Using Serious Games in Virtual Reality for Automated Close Call and Contact Collision Analysis in Construction Safety

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Abstract –

Injuries and fatalities resulting from workplace accidents remain a global concern within the construction industry. While education and training of personnel offer well known approaches for establishing a safe work environment, Serious Games in Virtual Reality (VR) is being increasingly investigated as a complementary approach for learning. They yet have to take full advantage of the inherent data that can be collected about players. This research presents a novel approach for the automated assessment of players' data. The proposed method gathers and processes the data within a serious game for instant personalized feedback. The application focuses on close calls and contact collisions between construction workers and hazards like equipment, harmful substances, or restricted work zones. The results demonstrate the benefits and limitations of safety information previously unavailable, or very hard or impossible to collect. An outlook presents work ahead for practical implementation in existing risk management processes.

Keywords –

accident investigation, close call, construction safety, equipment contact collisions, hazard, human-hazard interaction, risk prevention, serious game, situational awareness, virtual reality, workforce education and training.

1 Introduction

The original inspiration to conduct this research stems from a scientific study on construction accident investigations [1]. It found that approximately 13% of all construction workplace fatalities in the United States relate to too close contact with construction equipment or parts of it (like attached loads) [2]. While construction equipment is dangerous, other industries in engineering suffer from similar problems. As shown in Fig. 1, the location (marked with "x") of 29 coal miners killed while at work between 1984-2004 could only be determined after the tragic loss of their lives. The image depicts detail to the miners who were either remotely operating (72%, indicated by a blank circle) or maintaining (grey shaded circle or square) a continuous miner. The figure is – due to its rarity of pointing out the victim's location – regularly shown in construction safety education classes. However, current learning methods do not engage the trainees in other effective ways of self-experiencing high risk work activities. These often cannot be implemented, especially in field-based safety training where they would endanger one's life [4, 5].

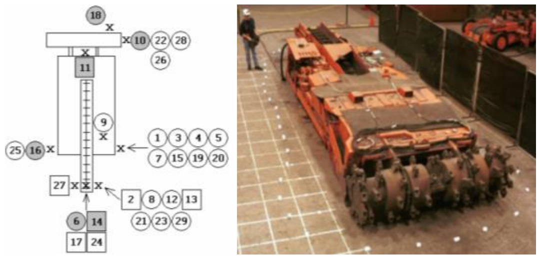


Figure 1. Location of victims with respect to a continuous coal miner (closely related industry) [3]

The novelty of the proposed approach is to provide a safe learning environment where mistakes can be made without suffering the normal consequences. The general hypothesis is that wrong judgement – whether conducted knowingly or not – can be discovered and eliminated by training early on, before it happens at the workplace [6].

Several best practices exist today to mitigate risk in organizations early, starting with a good safety culture and tight safety processes. The layers in the hierarchy of controls, however, still have to take full advantage of data that can be provided by technology during training sessions. Data mining in serious games can offer participants instant personalized feedback.

This research first designed a safe learning process, then a learning platform using serious games in virtual reality (VR). The implementation of a realistic VR environment was supported by the latest, commercially-existing head-mounted display (HMD) units and actual three-dimensional worksite models and schedules (4D) using Building Information Modeling (BIM). Several hazards related to close calls (aka. near misses) and contact collisions between construction workers, equipment or its parts, harmful substances, and restricted zones were added to the virtual construction scene. Consequentially, close calls and contact collisions were defined based on given occupational safety and health standards. Participants with some construction experience tested the scenario individually while personal safety performance data were collected and analyzed in real-time. Instant quantitative analysis and visual safety performance information became available that is used for personalized feedback and improvement.

2 Background

For years Virtual Reality (VR) has been used for training purposes. A high number of VR applications exist in the fields of military, aviation, and medicine. For example, a serious game (defined ‘serious’ because of a primary purpose other than pure entertainment) helped to increase the awareness of airplane passengers in case of an emergency situation [7]. Like many studies, it evaluated two user groups (one group using the traditional approach with safety cards, the other using a serious game) based on questionnaires and pre- and exit-interviews. Studies related to construction [4-5,8-12] concluded that VR-based safety awareness training offers more engaging learning environments. Study participants also reported to favor personalized feedback over no feedback (as commonly in lectures, videos, or demonstrations) [5]. Some of the benefits of VR-based safety training are:

- presents trainees with hazards directly and realistically without compromising their own safety;
- holds the attention of trainees better than conventional classroom teaching does;
- gives trainees a measure of control in the environment, thus reinforcing learning; and
- allows trainers to repeat learning content for many participants under the same training conditions.

