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A PILOT STUDY OF A 3D GAME ENVIRONMENT FOR CONSTRUCTION SAFETY EDUCATION

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SUMMARY: *Education is crucial to promoting a safe and healthful working environment in construction and teaching students to identify potential job hazards is its very first step. The authors proposed a 3D video game, Safety Inspector, to provide a comprehensive safety training environment in which students assume the roles of safety inspectors and walk the game site to identify potential hazards. Violations of different modelling difficulties and various levels of safety knowledge for identifying these violations were listed to guide the development. The game was also designed with an agenda to address features such as realism, self-learning, non-linearity, interactivity, etc. Torque 3D game engine was leveraged for implementing the game system and Autodesk 3ds Max as well as MilkShape 3D were used to create the needed but unavailable 3D objects. An important development strategy was approximation - this applied to both the definition of object collision boundaries and the texture mappings. A small group of students from the Department of Construction Management at the University of Washington helped test the preliminary game system. The testing results indicated that with the game students increased their learning interests, enjoyed the learning process, and were motivated to refresh their safety knowledge. In addition, students also showed optimistic attitudes towards using the game scoring as a way to reflect their safety knowledge. In overall, the evaluation results suggested a positive outlook of the game and encouraged the continuous development of Safety Inspector. However, the prototype system did not incorporate all the desired violations or features and should be further enriched in its next version. Pedagogical issues newly discovered during the game evaluation process are to be addressed as a part of the future work.*

KEYWORDS: *construction safety, hazard recognition, video game, education, computer-assisted learning.*

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1. INTRODUCTION

Understanding the fundamentals of jobsite safety is important to the day-to-day construction operations. According to the US Bureau of Labor Statistics (BLS), in the US, there are more than a thousand work-related fatalities in construction each year and in average one out of seven construction employees is injured due to work-related accidents. Construction constantly remains one of the top three dangerous industries in the US, with the greatest total number of work-related fatalities among all industries. Promoting safety education and preparing our future taskforce for a safer and healthier work environment is in no doubt a critical agenda amongst other highest priorities in construction.

The education of construction safety leverages very little numerical calculation but emphasizes a lot on the (1) identification, analysis, and control of work hazards, and (2) interpretation of safety regulations. Because the daily business of construction involves the uses of blueprints, maps, schedules, etc., construction students are well trained to capture information from visual patterns, making visual aids such as figures, images, or even videos effective tools to communicate potential hazards (Lin, 2009). In safety education, students are often asked to demonstrate their hazard recognition abilities as a way to verify their learning outcomes through means of observing and critiquing on-site images, or conducting and reporting their actual site visits. It is true that a picture is worth a thousand words. But presenting a static image of a "particular" onsite operation or set-up (e.g. scaffold without toe boards) intrinsically restricts the discussion to what is captured in the picture only. This is useful sometimes for focused discussions. But in comparison to walking actual jobsites, this could also limit the challenge and does not truly reflect a student's comprehensive ability on hazard recognition. Indeed, visits to construction sites are unique experiences that cannot be completely replaced by other learning methods. However, they come with a number of constraints (sometimes even safety concerns!) and cannot be arranged as often as needed.

While digital games have being routinely listed as the most important and influential medium by college students (Games-to-Teach Team, 2003), what are the opportunities and possible limitations for game applications in the course of constructions safety education considering existing learning needs, approaches, and limitations? In particular, can the strengths such as virtual reality and interactivity of 3D video games provide rich visual information to facilitate construction safety education? Computer-assisted game applications in architecture, engineering, and construction (AEC) training and education are not new interventions and some of the pioneer projects could even be dated back as early as 1969 (see Table. 1). Wisdoms from these previous efforts illustrate the revolution of computer-assisted games in AEC as technology advances and offer guidance to the follower researchers. However, only until recent years that a small number of researchers started looking into the virtual, 3D environment for delivering learning experiences (e.g. the virtual surveyor from Lu et al, 2009). Incorporating such an environment into video games for learning experiences that are both *entertaining* and *engaging* is even rarer and can be considered as still in its infancy. To this end, the authors proposed a 3D video game development initiative to explore how the game technology can intertwine with safety education and complement existing learning approaches such as job walks and observations of on-site images.

For safety education, the game aims to provide a "safe" training environment that engages students in comprehensive hazard recognition challenges as a way to evaluate student learning performance and increase student learning interests. In addition to this, the game development process is expected to serve as an operational model of available technologies for those who are also intrigued by educational video games in AEC. In addressing the above objectives, this paper reports the authors' overall game development plan, the implementation of a preliminary prototype system, Safety Inspector (SI), and the game evaluation.

TABLE. 1: Summary of Computer-assisted Game Applications in AEC.

