Development of a Twin Model for Real-time Detection of Fall Hazards

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Abstract -
The Architecture, Engineering and Construction (AEC) industry is still one of the most hazardous industries in the world. Researchers impute this trend to many factors such as the separation between the phases of safety planning and project execution, implicit safety issues and, most of all, the dynamic and complex nature of construction projects. Several studies show that the AEC industry could greatly benefit of latest advances in Information and Communication Technologies (ICTs) to develop tools contributing to safety management.

A digital twin of the construction site, which is automatically instantiated and updated by real-time collected data, can run fast forward simulations in order to pro-actively support activities and forecast dangerous scenarios. In this paper, the twin model of the Digital Construction Capability Centre (DC3) at the Polytechnic University of Marche (UNIVPM) is developed and run as a mock-up, thanks to the adoption of a serious game engine. This mock-up is able to mirror all the relevant features of a job site during the execution of works from a safety-wide perspective. In such a scenario, virtual avatars randomly explore the construction site in order to detect accessible, unprotected and risky workspaces at height, while warning the safety inspector in case additional safety measures are needed.

Keywords -

Digital Twin; Building Information Modelling; Real-Time Health and Safety Management; Complex Systems

1 Introduction

Nowadays, the AEC industry represents one of the most hazardous productive sectors [1]. In fact, although it employs only about 7% of the world's work force, yet it is responsible for 30–40% of fatalities. Statistics, which are referred to different countries, demonstrate that the construction safety is a perennial global problem.

In the United States, the census data from the U.S. Bureau of Labor Statistics (BLS) showed that as many as 774 workers died from injuries they suffered on construction sites in 2010, accounting for 16.5% of all industries. The fatality rate accounts for 9.8 per 100000 full-time equivalent workers and is ranked the fourth highest among all industries. Within the two decades of 1990 and 2000, more than 26000 U.S. construction workers died at work [2]. That equates to approximately five construction worker deaths every working day. Out of these fatalities, 40% involved incidents were of the type falls from height. Further investigations showed that inadequate, removed, or inappropriate use of fall protection equipment contributed to more than 30% of those falls [2]. Statistics about other countries, such as China [3], United Kingdom [1] and Germany [4], confirm high percentages of fatal accidents in the construction industry and point out falls from height as one of the most frequent causes. As a result, it is evident that the construction industry is far from the vision of "zero accidents/injuries" espoused by many construction-related companies [1].

The high number of fatalities is generally imputed to several causes, such as the separation between the phases of safety planning and project execution [2, 5], implicit safety issues and, most of all, the dynamic and complex nature of construction projects, which require ever-changing safety needs [5]. Construction safety issues can be properly described as complex sociotechnical system [6], which cannot be tackled simply adopting a best-practice approach defined ex ante. Conversely, the answers to such problems can be described as emergent practices [7].

The AEC industry is often regarded as being hesitant in adopting innovative technologies, due to the inherent difficulties of its unstructured and changing environment [1, 8]. Nevertheless, many research studies [9, 10, 11] demonstrate that the application of the latest advances in ICTs in the safety management field can help to proactively respond to hazardous scenarios and enable the shift from reactive to proactive safety management.

1.1 Rule-checking systems

Some research studies [2, 12] apply commercial systems, such as Tekla® [13] and Solibri™ [14], to execute BIM-based rule-checking analysis for the detection of fall hazards. Rules, once they are translated from human language into a computer-readable format, can be executed supporting labor-intensive safety checking tasks in a little time. In this direction, authors in [15] propose an ontology-based approach for construction safety checking, modelling safety constraints with Semantic Web Rule Language (SWRL). The authors, assuming fall from height as a test case, demonstrate the potential of this methodology for the assessment of fall hazard on the base of hole's acceptance criteria defined by safety regulation. In fact in similar circumstances, i.e. when a dimension has to be compared with a threshold value, a rule-checking system drives to reliable results.