VR learning scenarios were criticized by some for being unsophisticated and unrealistic compared to the real world experience [12]. A reason is that creating VR scenarios is a very time-consuming task, requiring a lot of attention to fine details [5] such as programming logic, whereas [6,13-14] proposed using BIM to increase the realism level of VR scenes. While using 4D models adds additional return-on-investment to create BIM data (e.g., beyond its use in design/planning tasks or for providing visual walkthroughs), reducing motion sickness for some players, teaching people unaccustomed to computerized environment, creating multi-user environments (incl. training larger groups), and providing options to instantly record and analyze the players’ behaviors seem to be challenges for realistic VR-implementations. Known limitations are:

- Although hard- and software technology are rapidly evolving, the investment of developing training materials and virtual construction scenarios is high.
- Several studies [5,10-12] claim that the gained safety knowledge of some trainees may remain at similar levels compared to standard learning approaches.

While some of the issues create needs for additional research, they remain outside the scope of this study (e.g., motion sickness and multi-user environments). This study addresses an effort towards real-time data collection and instant analysis in an immersive serious game for a more detailed construction worker-equipment close call and contact collision assessment.

3 Proposed method

This section explains noteworthy details to the research methodology, its objective and scope definition. As illustrated in Fig. 2, the developed virtual safety learning platform consists of a user (e.g., (un)skilled construction worker), a virtual construction site environment (e.g., 3D content generated from 4D models or open source libraries), scene- or object-related content (e.g., typical sounds), and soft- and hardware technology (e.g., authoring tools and head mounted displays, respectively).

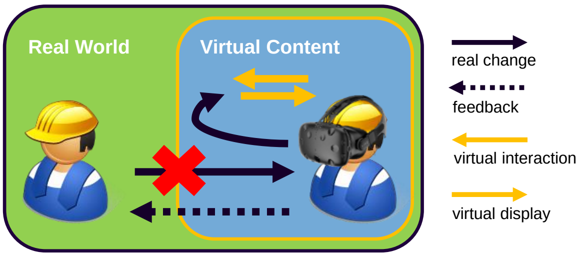


Figure 2. VR safety learning platform [15]

While a person may have previous education and experience (i.e., related to construction safety), advanced tools for automated, in depth, and personalized performance analysis and feedback are not existent in today’s practice (research objective). Personal safety skills particularly to close call and contact collision detection and analysis of construction workers to hazardous equipment or restricted work areas will be tested (research scope definition). VR technology is used as it provides a safe work environment (called an experimental testbed) where humans can make mistakes without suffering the losses they would typically experience in the real world. Thus, further processing of any worthwhile information generated in the virtual world (e.g., the location of close calls or contact collisions, their frequency and types) might be applied to improve the working conditions in the real world. Since 4D-models normally exist before construction starts, such information (e.g., relations between 3D objects and construction sequence) will be used to generate realistic virtual work environments. The following explains how VR is used to advance the analysis and control.

3.1 Visualizing and controlling

VR consists primarily of hard- and software components. While multiple commercial systems exist, this approach used the head mounted display (HMD) HTC Vive Pro (2018 Version) for visualization and control and the game engine Unity3D for authoring content. Although VR raises the immersion effect of the user, it is still challenging to achieve a high realism of VR scenes. Two controllers give a player the opportunity to interact within the virtual construction scene. The lighthouse-system tracks the head-mounted display and controller movements via the emitted infrared rays. A computer combines and finally sends data from the graphics processing unit to the displays of the virtual reality headset. To reduce latency and diminish motion sickness the refresh rate should be close to 90 Hz [14].