Purpose	Developed By
The Construction Management Game, which simulates the bidding process.	Au et al (1969)
Constructo, which simulates the weather and labor productivity effects on project management in a network format.	Halpin and Woodhead (1973)
Super Bid, which simulates the bidding skills of project managers.	AbouRizk (1992)
COMMITED, which simulates the tendering process.	Hornibrook (1996)
Survey learning.	Smith and Roberts (1997)
Parade of Trades, which demonstrates impacts of workflow variability on succeeding trade performance.	Coo and Tommelein (1999)
The Hong Kong Game, which simulates the planning of on-site construction activities.	Marsh and Rowlinson (1999)
Contract and Construct (C&C), which simulates and teaches students the tradeoffs between cost, quality, time, safety, decision making, and people management.	Martin (2000)
Construction Marketing Game, which enhances the awareness of construction managers about marketing in construction.	Bichot (2001)
VIRCON, an interactive system for learning construction planning.	Jaafari et al (2001)
The Equipment Replacement Game, which simulates the buy and sell decisions about construction equipment.	Nassar (2002)
B.I.G., developing a student's capability to analyze situations, gather data, and make strategic decisions while balancing time, cost and quality.	Johnston et al (2003)
Safety training on the process of steel erection.	Irizarry and Abraham (2005)
Virtual reality surveying application	Ellis et al (2006)
Virtual surveyor training for civil engineering students.	Lu et al (2009)
The Excavation Game, emphasizing the importance of monitoring cost, time, and quality of any project.	Sherif and Mekkawi (2009)

2. STORYBOARDING

A student playing the game assumes the role of a controlling contractor's safety inspector and has the responsibility to point out all on-site hazards during his or her virtual job walk. In a limited amount of time, the safety inspector is to explore the entire jobsite with an attention of detail (e.g. go through every floor and every room of a building that is under construction), be aware of the specialty operations (e.g. crane erection) occurring on site and check them out, and identify any unsafe environment or behavior observed. The safety inspector will have tools such as the site plan and a list of activities scheduled for the day of the walk. Each successfully identified hazard will be awarded and also illustrated with extended explanations, best practices, applicable safety rules/regulations, and corrective actions. In the game, this is to help the safety inspector communicate with on-site fellow workers and to provide a point of reference (as well as authority!) should further information is needed. The safety inspector who receives the most awards will be recognized with the prestigious title – safety director.

As with any video game, the challenges are set out at different levels depending on the required depth of safety knowledge. For example, "missing hardhats" is an obvious violation but "means of access/egress over twenty-five feet of reach for the workers in a trench" is not so explicit. In the later case, a safety inspector not only needs to know about trench safety but also how operations should be set up in specifics. Table. 2 is a preliminary hazard classification derived from the US Washington State Labor and Industry (WA L&I) safety training materials prepared to guide the game development in general. In Table. 2, there are three levels of required safety knowledge and two levels of game modelling difficulty. A static activity or work environment without movements (e.g. unprotected rebar) is a lot easier to model than an activity in action (e.g. worker reaching too far on a ladder and losing balance). Having a classification of hazards as such strategically helps the authors focus on particular hazards in the first version of the game deployment so that research insights can be obtained before a full-scale game is implemented. Hazards that are better explained by visual descriptions (e.g. loose items aloft on installed steel beams) are also supplied with images to showcase the typical scenarios during game analysis and implementation. This is intended to assist with the game design in terms of objects nearby, object dimensions, object textures, and the relative locations between objects.

TABLE. 2: Classification of Common Safety Hazards for Modelling.