It must be noted that sometimes safety assessment is contextual, that is it depends from complex geometries and spatial dependencies (e.g. non-perpendicular crane cable that lifts up and swings) or ever-changing site conditions (e.g. temporary structures that aid construction processes and are often not modeled). In cases like these, it is hard to define general rules by means of safety checking constraints which cover all possible scenarios; moreover, information provided by a BIM model can result incomplete, inaccurate or not updated. As a consequence, the correctness of the rule-based safety analysis may be largely affected.

1.2 Real-time tracking systems

In some research studies, prototypes of self-updating BIM models based on sensor data for real-time Health and Safety (H&S) management have been developed. The paper [9] proposes an application which aims to improve environmental safety in construction sites; the BIM model displays the latest data from temperature and humidity sensors and the real-time status of various locations, with a focus on the ones affected by atmospheric hazards. Another research work [10] integrates a rule-checking system and a Real-Time Location System (RTLS) to place dynamic virtual fences and to check whether tracked real fences are properly installed. In the system developed in [11], once risks are assigned to building components, a warning can be sent to tracked workers on site in case they come too close to hazards. A requirement for this approach is that hazards are identified and classified in advance.

1.3 Contribution to research

In this work, the development of a digital twin for H&S management in construction sites to prevent falls from height is reported and tested. This approach can be used to complement BIM-based rule-checking systems, which work well when they come to checking compliance with safety codes, regulations and best practices. But, as already stated in Section 1, construction sites represent a type of complex systems and unexpected emerging hazardous scenarios cannot be anticipated unless a digital twin is put in place.

The research study reported in this paper concerns a methodology to develop a digital twin of construction sites, which makes it possible to find out in real-time hazardous scenarios possibly leading to falls from height. A forward-looking simulation approach, run in real-life conditions and implemented in Unity3D^{TM}, and a real-time monitoring sensor network, to update the status of the ever-changing environment and of involved workers, have been integrated and tested in the Digital Construction Capability Centre (DC3) of the Polytechnic University of Marche (UNIVPM at Ancona, Italy).

This paper is organised as follows: Section 2 introduces digital twins as a candidate solution for the management of complexity. Section 3 provides a description of the developed system architecture, whereas in Section 4 simulation and results are reported. Finally, Section 5 is devoted to conclusions.

2 Management of complexity

2.1 Complex systems

2.1.1 Basic of complex systems

A complex system consists of many elements affected by non-linear interactions [16]. As a consequence, small causes may lead to large consequences, and vice versa; this implies no immediate apparent relationship between causes and effects. Interactions, which cause system changes over time, consist of transference of energy or information, usually have a fairly short range and show recurrency, they being affected by loops. Furthermore, the constant flux of energy ensures the survival of a complex system and its history affects the present behaviour. A complex system is usually open or it is hard to define its borders. The scope of such a system is not an intrinsic characteristic, but is usually determined by the purpose of the description and is often influenced by the position of the observer; this process is called framing. Finally, each element ignores the behaviour of the system as a whole and responds only to information that is locally available. The complexity feature emerges as a result of interactions among constituting elements. The most representative examples of complex systems are the human brain, the behaviour of a flock of birds and economic systems of the modern society [16, 17].

The Cynefin framework (Cynefin in Welsh pronounced kunev-in means the multiple factors), introduced in 1999, is a decision-making conceptual structure which proposes strategies to properly tackle each one of the five domains: "simple", "complicated", "complex", "chaotic" and "disordered" [7]. Whereas cause-and-effect relationships can be detected by everyone in the "simple" domain and by experts in the "complicated" one, the same cannot be said in the "complex" one, where the reason why things happen can be understood only in retrospect, causing unpredictability. In the "complex" domain, the Cynefin suggests to probe and sense eventual emergent instructive patterns to be used as responses.

In this research study, the high-level strategy proposed by the Cynefin framework has been assumed. In practice the digital twin, enabling forward-running simulations, makes it possible to "probe and sense" future scenarios;

emergent safety measures can be suggested and applied in real-time.