3.2 Processing

The second technology which was used is the gaming-engine Unity3D. While the virtual construction scenario is created in Unity3D, it offers programmers many additional functionalities like collision detection or physical handling. To use the HTC Vive tracking system in Unity3D the “steamVR”-plugin” [17] is needed. This plugin contains necessary objects like the “[CameraRig]”-object which handles the communication between the HTC Vive tracking system and the operating computer. The “[CameraRig]”-object has three child-objects: “Controller (left)”, “Controller (right)” and “Camera (head)”. Both of controller-objects are used to handle the player’s input. They visualize the controller’s position and rotation in real-time. The “Camera (head)”-object is used to show the direction of the player’s view. A player uses the touchpad of the right HTC Vive controller for moving within the VR scene.

3.3 Authoring content and model functions

Construction site models from a real project and additional 3D models (e.g., equipment and materials) from the internal Unity3D Asset Store, online libraries for free share or for purchase, self-modeled models, or other sources served as content to create a serious game which was tested by players. To increase a player’s immersion effect, the selection of 3D models plays a pivotal role. Compulsory to the construction scene model were models of a construction worker, a tower crane, a skid steer loader and several smaller construction objects to illustrate two restricted work areas.

Unity3D supports files with .fbx-, .dae-, .3DS-, .dxf- and .obj-extensions [17]. All selected models were converted into the file extension .fbx and made available for further use in Unity3D. They should have the same quality in order to keep the player´s experience, an realistic level. The acceptable number of polygons are preferred, because a higher number influences the computing performance negatively. Once the required models with the supported extension are fetched, they can be imported into the Unity3D-project. While recently announced plugins allow exporting/importing native building information models into Unity3D [17], this research used a self-developed approach [12] to import .IFC models directly. Via drag-and-drop the models can finally be placed into the Unity3D-scene. Within the scene the position, the rotation, and the scale-properties of the models can be adjusted using the inspector-window.

3.3.1 Construction scene

For this research, an existing building project incl. the 3D models (e.g., model of neighboring buildings, detailed site layout plan, pit model and structural model, incl. reinforced concrete walls, columns, and slabs) and the construction schedule served as the main source of information. Fig. 3 shows the resulting scene model.

Figure 3. Construction scene (isometric view)

3.3.2 Construction worker

A 3D-model of a construction worker (Fig. 4) allowed to visualize the movement of the player. The following pseudocode explains the movement in the scene.

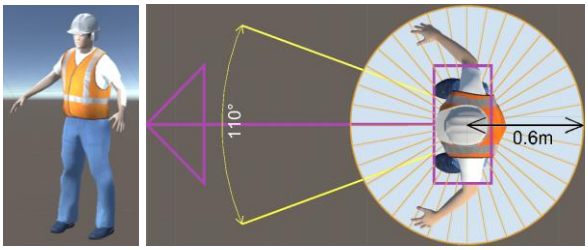


Figure 4. 3D model view of the construction worker with PPE (left); the bounding cylinder field-of-view of head-mounted display (right)

The Start-function initializes the right HTC Vive Pro controller, when the simulation starts. The Update-function checks in every frame whether the worker has pressed the right controller's touchpad. The task of this pseudo C#-script is to move the 3D-model of the worker dependent on the input of the right controller's touchpad.

Pseudocode 1: Movement of the construction worker

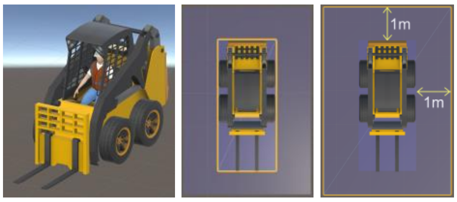
```
Start(){
  rightController.initialize();
}
Update(){
  if(rightController.touchpadTouched)){
    WorkerPosition += touchpadInput * movementScale;
  }
}
```

The developed approach displays two additional items (Fig. 4): (a) an arrow that visualizes the direction of the worker's field-of-view (FOV) in real-time and (b) a circular layer, defined as the safety envelope [6,18]. A player's FOV covers 114° [19] (compared to 110° of the Vive tracking system). The arrow's purpose is to give trainers or by-standers administering or observing a training session an immediate understanding which direction the player is looking at. Data collected to the FOV can further be analyzed, as explained later.

The construction worker's safety envelope has a radius of 0.6 m and represents a typical adult person's shoulder width [5]. This segmentation assists in the counting of the number and the direction of close call or contact collisions. Segments with higher counts thus explain how often and from where the worker collided with hazards.