	Level of Modelling Difficulty – Low	Level of Modelling Difficulty - High
Required Level of Safety Knowledge - Low	1. PPE – missing hardhat when standing underneath scaffolds 2. Hammer rests on the edge of the scaffold 3. Scaffold missing guard rails and toe boards 4. Unprotected rebar 5. Worker standing underneath the hoisted loads 6. Standing on a window sill w/o PFAS 7. Concrete pump goes above power lines 8. Holes on the floors w/o covers 9. No perimeter cables along the perimeter steel columns 10. Worker smoking next to tanks that store flammables 11. No guardrails around stairwell 12. Uncapped rebar 13. Personnel inside the swing radius of a crane	1. Electrical – distance between the crane and the power line is larger than ten feet 2. Trench over four feet deep with no protection systems in place 3. Unnecessarily steep (pitch larger than twenty degrees) and narrow (smaller than eighteen inches) walkways 4. Walkboards four feet or more above grounds 5. PPE – carrying lumber w/o gloves 6. PPE – missing safety glasses when using nail guns 7. Material handling – hoisting personnel 8. Carrying a tool by the cord 9. Worker climbing scaffold bracings 10. Cement truck backing onto a worker 11. Worker on the ladder reaching too far
Required Level of Safety Knowledge - Medium	1. PPE – using bump hat (instead of hardhat) 2. Material storage – lumber stacking too high 3. Material handling – rigging when the shackle is used upside down 4. Scaffold base plate sits on shaky objects instead of on firm foundation 5. Scaffold platform not fully planked 6. Skylight not covered for roofing construction 7. Trench - spoil pile too close to the trench, no means of egress/access, equip working right at the edge, walking outside the trench box 8. Rusty or damaged shoring posts 9. Waste dump w/o fencing 10. Nails remaining on lumber 11. Workers on aerial lifts w/o fall protection 12. Tripping hazards due to messy housekeeping (e.g. cords all over the place) 13. Electrical tools not in use are plugged in 14. Workers wearing athlete shoes 15. Ladder not properly secured or set up 16. Man using jackhammer w/o hearing protection 17. Climbing stairs w/o three point contacts 18. Crane outrigger on unstable bases 19. Elevated concrete pouring bucket on top of employees 20. Concrete pouring hose on the shoulder, kinking 21. Unsafe pedestrian walkway 22. More than one person on a ladder at one time	1. PPE – beard guy wearing a tight-fitting respirator when spraying paint 2. Loose items aloft on installed steel beams
Required Level of Safety Knowledge - High	1. Material storage – stacking pipes in racks facing main aisles 2. Step ladders on top of scaffolds 3. Bundles of metal decking on top of joists w/o bridging 4. Multiple lift w/ more than five members or w/ members too close to each other 5. Using the stepladder to gain access to upper levels	1. Material storage inside buildings under construction shall not be placed within 6' of any hoist way or 10' of an exterior wall 2. Trench – means of egress/access over twenty-five feet of reach, ladder not extending three feet above the trench box, box too low 3. Post-tensioning operations w/o barricades to limit employee access 4. Un-braced masonry wall over eight feet in a control access zone 5. Steel columns w/ only two anchor bolts on the bottom 6. Workers standing on buckets to reach for high objects 7. Change in elevation more than nineteen inches w/o adequate stairs/ramp access 8. Workers on walkways exposed to opening w/ extreme hazardous conditions w/o guardrails (even though the walkways are only one or two feet above ground) 9. Window openings on or above the second floor where the sill is less than thirty six inches from the floor w/o

	guardrails
	10. Ladders not set at a four-to-one angle
	11. Only one seat is installed before releasing hoist lines when installing a joist over sixty feet

3. DESIGN ANALYSIS

The characteristics of effective computer-aided learning proposed by Sherif and Mekkawi (2006) are referenced here to provide a framework for illustrating the game analysis and design.

3.1 Realism

The visual effect of a 3D video game could sometimes become its bottleneck because of the requirements on hardware computers. For SI, on one hand, it is desirable to create an extremely realistic game environment that mimics all the happenings on an actual job site. On the other hand, the associated computational cost calls for a balanced approach which cuts down unnecessary visual effects in the game. For example, the rendering in Autodesk Revit Architecture can convert a design sketch into a photorealistic, as-built image. This level of visual quality is unbeatable but is also too computationally expensive to have in SI, especially when dynamic movement of a player or interaction among game objects is required. Therefore, using images of fair quality textures is a satisfactory and more preferred option. Specific details can then be illustrated by supplemental images of the workers, fleets, buildings, equipment, tools, materials or operations in question.

Besides the visual effect, it is desirable to reduce the complexity of “collision boundary”, i.e. a hidden boundary of a game object. Game objects are defined by both their geometric properties and collision boundaries. Game objects interact with each other through the “collision detection” mechanism - if two game objects are virtually collided, some actions or changes on the game objects would take place. For very complicated objects such as construction cranes, shape approximation helps reduce the complexity of collision boundaries and make “collision detection” computationally easier. It is therefore a recommended technique for the development of SI.

3.2 Self-learning

The SI game is positioned to engage students in challenges that involve comprehensive hazard recognitions and to inspire student learning. The game is intended to be used with other pedagogical approaches and does not act alone as a single solution for the purpose of learning construction safety. However, although no formal lesson plans are programmed as a part of the game design, challenges, competition, and entertainment aspects of the game could motivate students to refresh or increase their safety knowledge. In addition, extended discussions, best practices, applicable safety rules/regulations, and corrective actions for identified violations are to be incorporated in the game as self-learning resources (or at least as a point of reference).

3.3 Non-linearity and Interactivity

Non-linearity means that the game interactivity is provided at different levels, depending on the actions committed. At the physical level, a student orients in the game through mouse or keyboard controls. At the sensing level, a student visually and aurally examines the game job site for hints on any potential job hazards. At the knowledge level, a student provides inputs about the potential hazards. Because students can walk around freely in SI without a predetermined agenda, the experience is determined on the fly and not prescribed.

