



A Full-immersive CAVE-based VR Simulation System of Forklift Truck Operations for Safety Training

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ABSTRACT

This paper proposes a CAVE-based virtual reality simulation system for safety enhancement of forklift truck operations in warehouses to improve warehousing management. The system provides a virtual environment in which drivers can fully immerse to practise forklift truck manoeuvres and pallet operations. Truck drivers can easily review and rectify their driving techniques, and more importantly, “virtual accidents” can be created and visualised to enhance safety awareness without any real dangers. As a result, they would become more vigilant and skilful in handling adverse conditions; warehouses would become safer, more efficient and cost-effective to manage. The paper first discusses the design and implementation of the simulation algorithms in the CAVE system; it then describes the integration with an intuitive human-machine interface (HMI) based on the infra-red motion tracking system to enhance driving operations and user experiences. Examples of accident-like scenarios will also be demonstrated.

Keywords: virtual reality, forklift truck, VR training, simulator, CAVE.

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1 INTRODUCTION

Forklift trucks play a pivotal role in warehouse management for lifting, transporting and handling goods or materials. Its high flexibility facilitates material handling operations in a timely and cost-effective way, thus enhancing the efficiency and productivity of a company. However, a forklift truck with overwhelming power can turn into a dangerous weapon, causing serious damages, injuries or even fatalities [1]. Very often, forklift truck accidents not only cause severe interruptions to the operation of warehouses, but also diminish the performance and profitability of companies, which may be subject to huge fines and legal liabilities [2,3]. Therefore, forklift truck safety is of paramount importance to smooth operation and profitability of companies, particularly in the logistics industries. To address the above issue, training can be one of the solutions. According to Occupational Safety & Health Administration [4] in America, about 70% of these accidents could be actually avoided with proper safety training.

However, while traditional training courses are useful for enhancing the skills of forklift truck drivers, they are not particularly effective in reducing accidents. Indeed, the main cause of forklift accidents is related more to drivers' poor safety awareness and driving mentality than to their lack of skills. Drivers

tended to overlook hidden hazards until they turn into fatal accidents. For this reason, an effective way to improve safety awareness and driving mentality of forklift truck drivers is to create various sorts of accident scenarios for them to encounter during the training process.

Indeed, the needs and values of simulation of forklift truck operations have been reaffirmed by the National Safety Council (NSC) of United States. A forklift truck simulation package [5] has been jointly developed by Etcetera Edutainment and the NSC to provide users hands-on experience of operation a forklift truck in a virtual warehouse filled with people, vehicles and safety hazards that they may encounter. However, the simulation is based on desktop display with only a front view. This could hamper the simulation result because side views are also useful and needed for making turns in a narrow aisle. In Bergamasco's work [6], a forklift truck simulator has been built inside a virtual cockpit for training. A front view and a back view are located in the simulation. However, the project mainly focuses on fulfilling mission in each module rather than studying the reaction and feedback received from forklift truck drivers during simulation.

For better visualization, the simulation should be run in a full-immersive environment, characterised by a room-like CAVE (Cave Automatic Virtual Environment) environment consisting of multiple screens [7] which can block off much disturbances. By fully immersing forklift truck drivers into hazardous and even fatal scenarios in VR, they can go through the "accidents" in detail - how they ever happened and what damages and casualties were inflicted. Forklift truck drivers will be able to see for themselves the dire impacts of all sorts of possible accident scenarios. Subsequently, they will become more vigilant to the latent dangers in their working environments. Moreover, if guidance is provided along with simulation, forklift truck drivers will learn the operation skills to improve their ability in handling adverse or extreme conditions. Thus, many forklift accidents can be prevented.

We therefore propose a full-immersive CAVE-based virtual reality system for safety enhancement of forklift truck operations in warehouses. The system provides stereoscopic simulation of forklift operations in a virtual warehouse for a driver to practise all sorts of manoeuvring and pallet loading and picking operations. By building accident scenarios, drivers can learn to respond to hazardous situations like tipping over and skidding of forklifts, etc. Hence, the safety awareness and mentality of forklift truck drivers will be enhanced.

A main feature of this system is the integration of VR tracking tools to replace traditional input devices, such as keyboards and mice, which are inconvenient for human-machine interactions in the CAVE environment. An intuitive human-machine interface (HMI) based on the infra-red motion tracking system was introduced to facilitate driving control. It provides operation menus for a driver to interact with the system with simple hand gestures like "GRAB" and "DROP" motions. In addition, a head tracking device was incorporated to enhance VR immersion and user experience of forklift truck operations.