3.3.3 Equipment

A model of a skid steer loader with operator [17] (Fig. 5) travels (for now) on a pre-scripted path within the scene. The purpose is to cause, and later help analyze model interactions from construction workers and equipment. To add further complexity to the scene, a tower crane with a moving load (Fig. 6) was added to the scene.



(a) (b) (c)

Figure 5. (a) 3D model of skid steer loader and operator, (b) bounding box encompassing all physical elements, and (c) 1 m-safety envelope

Figs. 5b-c further shows two different layers which are important for the close call and contact collision data recording and analysis. The first layer bounds all of the physical parts of the skid steer loader to a box. The second layer represents, according to the ISO 5006 standard, a 1 m-safety envelope to each side of this bounding box [20]. No worker is allowed to enter either area, otherwise a contact collision or a close call, respectively, is called. The crane load is also given a 1.5 m safety envelope.

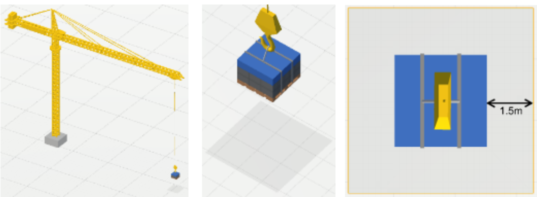


Figure 6. Model of tower crane and load

3.3.4 Harmful substance, restricted work zone, and other object models

Among the many potential construction hazards are the handling of harmful substances and the prohibited entrance in restricted work zones. A gas bottle and an electric power generator (Fig. 7) were placed in the scene as representative examples. The safety envelope of the gas bottle was set to a 1 m radius. 3 security fences around the generator and a nearby wall formed a restricted work zone of 2.5 m×3 m. Despite shortcut options, no player was allowed to enter either one. The scene also consisted of a recycling container, which each player had to fill with recycling bags.

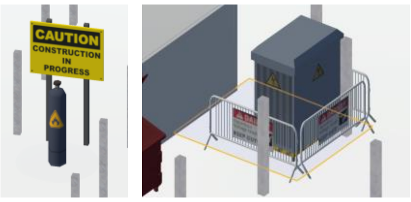


Figure 7. Models of harmful substance (left) and restricted workzone with security barriers and a shortcut option (right)

3.4 Player's mission

Each player was in the role of the construction worker. Equipped with the HMD and controller's touchpad a player traversed through the scene. Their mission was to pick, walk, and finally place 5 recycling bags, one after the other, in a nearby container. Figure 8 shows the construction scene. The gas bottle and the generator with its associated fences were placed in such way that all players had the opportunity of entering their respective safety envelopes. For example, a player may squeeze by the security fences (an obviously shorter, but more dangerous path). While completing their mission, the players further had chances to interact with the skid steer load and crane load.

3.5 Data gathering in VR

3.5.1 Close calls and contact collisions

The second pseudocode shows how to detect a close call or a contact collision between the construction worker's and the crane load's safety envelopes:

Pseudocode 2: Collision detection

```
OnCollisionEnter(){
  If(collision.name == “CraneLoadLayer”){
    CollectDataOfCollision();
    CreateCyanSphereOnGround();
  }
}
```

The OnCollisionEnter-function (provided in Unity3D) detects collisions between two objects: A pseudo C#-script attached to the construction worker's safety envelope layer checks whether it collides with, for example, the crane load's safety envelope layer. If it does, it collects timestamped data of the actual positions and speeds of the construction worker and the crane load. Simultaneously, the CreateCyanSphereOnGround-function sets a cyan colored sphere (a visual marker) at the position of the close call position in the virtual scene.

While placing a visual marker provides real-time feedback for the user (and might be helpful in sensitizing his/her behavior), it might influence the data recording in the remainder time of playing the serious game. For this reason, the option of visualizing the markers right away can be set inactive.

The developed serious game designed 6 different collision types (colors). Fig. 8 shows the visual markers obtained from participant 1 in the construction scene. As explained later in detail, it includes the trajectories of the skid steer load and the crane (both scripted, in blue and red colors, respectively) and the construction worker (participant's actual path, in green color).

