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Comprehensive needs analysis for the development of construction safety education tools in immersive reality

Abstract

Construction industry remains one of the most hazardous industries to work in, despite numerous efforts by researchers and practitioners to improve levels of Health & Safety (H&S) and reduce the number of accidents which occur on the construction sites. A potential method to reduce the number accidents is to educate construction workers in hazard identification and to raise their awareness of the risks they face at the construction site through the use of emerging technologies such as Virtual Reality (VR) and Augmented Reality (AR). This paper presents the first intellectual output of an Erasmus+ project titled Construction Safety with Education and Training using Immersive Reality (CSETIR), whose goal is to examine and apply such VR and AR tools to improve the levels of H&S. Through the literature review and discussions with relevant stakeholders, most appropriate training methods were identified for the development of safety educational tools in the following project phases. VR and AR technologies have the potential to train construction workers in H&S, especially those who have little experience in construction safety, workers with literacy limitations and workers that do not speak the local language. Visual training tools, especially immersive ones, also provide better retention of acquired knowledge and skills. An immersive reality safety education tool, therefore, has the potential to increase the levels of construction H&S and to reduce the number of accidents at construction sites.

Keywords

Construction Health & Safety, Safety training, Immersive reality, CSETIR, Needs analysis

INTRODUCTION

Construction industry for long has been and still remains one of the most dangerous industries to work in. Across the world, around 6 to 10 % of the workforce is employed in construction (Raheem and Hinze, 2014), while the industry contributes to around 20% of all work-related fatalities (EUROSTAT, 2015, U.S. Bureau of Labor Statistics, 2018). Nonfatal injuries are also very common, with construction industry taking third place in the EU by the total number of accidents and first by incidence rates (EUROSTAT, 2018). Furthermore, since Al-Aubaidy et al. (2019) estimate that as much as 50% of the injuries on the construction site are not reported, the number of accident and the significance of the issue at hand is even higher.

Since traditional accident prevention measures cannot reduce the accident levels to an acceptable degree, various tools are being developed and utilized to reduce the impact of construction work on safety and health of its workers. One of such tools will be a product of an Erasmus+ funded project, titled Construction Safety with Education and Training using Immersive Reality (CSETIR). The tool will allow the creation of virtual environments that simulate construction scenarios, allowing the identification and prevention of risks for teachers, technicians, and engineers. CSETIR aims to develop immersive and interactive VR and AR solutions in order to train construction workers and to prevent accidents.

This paper presents the results of a needs analysis conducted at all project partner institutions: Slovakia, Croatia, Portugal and Greece. Through the literature review and discussions with relevant

stakeholders, most appropriate training tools for significant safety issues were identified to enable the development of safety educational tools in the following project phases. The needs analysis provided a detailed understanding of previous research in the field and has shown what are the priorities of the intended users with regards to hazard scenarios in safety training.

PROJECT BACKGROUND

Based on several literature reviews, involvement in several international conferences, involvement in H&S organizations and the construction sector, it became clear that integrating technologies such as AR/VR into safety training were considered relatively new and were not getting enough attention. After meeting with safety professionals, contractors and consultants from several countries it seemed that enterprises were isolated from academia and were not using advancements of technologies and tools that might assist workers. Although some enterprises demonstrated using some digital education and training techniques, these methods were not reaching their full potential and included a lot of limitations (Soeiro et al., 2020b).

The project was designed based on joint analysis and partners' know-how and experience, to propose viable solutions. The specific aims for the project are (Soeiro et al., 2020a):

a) Developing, implementing, validating and tuning of interactive IR approaches to promote multidiscipline creativity, innovative thinking, and practical skills in the digital era;
b) Ensuring education and research are mutually reinforcing, and strengthening the role of institutions in their local and regional environments;
c) Exploring synergies and stimulating greater dialogue between HE, enterprises and VET schools, in the scope of community and outreach activities;
d) Supporting the civic and social responsibility of students, workers, engineers and technicians.

To address the goals, the project will develop innovative and interactive AR/VR solutions based on BIM modelling capacities to prevent accidents and train workers. The project intends to create usable tools for teachers, technicians, and engineers that could be used in any construction project. Project also aims at offering training sessions online on an online platform (project website and a wiki page) to grant learners and trainees access to interactive material and resources. These tools will range from applications to be used on smartphones to virtual reality contexts depending on the needs of training (Soeiro et al., 2020b).

Although all workers receive training and orientation meetings, they are not receiving on-the-job, hard-knocks-type training that simulates the site conditions which is necessary since every construction site is unique with different activities, schedules, approaches etc. Many training programs have shown to be effective, but however, they lack the flexibility and the ability to adapt to the current site environments, to be modifiable according to the workers' and students' needs and capabilities and are often not appropriate for people who have limitations or special educational needs, as well as foreigners or immigrants.