This paper presents the design and implementation of the proposed system and the integration of HMI. Section 2 describes the system design of the imseCAVE. Section 3 gives a general picture of the architecture and modelling of forklift truck simulation. Section 4 demonstrates the integration of VR tracking tools. Finally, section 5 discusses the result, limitations and areas for future development.

2 THE DESIGN OF IMSECAVE

The imseCAVE at the University of Hong Kong is a typical example of the CAVE system. It is a fully immersive and interactive visualization system for users to participate in a cube-like structure with walls for VR simulation. It provides a low cost platform for design, analysis and evaluating the complex engineering systems or operations. Fig. 1 shows the schematic layout and the specification of the control computers of the imseCAVE. It consists of eight computers (PCs) with medium-to-high configuration in both graphical and processing units linked together. One of them is the Master while all others are Slaves. Eight corresponding projectors are installed in pairs to project respective views on four screens: front, left, right and floor, separating the L/R views of human eyeballs. Due to inter-pupillary distance, each eye captures a slightly different perspective image. Virtools™ is the graphics

kernel used for generation of these images. To see a stereoscopic 3D image with both eyes, we should first place a linear polarizing filter in front of each projector in order to omit either the vertical or the horizontal light rays. After that, we can spot the image with depth by using a pair of 3D polarized glasses that merely allows one of the linear lights to pass through, resulting in a virtual 3D image effect.

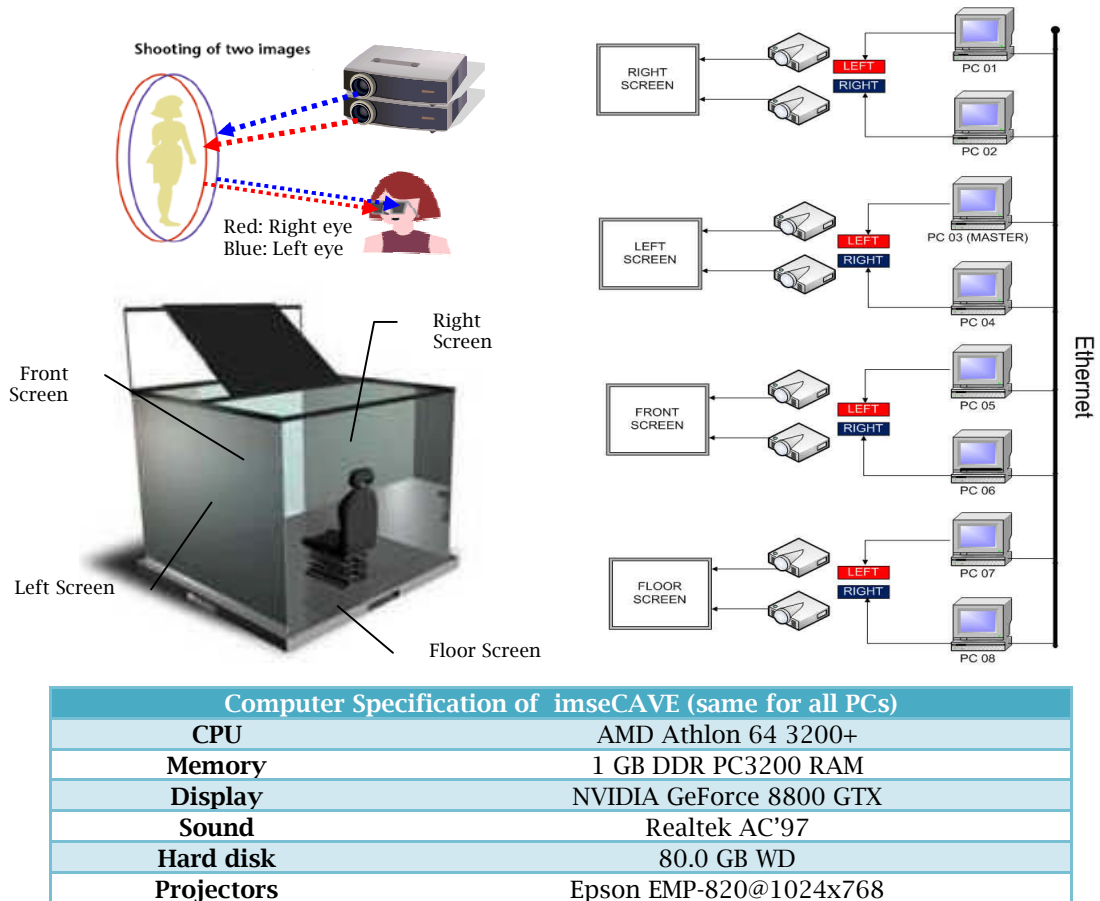


Fig. 1: Schematic layout of the imseCAVE and specification of control computers.