3.4 Degree of Guidance

Besides guidance on how to interact with the game (e.g. orientation, building access, violation identification, on-screen displayed information, etc.) students might also need some sample scenarios to illustrate what to look out for (e.g. workers, fleets, buildings, equipment, tools, materials, operations, etc) before they play the game. At a minimum, the safety inspector should have tools such as the site plan and a list of activities scheduled for the day of the walk. These tools will indicate what specific areas the safety inspector should pay extra attention and provide a starting point for hazard identification.

3.5 Uncertainty and Novelty

Because supplemental images are to be furnished in the game for the workers, fleets, buildings, equipment, tools, materials or operations under question, uncertainty can be incorporated in the game by randomly selecting applicable images to construct the situation. This way, the job walk becomes an unpredictable experience even if a student were to play the same game level multiple times.

3.6 Assessment of User's Performance

The final game report after each play should reflect how a student performs in the game compared to his or her peers. This will help both the student as well as the instructor evaluate the student's hazard recognition ability and point out areas where the student has mistakenly recognized (or ignored). Analysis of the game log will further indicate common areas where learning help is most needed (e.g. a particular hazardous situation that most students have missed).

3.7 Enjoyment

Some said that lowering the barrier between education and entertainment is an important challenge (Prensky, 2003). Even though SI is an educational game, its intrinsic video game features are expected to be much more entertaining than the traditional learning methods, making the game playing a fun and enjoyable educational experience. A viable strategy to boost the game entertainment is personalization, e.g. allowing a game player to select a customized outfit or embedding landmarks well-known to the targeted game players.

3.8 Safe Learning Environment

It is intuitive that compared to actual job walks, students can play the role of safety inspectors and "safely" navigate through the game job site with minimum risks in SI.

4. PROTOTYPE IMPLEMENTATION

Section 3 explains the overall game development plan and Section 4 illustrates how important design features from the plan were implemented, although not all items on the "wish list" were materialized. In the current version of SI, audio effects and supplemental images illustrating the violation details have not been incorporated in the game. Extended discussions, best practices, applicable safety rules/regulations, and corrective actions for identified violations have also been condensed.

4.1 Game Objects Design

4.1.1 Construction Site

The construction site is separated into three areas with each area encompassing different construction phases (i.e. earthmoving, structural work, and finish) and violation scenarios pertinent to those phases. The very first step to implement a scenario in SI is to plug in the construction elements typically situated in the scenario. For example, to recreate the improper set-ups of scaffolds for masonry work, scaffold objects are placed in the finish area for modelling the missing planks. The entire site is also mapped with textures in order to convey a realistic sense of the construction field, addressing the realism requirement in the game design.

4.1.2 Workers and Fleets

By design, workers wear outfits (either appropriate or inappropriate) of some sort and are equipped with some construction tools because many safety regulations are related to dress codes and tool handling. Worker movements and actions are modelled to implement safety violations that involve dynamic operations. This is to add a realistic sense of a construction field and to fulfil the realism requirement in the game design. Construction fleets are modelled similarly. Although not yet been implemented, extra laborers and construction fleets together with their sound effects are to be added in the future to further enrich the game.

4.1.3 The Surrounding Environment

The construction site is designed to include most of the elements that are likely to be on a construction site; e.g., office trailers, cars, trucks, fences, power lines, trees, foliage, traffic signs, safety signs, and so on. Buildings and roads adjacent to or outside the game site are modelled with minimal details to improve the outlook of the game without sacrificing its overall game speed. This modelling strategy corresponds to our game analysis in the sense that unnecessary visual effects should be reduced.

4.2 Safety Violations

Safety violations targeted for the game implementation are previously listed in Table 2. One of the dimensions to categorize these violations is by the level of knowledge that learners need to perceive the violations. Using this dimension, the categorization can naturally evolve into three game stages (e.g. easy, moderate, and difficult) for SI. However in the current stage of the game, a mixture of easy-to-moderate violation recognition challenges was implemented instead for testing purposes.

4.3 Game Logic Design

The playing logic is quite similar to that of many action games. In particular, a learner begins by exploring the construction site after SI is initialized. While travelling around the construction site, the learner encounters game objects which may or may not constitute job hazards. If the learner is convinced that the game object presents a potential job hazard, he or she can point out the potential violation by clicking on the game object. If the object truly constitutes a violation, instructional messages relevant to the violation (Fig. 1) are displayed on screen and the learner gets points corresponding to the level of the hazard recognition challenge. This self-guided trial-and-error process continues until termination conditions are met. The game is terminated if a learner successfully finds out all safety violations or is out of time. After finishing a stage, a learner can either go to a different stage or simply exit the game.

FIG. 1: Point earning with an instructional message when a player correctly identifies that the mobile crane is too close to an overhead power line.