2.1.2 Complex systems in H&S management

In the AEC industry, safety issues can be regarded as complex sociotechnical systems [6]. Stakeholders include manufacturers, main contractors and subcontractors, design staff, project and site managers. Moreover, construction sites, which are usually interested by crowds of workers, adjacent buildings and facilities, complex weather phenomena, result in a very dynamic operating environment. In other words, the safety status is an emergent property of a system, whose components are subjected to non-linear interactions that cannot be anticipated [18]. In the research study [6], authors have studied a tower crane safety issues as a systemic problem, assuming the safety risk management framework defined by [19] that was specifically developed with complex sociotechnical systems in mind; as a result, a list of factors affecting tower crane safety has been identified.

2.2 Digital twins

2.2.1 Basics of digital twins

The first definition of the concept, nowadays known as the digital twin, was made in 2002 by Michael Grieves, in the context of an industry presentation concerning Product Life cycle Management (PLM) [20]. A digital twin can be defined as a virtual representation of a physical product or process, used to understand and predict the physical counterpart's performance characteristics throughout the product life cycle [21]. To ensure an accurate modeling over the entire lifetime of a product or of its production, digital twins use data from sensors installed on physical objects to determine the objects' real-time performance, operating conditions and changes over time. Using this data, a digital twin evolves and continuously updates to reflect any change to the physical counterpart, creating a closed-loop of feedback in a virtual environment that enables companies to continuously optimize their products, production, and performance at reasonable costs [21].

The statements "digital model", "digital shadow" and "digital twin" are often used as synonyms, although they differ from each other in the level of data integration between the physical and digital counterparts. A "digital model" is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object. If there further exists an automated one-way data flow between the state of an existing physical object and a digital object, one might refer to such a combination as "digital shadow". If further again, the data flows are fully integrated in both directions, one might refer to it as "digital twin" [20].

2.2.2 Digital twins in the AEC industry

In the near future, digital twins are expected to take a center stage in the AEC industry too, advancing rapidly beyond BIM and enabling asset-centric organizations to converge their technologies into a portal or immersive experiences [22]. The result will be better informed decisions to improve network availability, to enhance workers safety, to ensure regulatory compliance and to reduce environmental impacts. Thanks to the application of Artificial Intelligence (AI) and Machine Learning (ML) methodologies, we envisage immersive digital operations, providing analytics visibility and insights to enhance the effectiveness of operations staff and help them anticipate and head off issues before they arise and react more quickly with confidence [22].

A real commitment in this context was demonstrated by the Centre for Digital Built Britain (CDBB) which published, at the end of the year 2018, the Gemini Principles to guide the National Digital Twin and to shape the information management framework that will enable it [23]. The National Digital Twin itself is not intended as a single, monolithic twin of the entire country's infrastructure. Rather, it will be a federation of many twins, representing assets and systems at different levels of granularity, brought together to generate greater value. A first application was developed implementing three interconnected work packages. The first one provides the BIM model of part of the University of Cambridge. The second one regards the integration of data from various sources to enable effective analytics and drive better decisions. Finally, the third one aims to develop novel applications for facility management that exploit the data captured through the digital twin [23].

3 System architecture

3.1 Technology stack

The digital twin model, proposed in this paper, for real-time H&S management is based on the system architecture composed by the following subsystems (see Figure 1):

- a Ultra-wideband (UWB) sensor network for localization;
- Node-RED™ programming tool;
- ArangoDB database;
- Unity3D™ game engine;

The first subsystem consists of a UWB sensor network. This infrastructure is in charge of tracking what workers and equipment are present in the real world's scenario

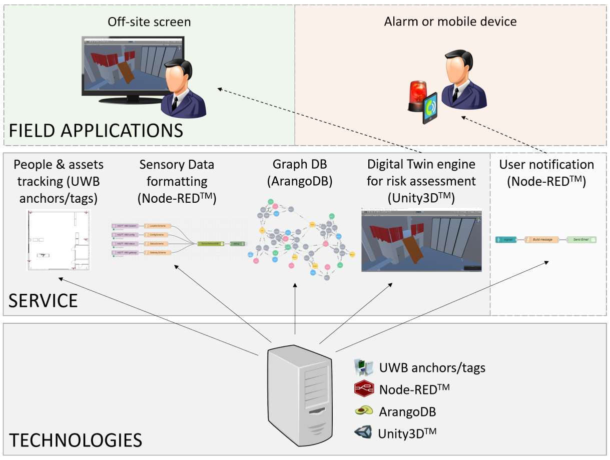

Figure 1. System Architecture.