3 THE ARCHITECTURE AND MODELING OF THE FORKLIFT TRUCK SIMULATION

The project can be broken down into four phases:

- Model Building;
- Setting up behaviours of the simulators in Virtools™ [8];
- Adding VR tracking tools like head/hand tracker;
- Building Case Scenarios for testing.

3.1 Model Building

All CAD models used in the project are drawn in scale using SolidWorks and 3dStudioMax. The forklift truck model, as shown in Fig. 2, is built according to the specification of Toyota Forklift 8-series 8FG(C)U [9]. The higher the number of objects or total polygons to be simulated, the longer the time is required for processing and synchronisation between each PC cluster.

Therefore, to ensure smooth simulation, texture mapping from 3dStudioMax was used to hold the total number of polygons at a minimum possible. In a similar way, all the interacting models like warehouse and pallets were drawn in scale respectively before they were imported into Virtools™ for processing and interactions.

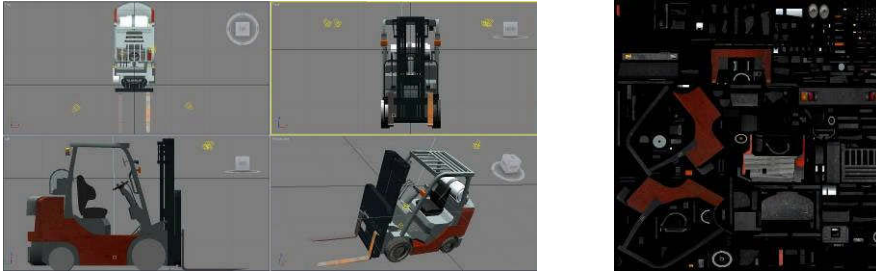


Fig. 2: The forklift truck model.

3.2 Using Virtools™

Fig. 3 shows an interface of Virtools™, which is an extensive real-time platform for creating highly interactive 3D experience through personal computers, game consoles and the Internet. Basically, it is a development system which considers 3D objects as individual components, associating with independent data.

In addition, Virtools™ works as a behavioral engine (CK2) by processing various behaviors assigned onto objects or entities. A behavior is actually a description of the ways certain elements act inside the given environment. In Virtools™, there are collections of ready-to-use behaviors in the form of Behavior Building Blocks (BBs) for users to create contents through the schematic interface. Using the built-in BBs in different combinations, developer can create motion behaviours without having to learn a new programming language.

One of the preset BBs “Physics Car” has been modified and used for mimicking the behaviors of a forklift truck. By modifying the parameters in the four data arrays which include “BODY”, “WHEEL”, “ENGINE” AND “SKIDDING OUTPUT”, various types of car behaviors can be mimicked. Through trials, a simulator of a forklift truck that uses rear wheels for steering was built. Apart from the truck movement, the forks and mast of the forklift were set together with physics hinges and made movable in vertical directions in order to manoeuvre the pallet loading/unloading process. Weights and fictions of the tires, pallets and grounds were set accordingly using the physics library of Virtools™.

After the required physics and dynamic behaviour of the simulator were tested and coordinated, VR distributed script was then called in the MASTER to synchronize the same composition in all seven SLAVES to driver multi-screen displays through projectors correspondingly using either effect distribution, or cause distribution, or both. The MASTER is solely responsible for processing the signals received from the input devices, driving wheel, and distributes the results to all SLAVES in parallel. It uses effect distribution to distribute almost all of the data, which need to be updated in real-time.



Fig. 3: Virtools interface.

