which the construction site is characterized by a large scale and complexity, resulting in difficulty of keeping track of the point and orientation from which the images are collected by the inspectors.

Indoor image-based registration

For each localised photo, data on $tvec_{error}$ and yaw_{error} have been gathered. The collected error data in terms of positioning and orientation will be compared with those of the LaMAR benchmark (Sarlin et al., 2019, Sarlin et al. 2022). In particular, interest will be directed at average error of the various scenarios with respect to the maximum error values (10 cm/1°) deemed acceptable in terms of $tvec_{error}$/ yaw_{error}. Afterwards, the threshold was lowered to 5 cm/1° and to 5 cm/0.5°, to further assess the reliability of registration process with more demanding standards. The results related to the various scenarios have been collected in Figure 7 and Figure 8, and they prove to be under the threshold took as reference for the experiments.

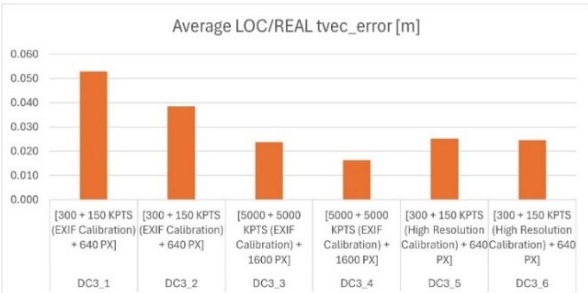

Figure 7: Average $tvec_{error}$.

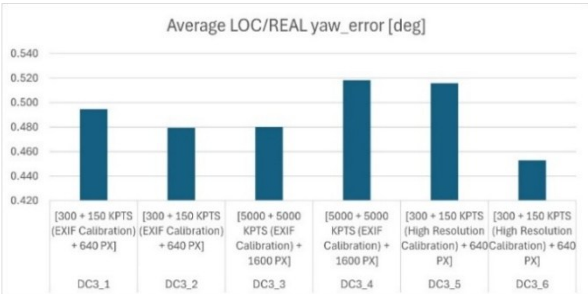

Figure 8: Average yaw_{error}.

```
#191151=IFCLOCALPLACEMENT(#131,#191150);
#191152=IFCBUILDINGELEMENTPROXY('0qUdu6gQf4f8Mk0ykWB8Dn',#18,'Safety_Info_Box:Safety_Box_Scaffold_Platform:946279',$,'Safety_Info_Box:Safety_Box_Scaffold_Pl
#191153=IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Safety_Box_Scaffold_Platform'),$);
#191154=IFCPROPERTYSET('16mTSIhyvF_YmKzUbmVqt6',#18,'Pset_BuildingElementProxyCommon',$,(#191153));
#191155=IFCPROPERTYSET('0M3USAAwS818$3BBmbD3ss',#18,'Pset_QuantityTakeOff',$,(#191153));
#191156=IFCRELDEFINESBYPROPERTIES('3M9x8SUmltSlkv1ZB9H6kf',#18,$,$,(#191152),#191154);
#191157=IFCRELDEFINESBYPROPERTIES('2GYvCClBRxZQKrnAsrzMJw',#18,$,$,(#191152),#191155);
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#191161=IFCPROPERTYSINGLEVALUE('MobileScaffold_SecondPlatform_Height',$,IFCTEXT('Vertical distance between plaftorms < 2.25 m'),$);
#191162=IFCPROPERTYSET('2YrNlatpP3bFvVQjQ5iBON',#18,'SafetyPrescriptions',$,(#191158,#191159,#191160,#191161));
#191163=IFCAXIS2PLACEMENT3D(#3,$,$);
#191165=IFCCARTESIANPOINT((0.,0.));
#191166=IFCAXIS2PLACEMENT2D(#191165,#11);
#191167=IFCRECTANGLEPROFILEDEF(.AREA.,'Safety_Box_Scaffold_FacadeDistance',#191166,0.050000000000000003,0.049999999999999156);
#191168=IFCCARTESIANPOINT((0.,0.,-0.024999999999999273));
```

Figure 9: Verification of safety prescriptions export in IFC format.

Safety prescriptions visualization in AR

After analytically demonstrating the reliability of spatial registration in terms of accuracy, the results of AR visualization for safety inspections are evaluated. First, it is verified that the safety-related information modelled within the Safety Boxes are correctly readable by the cloud platform in which it is hosted (Figure 9). Through AR, the inspector can interact with the Safety Boxes by opening a virtual panel that provides a brief textual description of the required inspections, and a graphical illustration accessed via the url code contained in the "SafetyUrl" parameter (Figure 10). This method enables the direct extraction of inspection tasks from the digital model and their on-site visualization precisely on the relevant safety equipment elements.

Conclusions

The scope of this study was to explore alternatives to the current safety inspection methods in construction sites, which are often costly and inefficient due to the low digitization of the construction sector. Despite the increased research efforts on safety monitoring over the past decade, practical field applications remain significantly constrained. This research work demonstrates tangible possibilities for enhancing construction site safety monitoring in terms of effectiveness. Initially, BIM-based models of safety equipment, specifically mobile scaffolds, were enriched with safety inspections related parameters and exported in IFC format through a user defined property set. Using AR devices combined with new registration technologies, inspectors are able to: (i) quickly visualize the safety checks required for individual components in real time, as well as (ii) collecting images of the construction site and automatically align them to the BIM model thanks to the metadata related to their localization and pose. This approach enhances traceability, reduces inspection time and costs, and improves regulatory compliance, contributing to a more efficient and transparent safety management process on construction sites. Embedding safety requirements directly within the BIM model enables the development of the SHP without the need for external applications, thereby streamlining process integration. More importantly, it encourages a pragmatic approach to construction site safety, treating it as a concurrent element alongside other design decisions (architectural, structural, etc.)