and sending data necessary for updating to the main system. An IoT programming tool, namely Node-RED^{TM}, wires together the UWB sensor network and the rest of the system's components. ArangoDB, is a database which stores the complete history of coordinates. The hearth of the developed architecture is the serious gaming platform Unity3D^{TM}, which hosts the digital twin's simulation environment and enables forward-running simulations to predict hazardous scenarios. In order to enable the safety manager to remotely supervise safety issues, forward simulations' results can be displayed in real-time to an off-site screen (see Figure 1). Furthermore, as soon as any fall hazard is detected, a warning can be immediately sent to the safety manager. This is made possible by sending a message, via SignalR, to Node-RED^{TM}, which can trigger an alarm or a smartphone notification (see Figure 1). In this way, the developed system can support real-time H&S management in order to prevent accidents or fatalities.

For the purpose of this paper, the left part of the system architecture (see the continuous-line of the Service box in Figure 1) has been implemented in the Digital Construction Capability Center (DC3).

3.2 Reality mirroring

Real-time sensing is devoted to the continuous mirroring of the digital twin. According to the system architecture depicted in Figure 1, workers involved in on-field activities can be tracked by means of UWB localization systems. This technology leverages the Time of Flight (ToF) technique, which is a method for measuring the distance between two radio transceivers by multiplying the time of flight of the signal by the speed of light. Thus, knowing the position of fixed UWB anchors and operating a trilateration algorithm, the position of any UWB transceivers (tag) can be determined, even if it is moving.

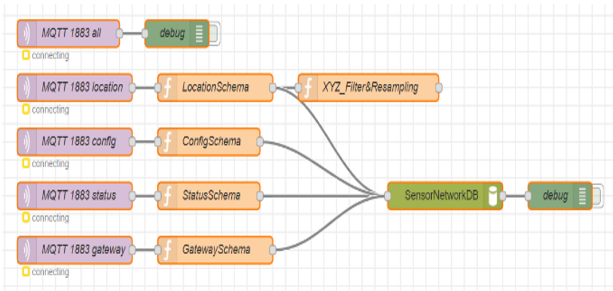

Figure 2. Node-RED flow for storing UWB messages in an ArangoDB collection.

For the purpose of this paper, five anchors were installed in known positions, whereas an UWB tag has been applied to the monitored piece of equipment, that is the ladder, in order to track its position.

In order to wire together hardware devices with the database and again with the Unity3D^{TM} game engine, the flow based graphical programming tool Node-RED^{TM} has been adopted. Node-RED^{TM} is a tool specifically designed for Internet of Things (IoT) applications. In this research, a dedicated Node-RED^{TM} flow wires together the position data coming from the UWB localization system with a database for their storage. The resulting flow built in Node-RED is shown in Figure 2.

During the development of a digital twin, different types of data must be stored and linked together in an emerging way. Therefore, ArangoDB has been selected here, because it is a native multi-model NoSQL open-source database for storing several types of information, including those types typically related to digital twins, such as the complete data history from sensors. Every changes happening in the ArangoDB collection that stores location messages is triggered to the serious gaming engine Unity3D^{TM} by means of the software library SignalR. Hence, sensors data are delivered to the game engine enabling virtual objects' positions to be updated in real-time. As soon as a dangerous scenario is predicted in Unity3D^{TM} by the forward simulations, a real-time notification can be triggered by sending a message to Node-RED^{TM} via SignalR in order to prevent fatal events.