4.4 Game Implementation

SI is powered by “Torque 3D” game engine through Torque Software Development Kit (SDK) V1.0. Torque 3D game engine was developed by InstantAction (formerly known as Garage Games) to serve as a platform for the development of 3D video games. The engine code is written in C++ with tools written in C++ and a proprietary scripting language, TorqueScript. The authors decided to go with this commercial game engine because of its relatively low development cost and its advantages in many perspectives (e.g. capability of web publishing, source code access, abundant discussion threads, capability to take advantage of existing 3D objects produced by software such as Autodesk 3ds Max etc). Success with an earlier generation of the game engine (i.e. Torque Game Engine, or TGE) reported in some research development (Moloney and Amor, 2003; Wyeld et al, 2007) also encouraged the authors to go with the use of Torque 3D. Although the official software documentation did not provide sufficient information for someone new to the game development, the authors were able to get a better grip of the engine by referring to publications (Maurina, 2006; 2008) which discussed the technicality of the old engine, TGE.

Main functionalities of the Torque 3D game engine include 3D rendering, physics, and animation that are necessary for implementing SI. To simplify the game development processes, Torque 3D game engine is manipulated through Torque SDK. Editors and tool kits such as the Terrain Editor, Shape Editor, and Material Editor in Torque SDK enable developers to complete games without laborious coding from scratch. Detailed game implementation is described in the following sub sections.

4.4.1 Creating Terrain

One of the first objects added to the game was the construction site terrain. The terrain was created (Fig. 2) by modifying a default terrain shape and textures using the Terrain Editor in Torque SDK. Because the earthmoving area is crucial to presenting a realistic construction site, its terrain was customized with a specific height and fully detailed textures (Fig. 3). Other terrain areas remained flat in their heights and were textured with less extended detail. After the site terrain was shaped, roads around the site were determined and incorporated into the game.

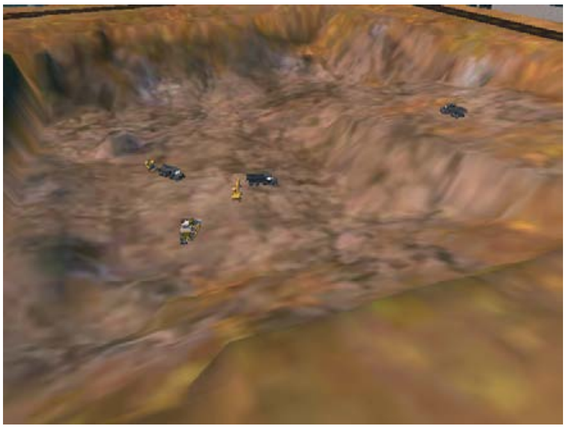

FIG. 2: Earthmoving terrain in Safety Inspector.

FIG. 3: The earthmoving terrain texture in Safety Inspector.

4.4.2 Creating 3D Objects

3D game objects had to be produced and then imported into the SI virtual space. These objects include but are not limited to worker characters, fleets, buildings, equipments, tools, materials, and background objects. Some objects were created from scratch and some were modified from existing 3D models. Autodesk 3ds Max 2009 was used to create/edit most of the 3D objects, although MilkShape 3D was also used occasionally. Creating 3D objects for games is quite different from developing 3D graphic work for architectural drawings. The main difference is that complex objects made of too many vertices and polygons cannot be used for developing games and it is very vital to maintain a balance between game efficiency and the realistic aspect of the objects. Fig. 4 and Fig. 5 show how texture mapping was applied onto selected objects (e.g. formwork and reinforcement) on site. Furthermore, the collision boundaries for each object were added in the object's 3D hierarchy for defining the collision detection mechanism among game objects.

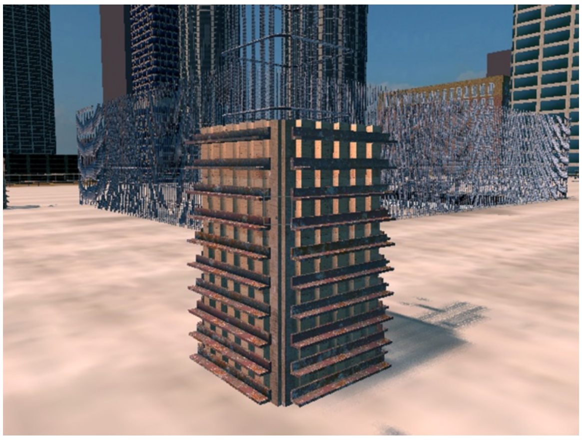

FIG. 4: Texture mapping for concrete formwork.