Future research should address pathological scenarios where image-based registration is likely to fail, such as environments with few visual reference points or monotonous, repetitive patterns. Other aspects that need to be addressed properly are cybersecurity and notarization, which are crucial since we propose to store images collected by inspectors into an online database, therefore it has to be guaranteed that those images are not fungible. Finally, as part of the planned improvements to the method, a new feature will allow inspectors to indicate whether the inspected safety requirement has been met or not, in addition to upload images to the platform. For example, inspectors can be asked to add flags directly in the virtual interface of the Safety Boxes to indicate the fulfilment of safety requirements and, in case of non-compliance, to leave a comment. This comment will be automatically included in the final report, helping to further reduce the time needed to complete it.

Figure 10: Safety prescriptions visualization in AR.

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References

Brilakis, I.K., Pan, Y., Borrmann, A., Mayer, H.G., Rhein, F.E., Vos, C.M., Pettinato, E., & Wagner, S. (2020). Built Environment Digital Twinning.

Corneli, A., Naticchia, B., Vaccarini, M., Carbonari, A., & Spegni, F. (2023). APPLICATION OF DIMINISHED REALITY FOR CONSTRUCTION SITE SAFETY MANAGEMENT. In Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality. DOI: 10.36253/979-12-215-0289-3.19

Corneli, A., Spegni, F., Naticchia, B., & Messi, L. (2024). DEVELOPMENT OF NATURAL LANGUAGE APPLICATION FOR CONSTRUCTION SITE PROCESSES SAFETY SUPPORT. Proceedings of the European Conference on Computing in Construction, 2024, 212–219. https://doi.org/10.35490/EC3.2024.317

Dias, L. A. (2009). *Inspecting occupational safety and health in the construction industry*. International Training Centre of the ILO.

Directive 1992/57/ECC. *Council Directive 92/57/EEC of 24 June 1992 on the implementation of minimum safety and health requirements at temporary or mobile construction sites* http://data.europa.eu/eli/dir/1992/57/oj

Dobrucali, E., Sadikoglu, E., Demirkesen, S., Zhang, C., Tezel, A., & Kiral, I. A. (2024). A bibliometric analysis of digital technologies use in construction health and safety. In *Engineering, Construction and Architectural Management* (Vol. 31, Issue 8). https://doi.org/10.1108/ECAM-08-2022-0798

Khudhair, A., Li, H., Ren, G., & Liu, S. (2021). Towards Future BIM Technology Innovations: A Bibliometric Analysis of the Literature. *Applied Sciences*, *11*(3), 1232. https://doi.org/10.3390/app11031232

Li, H., Lu, M., Hsu, S.-C., Gray, M., & Huang, T. (2015). Proactive behaviour-based safety management for construction safety improvement. *Safety Science*, *75*, 107–117. https://doi.org/10.1016/j.ssci.2015.01.013

Lin, K.-Y., Tsai, M.-H., Gatti, U. C., Je-Chian Lin, J., Lee, C.-H., & Kang, S.-C. (2014). A user-centered information and communication technology (ICT) tool to improve safety inspections. *Automation in Construction*, *48*, 53–63. https://doi.org/10.1016/j.autcon.2014.08.012

Messi, L., Carbonari, A., Franco, C., Spegni, F., Vaccarini, M., & Naticchia, B. (2024). A Holonic Construction Management System for the Efficient Implementation of Building Energy Renovation Actions. *Sustainability (Switzerland)* , *16*(5). https://doi.org/10.3390/su16051824

Messi, L., Spegni, F., Vaccarini, M., Corneli, A. & Binni, L. (2024). Seamless Augmented Reality Registration Supporting Facility Management Operations in Unprepared Environments, ITcon Vol. 29, Special issue Managing the digital transformation of construction industry (CONVR 2023), pg. 1156-1180, https://doi.org/10.36680/j.itcon.2024.051

Park, C.-S., Lee, D.-Y., Kwon, O.-S., & Wang, X. (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Automation in Construction*, *33*, 61–71. https://doi.org/10.1016/j.autcon.2012.09.010

Rey, R. O., de Melo, R. R. S., & Costa, D. B. (2021). Design and implementation of a computerized safety inspection system for construction sites using UAS and digital checklists – Smart Inspecs. *Safety Science*, *143*. https://doi.org/10.1016/j.ssci.2021.105430

Sarlin, P.-E., Cadena, C., Siegwart, R., & Dymczyk, M. (2019). From coarse to fine: Robust hierarchical localization at large scale. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, *2019-June*, 12708–12717. https://doi.org/10.1109/CVPR.2019.01300

Sarlin, P.-E., Dusmanu, M., Schönberger, J. L., Speciale, P., Gruber, L., Larsson, V., Miksik, O., & Pollefeys, M. (2022). LaMAR: Benchmarking Localization and Mapping for Augmented Reality. *ArXiv*. https://doi.org/10.48550/arXiv.2210.10770

Semeraro, G. (2022). *Il cantiere sicuro.* EPC Editore.