3.3 Implementation of the gaming environment

The use of serious game engines is a promising tool supporting research in real-time control systems, among the others. The first application regarding gaming technology in the area of research was found in the aircraft industry, with the use of Microsoft Flight Simulator for educational purposes [24]. Afterwards, serious game engines had a wide spread for other research purposes such as simulation and analysis, further demonstrating that mere entertainment is not the only feasible, nor the most promising,

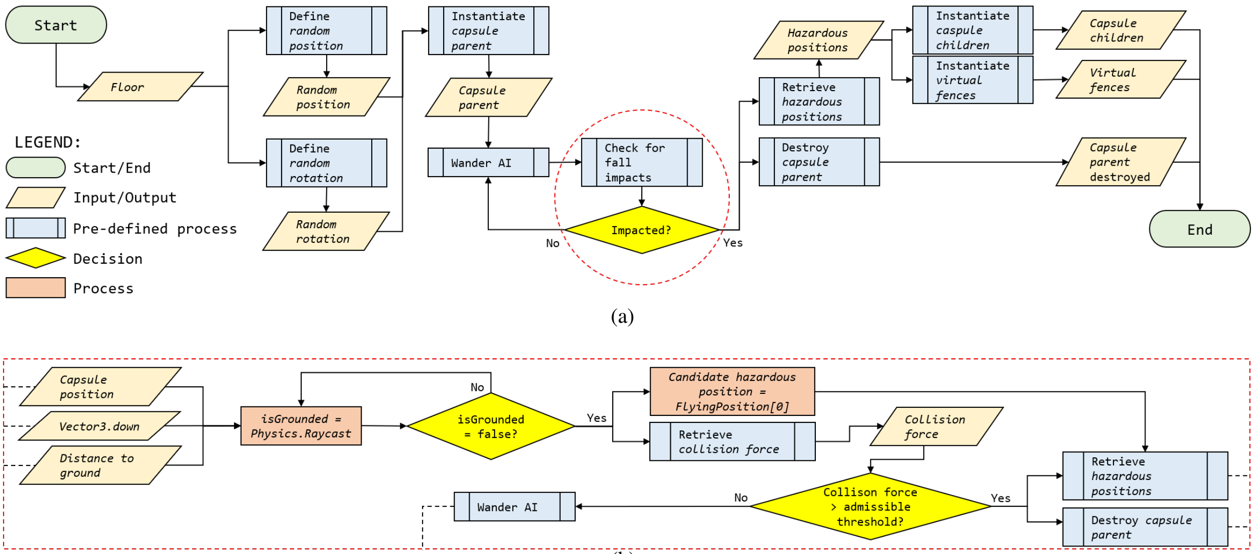

Figure 3. (a) Pseudocode describing the general logic of the digital twin developed in Unity3D^{TM} game engine in order to detect fall hazards; (b) pseudocode describing in details the virtual sensor which checks for fall impacts.

application. The great success of this approach is due to the difficulty of executing real experiments in some fields, especially in H&S management; in fact the need for establishing safe conditions to avoid direct exposure to risks would affect participants behaviour.

In this research study, game technology has been applied to develop the digital twin of a construction site for real-time H&S management. The use of a serious game engine facilitates the modeling of the environment, which includes the physical space, sensors and mechanical physics, and the implementation of simulation. For the purpose of this paper, the gaming platform Unity3D^{TM} has been adopted. The physical space of the digital twin, assumed as case of study, can be directly imported within Unity3D^{TM} as an IFC project with its structure. To this end, an IFC Loader, based on the IFC Engine DLL library [25], has been developed, in order to import topological information, materials properties and all semantic information from the digital model. This tool models the environment using one of the most powerful techniques in solid modelling, that is Boundary Representation (B-Rep). B-Rep represents a solid as a collection of connected surface elements, that is the boundary between solid and non-solid. The digital twin, in order to mimics reality, requires the implementation of human and artificial sensors, known as agents. The sense of sight, for example, must be implemented in digital twins to give humans' avatars the awareness about what is happening around them [26]. In Unity3D^{TM}, this can be done modelling the Field of View (FOV) as a collider by means of a set of quantitative parameters (e.g. FOV angle and elevation angle); a user can see an entity simply if her/his FOV collider intercepts the entity itself. The mechanical physics is a native functionality of game engines; hence, in the game scene every object is affected by gravity and occupies a volume just like in the real world. In details, these properties can be managed by means of the quantitative parameters stored respectively in the rigidbody and collider components of a virtual object. Furthermore, C# advanced programming makes it possible to define, directly in Unity3D^{TM}, a deformation behaviour which acts in response to a rising force applied to an object. To make an example, a ladder could inflect or even break down, if the weight of the overlying avatars is close to or higher than its mechanical strength. To sum up, Unity3D^{TM} hosts the digital twin and can work as a hub that is able to trigger co-simulations related to some specific disciplines and receive back results. In this way, multiple simulators (e.g. fire scenario, plants' functioning, etc.) can be coupled, by means of the models exchange standards (such as Functional Mockup Interface, FMI).