An additional benefit of such a "hands-on" experience and digital platforms like BIM and AR/VR simulations will be an innovative way of transmitting the diverse group roles of the construction site in a familiar language to the youth, supporting schools in their efforts to teach and to attract students to continue their education with a creative and interactive mindset (Sidani et al., 2019a). Workers and students will experience a more practical and innovative learning approach, mimicking their actual future professional careers.

METHODOLOGY

The first step of the research was to examine the available AR/VR tools on the market, in terms of both research and industrial fields. Due to a myriad of search results, and due to the fact that numerous literature review papers dealing with both application of AR/VR in particular and information technologies in general already exist (Li et al., 2018, Sidani et al., 2019b, Mihić et al., 2019, Zhou et al., 2015), this paper focuses on the most used and readily applicable tools. For each of the tool, a short description will be given, as well as their applicability for project goals in the later stages.

Following the description of the tools, the needs analysis for the project was carried out and the most important criteria were selected. Finally, the tools were graded based on the criteria and the most appropriate one was selected.

The results were validated by an industrial partner since the primary end-user of the tool is the construction industry. The industrial partner is one of the largest construction companies in Croatia with over 30 years of construction experience, with more than 500 employees and with the most developed H&S programme in the region.

RESULTS

This section of the paper will summarize the available and most used tools on the market in terms of BIM-based AR/VR in the research and the industrial fields, as well as list the relevant uses for subsequent intellectual outputs (IO): BIM tools (IO2) and the AR/VR Tools (IO3). The goal of IO2 will be to develop a BIM model library of hazard scenarios, while IO3 will deal with designing and creating actual AR/VR scenarios for safety training.

IO2 will use the results of this paper to determine which tools to use and explore. Several strategies can be considered when addressing the use of virtual environments to improve education and training for safety in construction sites. Indeed, the targets of training initiatives are a diverse group, including site workers, engineering graduate students and safety specialists, among others. The technical skills and education levels for these groups differ considerably, as do their work environments, and functions. This diversity must be considered when defining strategies and solutions, even when the suitable available hardware and software options overlap largely for the different user groups.

Fortunately, the same VR and AR hardware and the software components have been adopted in a range of applications. This is considered as an opportunity, as solutions that target one user group might be adapted for different uses. The main current VR and AR development technologies are cross-platform, which largely reduces the importance of the choice of specific equipment within similar types of hardware such as Head Mounted Displays (HMD) or motion controllers. Naturally, different training environments demand different types of hardware, due to cost, time and other practical considerations. For instance, despite recent developments in CAVE (Computer Assisted Virtual Environment) technology, which allow for lower-cost and quicker deployment, HMDs remain a more practical solution for virtual immersion, while computers and mobile devices are ubiquitous, and provide acceptable VR experiences in many instances.

The use of BIM models as a source of information (including geometry) for the virtual models is regarded as an obvious choice. BIM models are increasingly common in practice, they support different types of information, thus providing great flexibility when deciding on technical solutions, and are compatible with other components such as game engines. Alternative solutions, such as the use of generic 3D modelling tools would require the development of models from scratch, with no relationship with the actual construction process. This means that changes in design or in construction plans would not be quickly or easily reflected in the virtual training environments. These factors greatly reduce the feasibility of a non-BIM solution. Since BIM authoring tools are interoperable, and standard

open formats exist for exchanging BIM data, the choice of BIM tools is not considered to be a critical issue when designing a strategy for the development of training solutions.

Overview and analysis of potential AR/VR tools

The research of the available AR/VR tools on the market has discerned the following tools:

1. 3M - Construction Safety Virtual Reality Programs for Hands-on Learning (3M, 2020);
2. CAT Safety VR module (Caterpillar Safety Services, 2020);
3. SRI International Augmented Reality Solutions for Construction Inspection (SRI International, 2020);
4. Safety Compass - Augmented Reality Workplace Safety (Safety Compass, 2020);
5. VR Safety Training for Construction companies – LandMark VR (LandMark VR, 2020);
6. FULmax cube (FULmax, 2020);
7. Role of Visualization Technologies in Safety Planning and Management at Construction Jobsites (Azhar, 2017);
8. A framework for construction safety management and visualization system – SMVS (Park and Kim, 2013)
9. OSHA PIXO safety compliance Virtual Reality (PIXOVR, 2020);
10. Web-based Collaborative Virtual Environments (LIRKIS G-CVE, 2020).