For example, if the acceleration pedal is pressed, the forward motion of “Physics Car” will be triggered. As soon as the MASTER completes calculations, the resulting position, which is a world matrix, of the forklift truck will be collected and distributed instantaneously. After synchronizing the results received by all SLAVES, the forklift trucks will eventually be moving to the location calculated by the MASTER. Using the same mechanism, all the other moving objects in the simulation were distributed accordingly. However, this kind of distribution relies heavily on the computation speed and the performance of the MASTER. The more movable objects to be distributed, the more demanding will be on the processing power of the MASTER. Therefore, in the simulation, only those objects like pallets and cartoons interacting with the forklift truck are distributed.

3.3 MOMO Force Feedback Racing Wheel

Initially, the forklift truck in the system was solely controlled by keyboard and Num pad. However, such input devices have limitations in imitating the motion control in VR environment, making it hard to experience how a forklift truck actually operates in reality. Instead of constructing a bulky built-in driving panel inside the multi-purpose imseCAVE, a mobile racing wheel was used. Though it is primarily designed for PC gaming, its functions are sufficient to meet the requirements of performing basic forklift truck operations. Therefore, it is more preferable for the simulation prototype.

MOMO Racing Force Feedback Wheel, as shown in Fig. 4, is a gaming device from Logitech. It provides users with a switchable gear shift lever and a large no-slip foot pedal base. Six programmable buttons are also installed within easy reach on the wheel. These buttons are essential for full control of the forklift truck simulator. This driving wheel was supported on a wheel stand with adjustable joints for use in the ImseCAVE. Owing to its good quality and durability with a compact size, this setup can be transplanted into any CAVE systems.



Fig. 4: MOMO Racing Force Feedback Wheel as driving panel for forklift truck simulation.

3.4 Tracking Tools

Virtools™ not only generates all 3D models or objects but also controls a set of four virtual cameras that mimic the human user’s view to generate stereo images for projection on the four screens (front, floor, left and right) of the imseCAVE, based on the cameras’ locations. We used Virtual-Reality Peripheral Network (VRPN) to transfer the stereo glasses’ motion data, like position and orientation, from Tracking Tools™, assigning them to a virtual object in Virtools™ on which all the virtual cameras attach. Therefore, whenever the user is moving around in the imseCAVE, his movements are captured and transferred into Virtools™, which make changes to the 3D images accordingly.

3.4.1 Passive Markers and Glasses Gadget

In the project we used passive IR markers (plastics balls with IR reflective material on the surface) for the motion tracking of the user’s head. In the imseCAVE, the user needs to wear a pair of stereo glasses to view the 3D image on the projection screen. Three passive IR markers are placed on the stereo glasses, as shown in Fig. 5. By tracking the markers through a set of IR cameras, we can then track the user’s head motion, and thus, more specifically, the motion of the user’s point of view.

We adapted the IR motion tracking solution OptiTrack™ [10] from Natural Point for head tracking with a set of six IR cameras. The IR cameras emit IR rays that light up the passive IR markers as vivid trackers, which are captured and reconstructed in the software solution of OptiTrack: Tracking Tools™. In Tracking Tools™, we selected and connected the three trackers to form a triangle, as in Fig. 5, to represent the dynamic position and orientation of the stereo glasses.

3.4.2 Head Tracking

Operating a forklift truck is different from driving a normal vehicle. It often requires the driver to tilt his or her head for a better view in order to accomplish a task smoothly. However, it seems that the driving view of most driving simulators reported in available literatures is fixed. The driver cannot view the front operations from other angles, affecting the decision making process. Indeed, if the pallets to be handled cannot be viewed clearly from the side, the driver would not be able to locate the position of the pallets precisely, increasing the chances of accidents.