The pseudocode reported in Figure 3(a) describes the general logic at the base of the developed digital twin for real-time identification of fall hazards. At the first instantiation, virtual capsules are generated in a random position and rotation on the surface of a specific floor; instead, at the following instantiations it follows the logic explained below (see the third point in the bullet list). Each of these entities embeds an AI component which allows it to wander and explore the surrounding environment. A virtual sensor, indicated by the red dashed lines in Figure 3(a) and described in details in 3(b), has been implemented in order to evaluate if any possible impact due to a fall can be harmful and that point must be marked as an hazardous location. To this end, a ray casting algorithm is applied to check if the monitored object is grounded or not; in case of false evidence, which means that the capsule is falling, the first "flying" position is labelled as a candidate hazardous position. The retrieved collision force is then compared with the pain tolerance value of 6 kN, known from literature [27] and regulation [28] about fall-arrest equipment. If the collision force is higher than the admissible threshold, the following events are triggered:

- the point from where the fall has taken place is confirmed as an hazardous position;
- a virtual fence is instantiated in correspondence of the hazardous position as a graphic notification;
- new children capsules are instantiated in the hazardous position with random rotations in order to speed up the exploration of the environment in the nearby;
- the parent capsule is destroyed in order to avoid an overcrowding of capsules.

4 Simulation and results

The system architecture described in Section 3 has been tested in the Digital Construction Capability Centre (DC3), which is a laboratory of the Polytechnic University of Marche in Ancona, Italy. According to the definition of Digital Twin (see Section 2.2.1), the developed digital twin mock-up was meant to replicate the typical environment of the construction site, which continuously changes and evolves. For the purpose of this paper, the works at height scenario has been recreated inside the DC3 laboratory, as well as the evolution of the scene that can be encountered on a construction site.

The top image in Figure 4(a) shows the regular configuration of the DC3 laboratory, in which the floor above the changing room is not accessible since no access path exists; hence, there is no fall hazard affecting that floor area. As shown by the virtual replica of this scenario (see the bottom image in Figure 4(a)), the developed system populates the DC3 digital twin with virtual capsules able to wander on the main floor of the laboratory. It can be noticed that no barrier is suggested by the system and the boundary of the floor on the changing rooms is kept clean.

During the execution of the experiment, a real ladder has been placed connecting the laboratory floor and the floor above the changing room, thus allowing workers to reach that area for any reason, e.g. doing works or temporarily laying materials (see the top image in Figure 4(b)). Any human observer would infer that fall hazards have been generated, because workers reaching the higher level may fall down due to the absence of any barriers. Similarly to reality, wandering virtual capsules may reach the floor above the changing room and fall down (see the bottom image in Figure 4(b)). For each fall event occurring in the digital twin, the virtual sensor (described in Section 3.3 and by Figure 3) compares the collision force generated by each impacted capsule with the pain tolerance value of 6 kN, known from literature [27] and regulation [28] about fall-arrest equipment. As a result, if the collision force exceeds the threshold value, the system notifies that falling capsules have experienced harmful impacts and it infers that fall hazards have been introduced. By picking out the positions from which wandering capsules fall down because no fences are installed (see the top image in 4(b)), the virtual replica suggests that barriers must be placed in these areas (see the bottom image in 4(b)).