3M - Construction Safety Virtual Reality Programs for Hands-on Learning

3M (2020) has recently released a series of VR construction safety modules. 3M's virtual reality training platforms are available online. There are several modules on the website for training. This case study is for the preparation and construction phases.

- Software: Revit, 3D Studio, EON Studio, EON Viewer with CAVE.
- Hardware: HTC VIVE, Samsung Gear VR, Oculus Go, 2 Joysticks.
- Potential for IO2: BIM was not an essential tool inside this case study although integrating BIM will help for a training module.
- Potential for IO3: Platform where VR devices may be attached to get an immersive training experience.

CAT Safety VR module

Caterpillar Safety Services (2020) started their VR safety programme with safety in road construction by simulating real-life scenarios. CAT designed the VR tools as a multiplayer environment so a group of workers could train simultaneously. Application is implemented in the preparation phase. Training module presents a wrap-up to reinforce the positive lessons learned and stress that no emergency at the jobsite is worth risking the safety of the worker or anyone else.

- Software: Revit, Game engines.
- Hardware: Gaming laptop preloaded to run the program, HTC VIVE, 2 Joysticks.
- Potential for IO2: BIM is not applied in this safety experience.
- Potential for IO3: Communication and mobile modules are possible contributions.

SRI International Augmented Reality Solutions for Construction Inspection

SRI International (2020) uses AR to simulate job site operations for construction inspectors. By utilizing drones the tool is used for inspection by comparing the footage with BIM models. SRI international AR

tool is designed for site inspections. The application targets the construction phase for inspection by safety managers and engineers.

- Software: Revit, several data collection software.
- Hardware: Drones, Vehicles, AR Glasses.
- Potential for IO2: BIM is used to model and inspect possible errors or differences in the construction by comparing it with a BIM model using AR.
- Potential for IO3: AR captures images with headset and tags these with notes for sharing with other devices.

Safety Compass - Augmented Reality Workplace Safety

Safety Compass (2020) gives access to live information which is updated based on the worker's location. The tool uses AR technology to identify potential risks at the location via mapping on a tablet or phone. This application also allows interaction and collaboration of all construction site personnel.

- Software: Location tracking system (LTS), location database (LD), user identification interface (UII), user database (UD), Revit.
- Hardware: iPhone, AP sensor, computer, GPS.
- Potential for IO2: BIM is linked to the GPS and the mobile app can give risk alerts and notifications based on the location.
- Potential for IO3: Workers will be notified of potential risks pinpointed on an interactive mapping system. The AR app is effective and easy to develop.

VR Safety Training for Construction companies – LandMark VR

In LandMark VR (2020) the participants experience risky scenarios where each one has to choose adequate precaution in order to pass a certifying test. It uses full immersion by visual, sound, and physical effects. It has a multi-scenario selection, supports trainer and trainee real-time guidance, tracks individual behaviour, and can be tailor-made for conducting practical training. The scenarios are created in a CAVE environment.

- Software: Revit, 3D Unity.
- Hardware: CAVE, HTC VIVE, high-performance computer.
- Potential for IO2: The application did not demonstrate any BIM integration.
- Potential for IO3: Training solutions and scenarios were used with low-cost equipment.

FULmax CUBE

FULmax (2020) CUBE provides possibilities to communicate, share and collaborate as a team in an immersive BIM environment. It may introduce stakeholders to the virtual asset before it is built. The system may educate and train personnel and communicate onsite, simulate operational based activities virtually before setting foot on site. The tool may provide a dedicated BIM space for virtual exploration of the built asset coupled with the associated valuable BIM data. BIM models and data are processed in minutes for the FULmax environment. It is easy to navigate and to explore the digital asset and to access BIM data, it is a compact solution and it is ideal for reviews, stakeholder engagement and collaboration.

- Software: Unity platform.
- Hardware: FULmax CUBE system with projectors and projector screens.
- Potential for IO2: BIM models are used for creating virtual environments.
- Potential for IO3: Can support more than one person training at a time.

Role of Visualization Technologies in Safety Planning and Management at Construction Jobsites

The research (Azhar, 2017) used advanced visualization technology applications for safety in building projects which was tested in three projects, on their 4D BIM models. Only commercially available tools were used and tested by designers, engineers and contractors. The application targeted preparation and construction stages and the developed tools were used to train workers.

- Software: Revit, Sketchup, 3Ds Max, Unity 3D, AutoCAD, Synchro, MS Project, Camtasia, MS Movie Maker
- Hardware: Oculus Rift
- Potential for IO2: BIM was used in 4D simulations.
- Potential for IO3: VR used common and affordable tools.