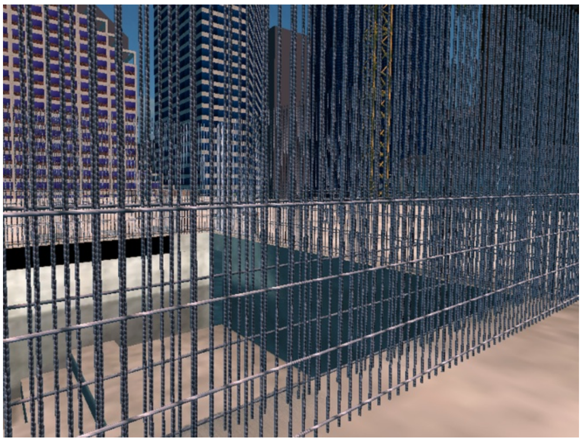

FIG. 5: Texture mapping for reinforcement.

4.4.3 Formatting and Importing Game Objects

While 3D object creation is important, importing 3D models into the game is another major milestone. For this purpose, completed 3D objects were imported into the game in the format of DTS (Dynamix Three Space) or DIF (Dynamix Interior File), both proprietary. DTS is generally used for representing non-structural game objects such as characters, fleets, and equipments while DIF is used for representing structural game objects such as buildings or other enclosing structures. DTS objects were produced by exporting 3D objects through a DTS exporter (e.g. max2dts exporter) in Autodesk 3ds Max 2009 and DIF objects were created through two steps, including exporting 3D objects into the file format of Torque Constructor and then exporting again the 3D objects in Torque Constructor into the DIF format. Torque Constructor is a format especially designed for drawing structures in Torque products.

Formatted game objects were incorporated into the virtual game space through Torque 3D SDK. Building objects were first arranged in compliance with the site design previously discussed. Equipment including a tower crane, a mobile crane, and scaffolds was set up around the building objects whereas fleets objects such as trucks, back-hoes, and cars were placed off the building objects but on the site. Next, laborers were placed at appropriate positions with mounted tools (e.g. hammers and drills) and accessories (e.g. hard hats). These tools and accessories helped create situations that can be cast into potential safety violations to challenge the game player. Then, the construction site was landscaped and enriched using objects such as temporary offices, cars, trucks, fences, power lines, trees, foliage, traffic signs, and safety signs. Lastly, background buildings and adjacent roads were set up outside the construction site (Fig. 6).

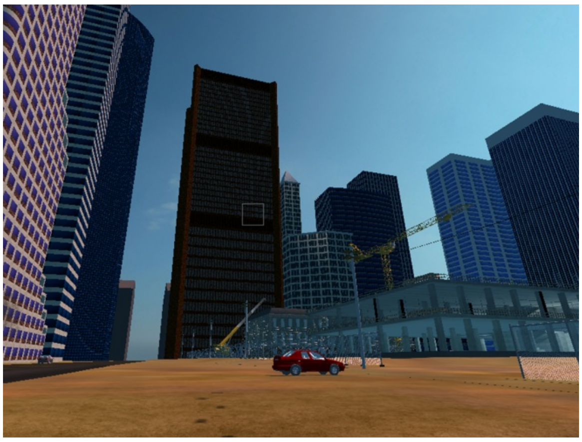

FIG. 6: A perspective view in Safety Inspector showing the background buildings.

4.4.4 Customizing Game Code

The game engine has been customized so that required properties, responsive actions, and dynamic behaviors of game objects could be accomplished. In particular, special objects called datablocks in Torque 3D engine were modified in order to define each object's properties (e.g. a worker's movement speed) and behaviors. The two most important and challenging tasks in code customization are modelling the dynamic movement of laborers and fleets, and determining the response of a game object when it is selected by players as the potential violation. Dynamic movements of laborers and fleets were accomplished by modifying Torque 3D's AiPlayer datablock. The response of a game object was specified by modifying codes related to collision detection.

4.4.5 Creating Graphic User Interface (GUI)

GUI was designed to display necessary information such as current total points and instructional/correctional messages so that a learner could obtain feedback along his or her game play.

5. EVALUATION AND DISCUSSION

5.1 System Evaluation

Before a full scale implementation and evaluation is attempted, a small group of students from the Department of Construction Management (CM) at the University of Washington (UW) were invited to test the game and to provide feedback on their learning experiences. A total of five students who all have taken the construction safety class required in the CM curriculum voluntarily participated in the game testing. Each student volunteer was given a short briefing prior to the testing to obtain some background information about the research (e.g. testing purpose, procedure, uses of testing results, etc). The volunteer was also introduced to the game mission and ways to interact with the game. Afterwards, the volunteer played the game for ten minutes and then filled up a feedback survey to help evaluate the research efforts. The entire process took twenty minutes per volunteer and was videotaped with student consents for further analysis. The game was operated on a Windows XP Professional desktop machine with Intel Core 2 Quad CPU and 3.25 GB of RAM. The evaluation followed the framework introduced in "Design Analysis" and was intended to assess the opportunities and possible limitations of SI in the course of construction safety.