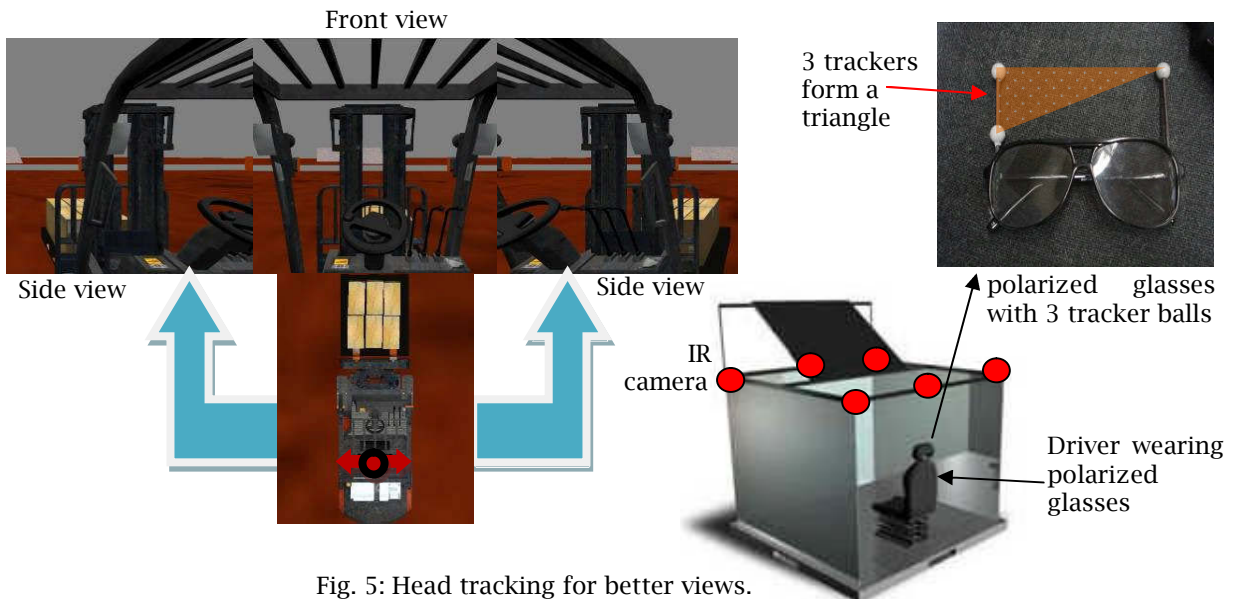


Fig. 5: Head tracking for better views.

To alleviate this problem, we implemented head tracking to improve the view of the driver, who wears a pair of polarized glasses with three markers are stuck on, as shown in Fig. 5. The markers on the polarized glasses form a triangular rigid body. When this rigid body is recognized by the infrared cameras, the position and orientation of the driver's head would be synchronized and transmitted to the Master. Eventually, each camera view of the forklift truck simulator will be aligned with the movement of the user's head.

3.4.3 Hand Tracking

As mentioned previously, it is not convenient to use typical input devices like keyboards and mice in CAVE. Hence, a hand tracker is adopted for control input. While the position tracking mechanism of the hand tracker is similar to that of the head tracker, its command processing is based on an intuitive human-computer interface (HCI) for selecting commands from a menu, as shown in Fig. 6. The driver, wearing a glove with tracker balls attached, can simply rotate the menu by swinging his or her hand and choose the specific function with a simple hand gesture. Details of the mechanism will be discussed in 3.4.4.



Fig. 6: Hand track based on the HCI for menu command control.

3.4.4 3D Rotatable Option Menu

To make use of the HCI, a 3D rotatable option menu was built. When the menu is activated, three options with the same colour will be highlighted in front of user each time, illustrated in Fig. 7. With respect to the user's eye level, which can be obtained through head tracking, the top and bottom lines' coordinates of the three menu buttons, the space between the user and the menu can be divided into two regions: Focus Region of "Area #1", "Area #2", "Area #3", and Non-focus Region of area either above or below the Focus Region. Fig. 8 summarises possible manipulation of the menu, namely navigation, selection and operation.

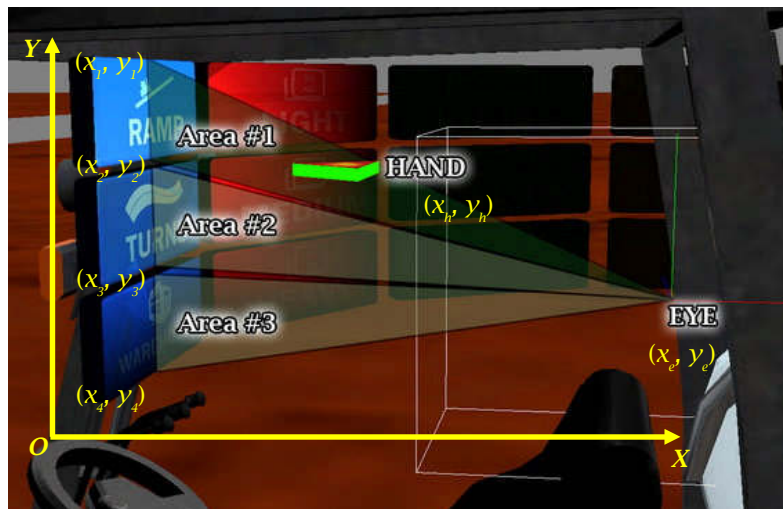


Fig. 7: The "Focus Area" Concept.