A framework for construction safety management and visualization system (SMVS)

The proposed SMVS (Park and Kim, 2013) tool is centred on a visualization engine for the integration of all information. Visualization engine is the hub of the SMVS that imports and exports external information such as BIM-based site model, safety information data, and sensor signal location data that is created in other software engines for its use in each system module. Microsoft XNA Game Studio 4.0 program environment has been employed considering the interoperability of data necessary to the system operation. All information from/to interfaces of the modules is displayed on the visualization engine browser (VEB). It is a framework for safety management and visualization system (SMVS) that integrates BIM, location tracking, AR, and game technologies. A prototype system has been developed and tested based on an illustrative accident scenario.

- Software: Microsoft XNA Game Studio 4.0, Visualization engine browser (VEB), risk identification interface (RII), location tracking system (LTS), location database (LD), user identification interface (UII), user database (UD), Revit.
- Hardware: iPhone, AP sensor, computer, GPS, mouse, keyboard, joystick.
- Potential for IO2: Integrates BIM with other tools.
- Potential for IO3: Game engine might be suitable due to interoperability.

OSHA PIXO safety compliance Virtual Reality

This training module (PIXOVR, 2020) for safety compliance tries to achieve realism in the virtual environment. Training processes explore these environments which also feature construction. For example, one mode is a safety sweep that tries to find potential OSHA violations, faulty equipment, inadequate storage of hazardous materials, and co-workers not wearing safety gear or working unsafely. It comprises of digital tests and assessments based on OSHA standards. This application focuses on the preparation and construction stages.

- Software: Unreal Engine.
- Hardware: Oculus Rift, Leap Motion, high-performance computers.
- Potential for IO2: Environments do not seem to be modelled in BIM.
- Potential for IO3: Training is based on OSHA standards, assessment is digital, randomized scenarios, several training methods and detailed in terms of graphics, sound and scenarios making it fully immersive.

Web-based Collaborative Virtual Environments (LIRKIS G-CVE)

Collaborative virtual environments mediate interaction in virtual space among more participants that may be spread over large distances. Globally, multi-user groups can participate together in one

completely immersive virtual environment to achieve goals. Distributed virtual environments can be purposely used as training tools for real-time 3D simulations or scenarios. Benefits of G-CVE are (LIRKIS G-CVE, 2020): multi-user, no expensive software or hardware needed, web-based (only web browser needed), without installation of any software, works on any operating system and any device (also with Oculus, HTC, MS Hololens products), switch to VR mode (with VR headset), open-source.

- Software: Web-based system, built on top of the Networked-Aframe framework.
- Hardware: Any online device/any operation system, any headset - Oculus, HTC, Microsoft Hololens, etc.
- Potential for IO2: BIM models can be imported into the tool
- Potential for IO3: Training solutions and scenarios executable on any device.

Needs analysis

The aforementioned cases were all studied to see which one or which ones would be best fitted to the goals of the project. Needs of the project were analysed and through a session with all project partner institutions and industry partners. The following needs of the project and consequently the deciding criteria were identified:

- Is the tool available for use
- Is the tool proprietary or freely available, and if proprietary is it affordable
- What are the hardware requirements (for computing power)
- Is any additional special hardware needed (i.e. special hardware elements, not including Head Mounted Displays (HMD))
- Does the tool have a desktop version in addition to a full virtual environment
- Does the tool have a smartphone version (i.e. for Samsung Gear) in addition to a full virtual environment
- Does the tool support multiple platforms (supports more HMD's such as HTC Vive, Oculus Rift…)
- Does the tool require additional supporting software, and if yes, is it available to use
- How detailed and realistic can the virtual environment be
- How simple is the tool to install and to use
- Does the tool support multiple users in VR at the same time
- How simple would it be to replicate the research results outside the project partners' institutions
- Is the tool appropriate to teach Health and Safety related topics
- What hazards/scenarios are available in the tool
- Does the tool support the import of user generated BIM models
- Does the tool support creating additional scenarios
- Does the tool have open source, enabling modifications to suit the user's needs

Initial brainstorm yielded 17 of the possible criteria for selecting the most appropriate tool. This number of criteria is too large to model a solution for the problem at hand, so in a further session, the criteria were prioritized and 8 of them were used in the decision making process.

The first and most important (and eliminatory) criterium was the availability of the solution. If the tool is not available for use, then all other characteristics are irrelevant. The second eliminatory criterium would be whether the tool is suitable to teach Health & Safety (H&S) topics. Other 6 criteria serve to differentiate and prioritize remaining tools to determine which would be more appropriate. Those were the ability to create and customize scenarios, the possibility to have multiple users, having open

source, being able to support various HMD's and to have mobile and desktop versions. Furthermore, the tool needs to be fairly simple to use and to replicate in outside the project partners' institutions. The tools and their characteristics with regards to the criteria are shown in Table 1.