A total of eighteen questions were listed in the survey with some questions being designed together (but were placed apart) to help verify the consistency of the survey results. For example, *question 1* asked the volunteers to rate how realistic the game reflected the everyday construction operations and *question 12* asked the volunteers if the game was visually appealing. Although results from the two survey questions were of different data types, they could be used to inform the consistency of student feedback and validate the game's *realism* characteristic based on the feedback. Besides questions that produced ordinal and nominal data, the survey also included open-ended questions for comments or recommendations that the students might possess to help improve the next version of SI. Table 3 summarizes the survey questions as well as their results (except the results for the open-ended questions, which are discussed in Section 5.2). Rating questions were based on a 1 to 7 Liker scale, with 1 being the lowest level and 7 being the highest level of the criteria in question.

TABLE. 3: Survey questions and results summary.

Survey Question	Responses
1. How realistic does the game reflect the everyday construction operations?	60% rated 5 or above 40% rated 4
2. Which visual aid provides you with a more comprehensive challenge of hazard recognition? The game or the image?	40% rated the game 60% rated the image
3. Which visual aid are you more comfortable with when given the task of hazard recognition? The game or the image?	40% rated the game 60% rated the image
4. Does the game motivate you to refresh your knowledge on some of the safety topics? Yes or no.	100% replied “Yes” 0% replied “No”
5. How much does the game intrigue your learning interests?	80% rated 5 or above 20% rated 4
6. Were you unsure about some of the potential violations in the game? Yes or no.	80% replied “Yes” 20% replied “No”
7. Is the learning experience facilitated by the game interactive? Yes or no.	100% replied “Yes” 0% replied “No”
8. How important is it to have learning guidance (e.g. safety tips, hints, related regulations) in the game?	60% rated 5 or above 40% rated 4
9. What types of learning guidance would you like to see in the game?	n/a
10. How challenging is it for you to identify the violations in the game?	40% rated 5 or above 60% rated 3 or below
11. How much does your game performance reflect your safety knowledge?	60% rated 5 or above 40% rated 4
12. Is the game visually appealing to you? Yes or no.	80% replied “Yes” 20% replied “No”
13. Is the game user-friendly and easy to operate for you? Yes or no.	80% replied “Yes” 20% replied “No”
14. Is the experience enjoyable compared to the traditional learning experience? Yes or no.	100% replied “Yes” 0% replied “No”
15. Do you think that the game scoring can be one way to measure your safety knowledge, in addition to your assignments, quizzes and exams grades?	80% replied “Yes” 20% replied “No”
16. What are the three best features of the game?	n/a
17. What are the three worst features of the game?	n/a
18. Any other feedback?	n/a

5.2 Result Analysis

Although statistical significance cannot be calculated due to the small number of volunteers, the evaluation still provides some overall insights about the game performance and will help the authors improve the game design in its next version. Something worth noted is that the characteristic “safe learning environment” is not discussed in specifics as it is self-evident that walking actual sites is much more dangerous than playing a video game on the computer!

5.2.1 Realism

Volunteering students seemed to have positive outlooks about the game appearance (based on *question 12* responses) and somewhat positive attitudes toward how the game reflected the everyday construction operations (based on the responses from *question 1*). Responses from *questions 2* and *3* corresponded to this observation and showed that the participated students still slightly favored images over the game environment, perhaps because they expected the game to have more on-site activities than what could be seen in the current version of SI.

5.2.2 Self-learning

Based on the responses from *questions 4* and *6*, most of the participating students were unsure about some of the potential violations in the game and all of them were motivated to refresh their knowledge on some of the safety topics. Students also gave positive feedback about how the game intrigued their learning interest (based on the responses from *question 5*). One student commented that “It (the game) was fun. I missed the guardrail and should’ve known that!” and another student stated “I wish we had it (the game) in our class”.

5.2.3 Non-linearity and Interactivity

All participated students thought the game was interactive (based on the responses from *question 7*) and most of them considered the game to be user friendly and easy to operate (based on the responses from *question 13*).

5.2.4 Degree of Guidance

Students gave out positive ratings on the importance of learning guidance (based on the response from *question 8*) and commented on how that information would help them in the game. We also observed from the taped videos the benefits of having guidance on how to interact with the game. In particular, one student was interested to know how many violations were in the game prior to the game play. It is arguable if this information is truly helpful or could adversely discourage a student’s full exploration of the virtual construction site. A part of the future work will be to investigate this topic from a pedagogical stand point.