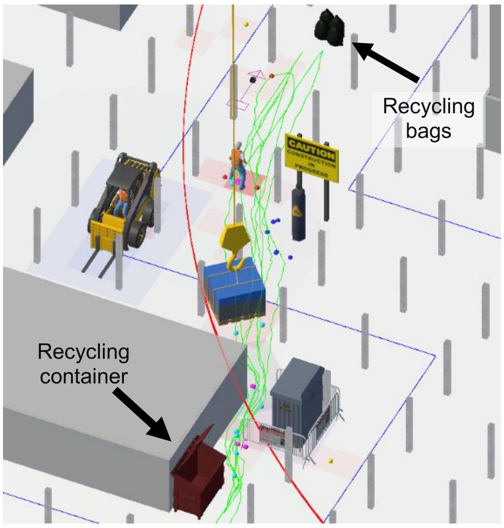


Figure 8. Various types of automatically detected close calls and contact collisions (incl. markers)

A collision point becomes red if the construction worker's safety environment layer collides with the skid steer loader's 1 m safety envelope layer (Fig. 5c). Black cubes are set to the scene's ground if the construction worker's safety envelope collides with the skid steer loader's bound box (0 m) (Fig. 5b). Every type of close call or contact collisions receives its own color (Table 1). This differentiation makes the post analysis between trainer and trainee more effective. For example, a black marker means the player made physical contact with the skid steer loader. While this may result in the real world in life-threating damage, a trainer may give a trainee special responses if such colors appear.

Table 1. Color scheme of close calls & contact collisions

Collision type	**Color (Size of safety envelope)**	**Marker color**
Construction worker (0.6m)	Skid steer loader (1m)	**Red**
Construction worker (0.6m)	Skid steer loader (0m)	**Black**
Construction worker (0.6m)	Crane load (1.5m)	**Cyan**
Skid steer loader (1m)	Crane load (1.5m)	**Yellow**
Construction worker (0.6m)	Gas bottle (1m)	**Blue**
Construction worker (0.6m)	Electric generator, Restricted work zone (0m)	**Magenta**

3.5.2 Trajectories

During the entire play time, the trajectories to each moving object are recorded. The blue and green lines, for example, show the trajectories of the skid steer loader and the construction worker, respectively. These can be visualized in real-time while playing or for later analysis (Fig. 8), for example, to reason about collision angle and speeds. The following pseudocode shows how the trajectories of objects are visualized:

Pseudocode 3: Trajectory visualization

```
Update () {
  DrawLine(oldPosition, currentPosition, green, 999);
  oldPosition = currentPosition;
  currentPosition = new Vector3(currentXPosition,
    currentYPosition, currentZPosition);
}
```

The pseudo C#-script is attached to the 3D-model of the construction worker. Its task is drawing the trajectory of the worker first using the internal Untiy3D-library (which offers the DrawLine-function). The function has the input values: 3D-vectors (oldPosition, currentPosition), a color (green), and a number (999). The latter defines how many seconds the line should be visible. The first 3D-vector defines the start position of the line (oldPosition: the position of the last frame) and the second 3D-vector defines the end position of the line (currentPosition: current frame). Finally a green line between both positions is drawn. The 3D-vector oldPosition is updated in every frame. Analogue thereto a similar pseudo C#-script is attached to the skid steer loader and the crane load (blue and red lines, respectively).

3.5.3 Heat map, statistics and video recording

In order to visualize the location and frequency of close calls, a C#-script generates a heat map after [6,18]. The heat map is divided into equally sized squares (1 m×1 m). Each square changes its saturation from a bright to a dark (red) color as the number of close calls in the square increases. Darker colors probably refer to a location on the virtual construction site that deserves further attention and/or corrective action by responsible safety personnel. Fig.9 shows in an example the different saturation levels. A built-in bird-view camera provides at the end of each serious game a screenshot of the resulting heat map. It can be used for feedback with the player.