Table 1. Comparison of the identified tools based on the selection criteria

	The tool is available	The tool is suitable to teach H&S topics	Ability to create and customize scenarios	Possibility to have multiple users in VR	Has open source	Supports various HMD's	Has mobile and desktop versions	Possible to use and to replicate in outside the project partners' institutions
1. 3M	YES	YES	NO	NO[1]	NO	YES	NO	YES[2]
2. CAT	YES	YES	NO	NO[1]	NO	NO	NO	YES[2]
3. SRI	YES	NO	NO	NO[1]	NO	NO	NO	YES[2]
4. Safety Compass	YES	NO	NO	YES	NO	NO	YES	YES[2]
5. LandMark VR	YES	YES	NO	YES	NO	YES	NO	YES[2]
6. FULmax cube	YES	YES	YES	YES	NO	N/A	NO	YES[2]
7. Visualization Technologies in Safety Planning and Management	YES	YES	YES	NO[1]	NO	YES	NO	YES[2]
8. SMVS	YES	YES	YES	NO[1]	NO	YES	NO	YES[2]
9. OSHA PIXO	YES	YES	NO	NO[1]	NO	YES	NO	YES[2]
10. LIRKIS G-CVE	YES	YES	YES	YES	YES	YES	YES	YES

[1] Only one user in VR, however others can watch on a separate screen
[2] Possible, but the intended user needs to buy the software and/or special hardware

After careful consideration of all identified technologies and having these requirements and criteria in mind, the tool "Web-based Collaborative Virtual Environments (LIRKIS G-CVE)" was chosen as the most suitable to use the BIM models and advantages of immersive reality tools for construction safety education. Final selection of the tool will however be carried out after all hazard scenarios are defined.

Discussion

This research identified 10 potential AR/VR tools to be used for safety training in the project. The tools each have a different goal and some were not initially intended for H&S training. For each of the tools, a short description was given, followed by information on what hardware and software is needed, as well as what is the tool's potential for use in the following project stages.

There were several BIM programs used by the tools, but major and most used was Autodesk Revit with the combination of BIM 360 for tracking, collaboration and document management. Along with Revit, other 3D and visualization software were used like 3Dmax, Blender, AutoCAD, ArchiCAD, Bentley and SketchUp. Visualization methods of the tools were structured as a gamified structure for training and risk predictions of accidents. Other methods based on BIM models rely on tracking devices to obtain an onsite visualization of the models, safety information data and sensor signal location data.

For gamification, most tools use Unity and Unreal Engine, and some use specialised or proprietary software for virtual scenario generation. On the hardware side, tools use either HMD's or CAVE systems, while some also feature a desktop or mobile version. Cost-effectiveness, availability of both hardware and software, and multiplatform support are important factors since the final safety training tool should be as widely available as possible. Some other selection criteria will be the ability to model custom scenarios, simplicity to use, multi-user support, etc.

The identified tools were presented to the industry partner and discussion was held on the possibilities to use each of them for safety training purposes. The partner validated the tools as having indeed the potential for safety training, with LIRKIS G-CVE having slight lead due to adaptability and multi-user support. Final selection will, however, only be carried out after precisely defining which hazard scenarios will be modelled for the safety training tool.

CONCLUSION

Construction safety training programmes exist in various forms, but mostly they are lecture driven, with no hands-on experience. This is not surprising since putting novice workers and students in potentially harmful situations is not possible and not feasible. For this reason, using immersive reality in safety training has gained some interest from the practitioners. Immersive reality can overcome the effectiveness issue of non-practical lectures and the ethical limitations of purposely putting people in harm's way. However, software solutions are not yet mature enough to offer complete safety training programmes.

The project described in this paper aims to aid in the effort of providing safety training in immersive reality. It plans to do so by developing a methodology for hazard scenario generation, as well as a few hazard scenarios. The first step of the project is described in this paper. It consisted of identifying what tools already exist in the market and checking for their suitability for the project goals.

One of the greatest limitations of the research is it not being a complete and comprehensive review of all AR/VR tools available for the construction industry and construction safety. However, such a comprehensive review was not the goal of the paper since literature review papers have already covered the topic. Furthermore, for a more comprehensive validation of the chosen tool, other contractors should be included, since each of them has their own specific safety issues and view of the topic at hand.

Future research steps are defined in the project documents and research on the next intellectual output regarding the use of BIM models in the AR/VR environment is already underway.

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