5.2.5 Uncertainty and Novelty

Since only fifteen easy-to-moderate violation recognition challenges from Table 2 were incorporated in the game, less than half of the participated students thought the game was somewhat challenging (based on the *question 10* responses). As mentioned earlier, all volunteering students have taken the construction safety class required by the CM curriculum at the UW and so they possessed the knowledge to identify potential violations. However, as the *question 6* responses indicated, most students were still unsure about some of the potential violations and that the experience was not prescribed, even though only a mixture of violations were placed in the game. In the next stage of the game development, supplemental images for the workers, fleets, buildings, equipment, tools, materials, and operations will be incorporated and randomly presented in SI.

5.2.6 Assessment of User’s Performance

The responses from *questions 11* and *15* consistently implied that participating students were positive about using the game to measure and reflect their safety knowledge in additional to their assignments, quizzes, and exam scores.

5.2.7 Enjoyment

All volunteering students who helped test the game enjoyed the experience, as is evidenced by the *question 14* responses. Students even commented on the background surrounding building that they saw in the game (e.g. Space Needle) and said that seeing these familiar landscapes helped them feel like working in downtown Seattle.

5.2.8 Miscellaneous Game Modelling Issues

One of the modelled violations was about ladder safety (i.e. more than one person on a ladder at one time) and the violation was coded into the ladder object, meaning that a player was supposed to click on the ladder when pointing out the violation. Almost all the players, however, selected one of the two workers on the ladder when identifying the violation. There is obviously a gap between the game design and the student perception. In addition, each game object can handle only one violation currently but it is not uncommon to see multiple violations committed by the same employee on site (e.g. a worker uses a ladder improperly is also without a hard hat). Another issue is about shape approximation. As mentioned earlier, it was desirable to approximate the shape of some complicated objects (e.g. construction cranes) for collision detection. However, the approximation also made the shape very bulky that it was sometimes difficult for the players to select adjacent objects (see Fig. 7) since the invisible collision-detection boundary was slightly larger than the physical shape boundary on screen.

FIG.7: Collision-detection boundary for the crane makes the selection of wood blockings a challenge.

5.2.9 Miscellaneous Pedagogical Issues

Violations listed in Table 2 are scenarios regulated by either OSHA or Washington state safety standards in the US. Bad practices (e.g. improper housekeeping), which are not necessarily violations but could still be cited by compliance officers using the "general duty clause", are not incorporated in SI. Besides, participated students commented on some identified violations and (verbally) came up with ideas to make the job safer. How could these spontaneous ideas be facilitated and captured in the game? Students also exhibited mentalities (i.e. catching mistakes) different from that possessed by real-life safety professionals (i.e. making the site safer) during the game play. It is therefore arguable at this point whether the total number of violations programmed should be made available to guide the game players.

5.2.10 Analysis Summary

In overall, students demonstrated positive learning interests when playing the game and results from the initial assessment encourage the continuous development of the research efforts. Because three out of the five participated students had never (or very rarely) played video games, we also learned that it is essential to exploit the appeal of SI to induce learning in an audience that does not play games (Bellotti et al, 2009).

5.3 Future Work

Next stage of the SI development will extend the scope of modelled violations, incorporate desired but unimplemented features leveraging the design analysis, and address new issues discussed in Section. 5.2. The emphasis will be to get the modelling experience up to speed and the required technology ready so that a more complete version of SI can be tested and evaluated by a larger group of users. This will help move the research from its exploratory mode to a stable model with the finish product of SI being available for game play on the web. Meanwhile, we also plan to recruit researchers whose expertises are in technology-assisted learning and education to collaboratively tackle the pedagogical issues unrevealed and guide the current focus of hazard recognition to problem-based learning in future.

6. CONCLUSION

Computer-assisted game applications are flourishing for AEC education. However, little has been reported on the approaches and performance of 3D video games for these applications. The authors conducted a pilot study to explore the opportunities and limitations of 3D video game technology in the course of construction safety education. Our pilot study showed an engaging and motivating learning experience for the participating students. However, it also pointed out the need to enrich the game environment by resembling more everyday construction activities. Since the game implemented was only a beta version, we expect to improve its realism in its next generation. In addition, the study revealed the game's potential in terms of measuring a student's hazard recognition capability, complementing existing approaches such as job walks or simply working with static violation images. However, we also recognized the need to introduce more pedagogical design considerations in the future so that the game application level could be raised from "hazard recognition" to "positive site safety improvement" (as discussed in 5.2.9). Technology-wise, the authors were able to leverage a low-cost commercial game engine for the game development. The pilot study helped us understand better the challenge and hidden issues when modelling safety violations through selecting and defining game objects (as discussed in 5.2.8). One of such issues is to reach the balance between shape approximation and operability of collision detection. In overall, the study helped us obtain an incremental knowledge about the 3D video game technologies and generated encouraging feedback as well as recommendations for improvement for future research. We expect to continue this line of work with the participation of pedagogical experts in the next stage.

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