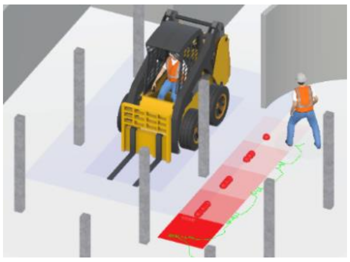


Figure 9. Close-up view of heat map: Increasing saturation visualizes higher number of close calls

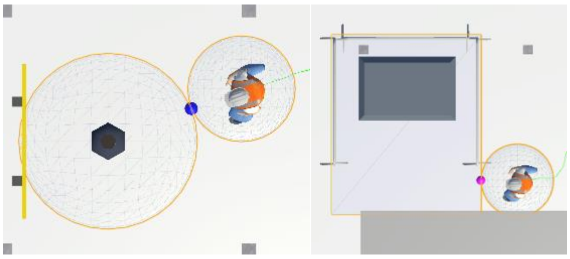
Further functions were scripted to offer detailed insights on the whereabouts and frequency of the recorded close calls. Examples like investigation of angles and speeds were mentioned already. Every gaming session was recorded using virtually placed cameras. Such video material was used occasionally for playback, giving the participant opportunity to explain behavior or simply modify the construction site layout. Although these options exist, they were not explored in this research at this time.

4 Tests and results

The results of testing 3 participants are presented. Every participant was able to choose their own path through the construction scene to complete the task. They were first instructed on the functionality of the VR equipment and told in advance that time to complete the task is of importance. Signs to restricted work areas in the scene and the possibility of oncoming traffic (a skid steer loader and a crane load) were not explained ahead of time.

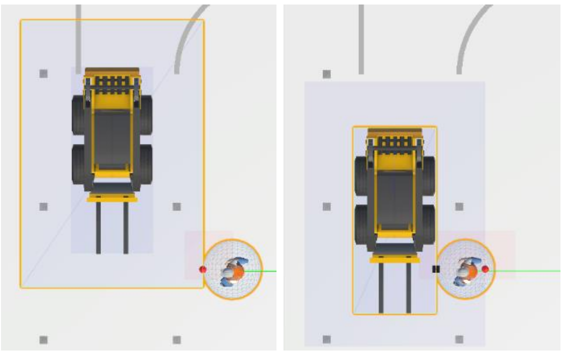
4.1 Close call and contact collision events

Within the developed serious game close calls and contact collisions occurred with static hazards: a participant (without the proper safety experience nor in possession of an adequate training certificate) was getting too close to a gas bottle (blue marker, Fig. 10a) or was entering a restricted work zone (magenta marker, Fig. 10b). The second observation shows a too close human-machine interaction. Red (Fig. 11a) and black markers (Fig. 11b) were left at the close call positions accordingly. Fig. 13 illustrates the third example of a recorded close call between the construction worker and the crane load.



(a) (b)

Figure 10. Construction worker: (a) proximity to gas bottle and (b) entrance in restricted zone



(a) Close call: t_1=120s (b) Collision: t_2=121s

Figure 11. Worker-skid steer loader close call and contact collision at two consecutive timestamps

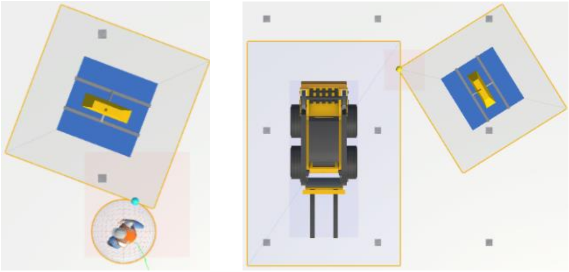


Figure 12. Close calls with crane load: construction worker (left) and skid-steer (right)

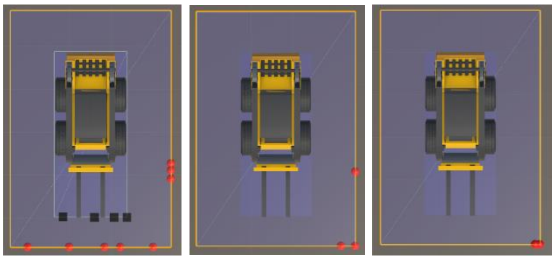
The required time for completion of the same work task by all 3 participants were 193, 298, and 177 seconds. While one might think that the number of close calls might increase with the speed a participant executing the mission, the third participant was the fastest and safest.

Table 2 summarizes the results of the independent tests. Participant 1 had by far the most close calls and was the only one who made contact collisions with the skid steer loader (4). The second participant had less, while the third had the fewest. In brief, the first test participant had 48 close calls within the 3 minutes and 13 seconds needed to complete the mission. In brief, while all participants deserve (additional or first time) safety training, the first participant should attend basic safety education (had 4 contact collisions, entered restricted work areas).