As a result, according to the logic described in Section 3.3 falling capsules underpin the real-time detection of fall hazards affecting real workers on site. Virtual fences, highlighted in red in the bottom image in Figure 4(b), have been instantiated in those positions from which harmful impacts have taken place. For the purpose of this paper, 300 virtual capsules, moving with a linear speed of 2 m/s, have been instantiated inside the DC3 twin model. Assuming these conditions and using a laptop equipped by an Intel® Core™ i7-8750H CPU 2.20 GHz processor with 16 GB of RAM memory, the digital twin engine takes on average about 2 minutes, after the ladder positioning, to detect all fall hazards affecting the rooms' top floor and place all the related virtual fences (see the bottom image in Figure 4(b)).

It must be noted that, in case a rule-based safety assessment system was implemented (e.g. labelling any surface above a critical height as an hazardous one) it would always suggest that barriers are needed along the perimeter of the higher floor area. In other words, in the simulated scenario the higher level above the rooms (see Figure 4(a)) would be always labelled as hazardous, even in case it is not accessible because the ladder is not present.

5 Conclusion

This paper proposes a system architecture of a digital twin model for H&S management and implements it for real-time identification of fall hazards. A digital twin mock-up of the DC3 laboratory, developed in Unity3D™, mirrors the construction site by means of a UWB localization system and runs looking-ahead simulation in order to detect fall hazards in near real-time. Especially in large construction sites, notifications of safety needs with a delay of a couple of minutes represent a valuable result if compared to the time usually taken by on-site manager to manually detect all fall hazards. Furthermore, off-site managers can benefit from the opportunity, provided by the developed system, of displaying safety alerts and giving suggestions about mitigation measures. The simulation-

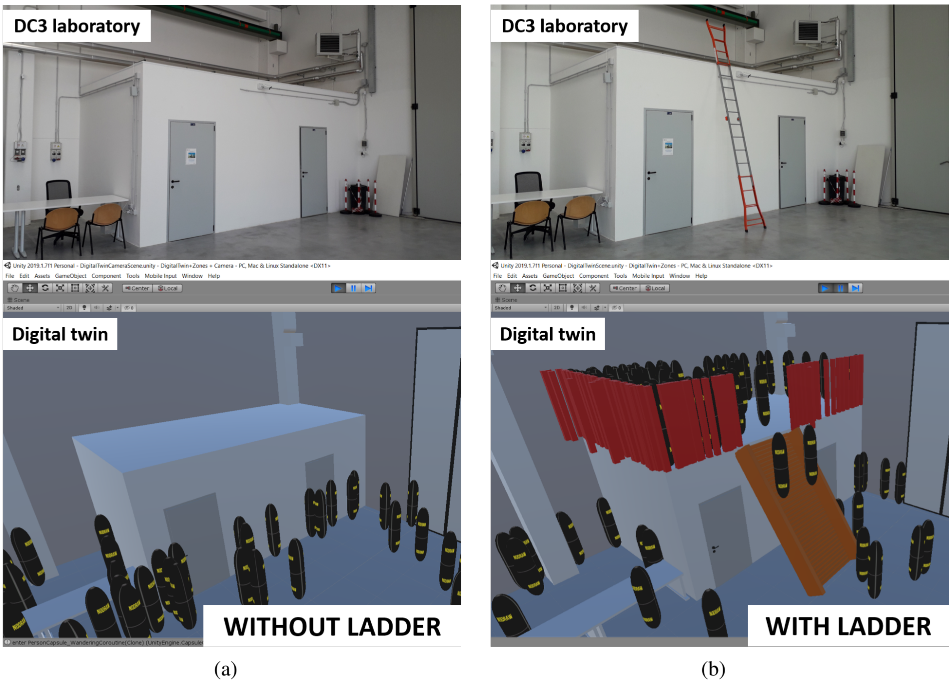

Figure 4. Construction site for works at height recreated in the DC3 laboratory (top images) compared with its mirroring digital twin (bottom images). The floor above the changing room is not accessible (a) until the ladder has been placed (b).

based approach described in this paper can easily be extended to similar scenarios where the strict application of pre-determined rules cannot work due to the dynamic nature of construction sites. On the overall, simulation results demonstrate that the proposed approach can cover the variety of scenarios in which a rule-based checking systems may fail, since safety assessment is contextual or hard to be modelled by means of pre-determined rules.

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