Table 2. Number of close calls

Type	Hazard	Participant			Sum / Avg
		1	2	3	
Crane	Overhead load	20	10	2	32 / 10.6
Skid steer loader	Close call (1m)	8	3	2	13 / 3.3
	Collision (0m)	4	0	0	4 / 1.3
Gas bottle	Proximity (1m)	10	0	0	10 / 3.3
Restricted work zone	Entrance	10	0	0	10 / 3.3

As explained in the introduction section, visuals are important to communicate the cause of close calls or contact collisions. Fig. 13 illustrates the precise location of each of the participants' self-made experiences. It appears that all participants in this study had such events in the front-left of the skid steer loader's driving direction. While this is quite the opposite to the equipment shown in Fig. 1, this in fact due to the scripted path of the skid steer loader (traveling only forward). Had a multi-user environment with a second or third player operating the equipment existed, the result may have looked differently.



(a) Participant 1 (b) Participant 2 (c) Participant 3

Figure 13. Close call & contact collision locations

Data in Fig.14 shows the performance of the first participant over the game time. The large number of crane load swings becomes visible. Future training may point out this important safety issue still very common to many workers on construction sites (and even in this virtual game).

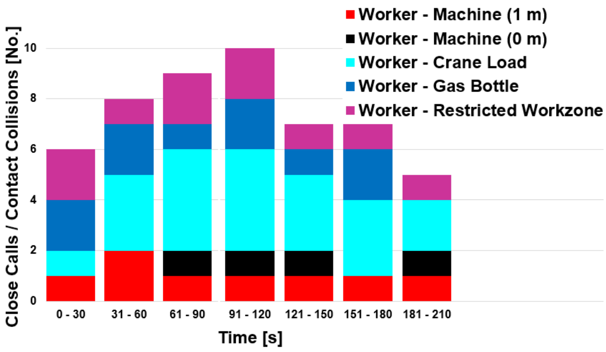


Figure 14. Close call & contact collision numbers

4.2 Heat maps

Heat maps were drawn. Fig. 15 displays the heat map of the first participant. Position and frequency of close calls and contact collision events become visible. While the other participants' heat maps were different, a site safety layout plan always could now be adjusted based on the observed 'hot spots' (arrows pointing to darker red cells). It seems in this situation that the construction worker's path collided with the skid steer loader, crane load, gas bottles and restricted work area. Skid steer loader and crane load had several close call situations as well. While some hot spots were expected (worker passing scripted equipment path), this may still result in decisions towards modifying the internal traffic control plan, for example, the installation of a guided crosswalk.

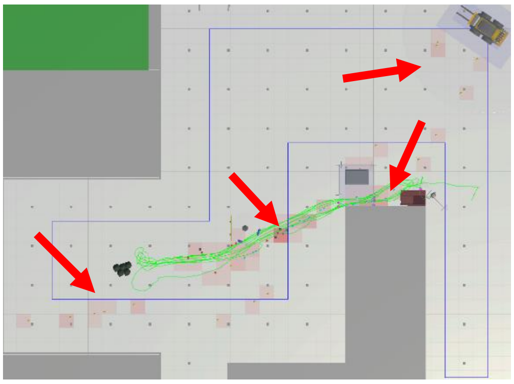


Figure 15: Heat map to test data of participant 1

5 Discussion and conclusion

Serious games in VR have been around since the late 20th century. They are applied games designed for specific purposes other than pure entertainment, however, so far hardly collect nor analyze data that is readily available in the game engine. This study developed and tested a serious game in VR that allows a player in a role (construction worker) to immersive into a construction scene (facing hazards). It became possible to record and analyze previously unknown data to close calls and contact collision to human-hazard interactions. Several benefits and limitations were found throughout the study that will help improve further research and development. In particular the difficulty of building realistic and meaningful (multiplayer) VR scenes, the size of the test group, human-behavioral issues, and impact on existing construction workface planning and safety processes (i.e. digital tools of any kind for pre-investigative construction risk analysis and prevention) play important future roles to make any kind of VR education and training an effective tool in construction.

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