Menu Navigation:

By implementing the "Focus Region" concept, we managed to develop a 3D rotatable option menu interaction that mimics the focusing behaviour of human's eye by detecting the hand position. When the user's hand is in a certain "Area", a spot light behind the user's head will light up the active menu button while the rest are dimmed away.

Menu Selection:

Whenever the user makes a decision with a simple hand gesture of "GRAB", the system will recognize it through the changing pattern of the rigid body formed by the hand trackers. The selected button will then pop up and be surrounded by a yellow bounding box to indicate the selection. In reverse, making a "DROP" motion will cancel the selection and return back to menu navigation.

Menu Operation:

After a button is selected in the menu selection, the user can call the function by lowering his or her hand to the pre-defined Activation Zone. If the user withdraws the decision, he or she can call off the function by making a “DROP” motion any time before his or her hand reaches the Activation Zone. The menu developed so far allows the driver to swap driving scenarios, vary the weight of loads, change the camera views and reload the forklift truck in case of accidents.

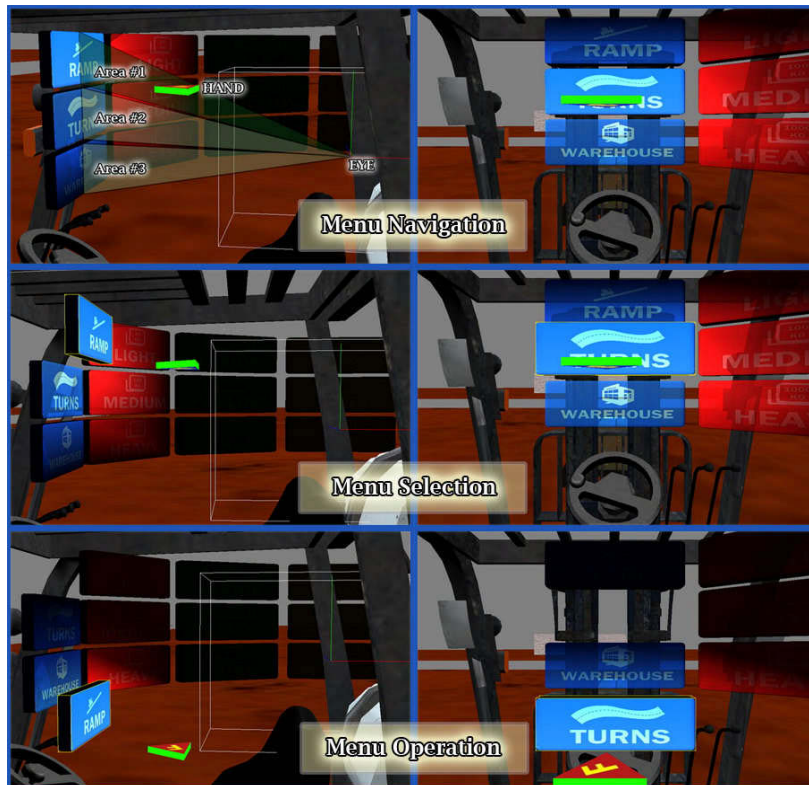


Fig. 8: Menu manipulations.

4 CASE SCENARIOS

A few scenarios of common accidents are incorporated for drivers to experience hazardous situations so that their safety awareness and driving mentality will be enhanced. According to the reports from National Institute for Occupational Safety and Health of US, forklift overturns were the leading causes of fatalities in forklifts accidents, representing about 25% of all forklift-related deaths [11].

To prevent a forklift truck from overturning, its centre of gravity (COG) should always lie within the stability triangle which was the safety zone [12-14], as shown in Fig. 9. However, when a loaded truck is driven too fast or makes a sharp turn, its COG may shift beyond the stability triangle (safety zone), resulting in tip-over or overturn of the truck. Therefore, one of the key objectives of the simulator is to imitate certain scenarios where the truck's COG becomes unstable. During simulation, drivers would continuously receive instantaneous dynamic feedbacks from the forklift truck. As a result, they would not only find their safety awareness boosted, but also become more familiar and skilful in handling adverse conditions in reality. In the following section, three most common accident-like scenarios are presented.

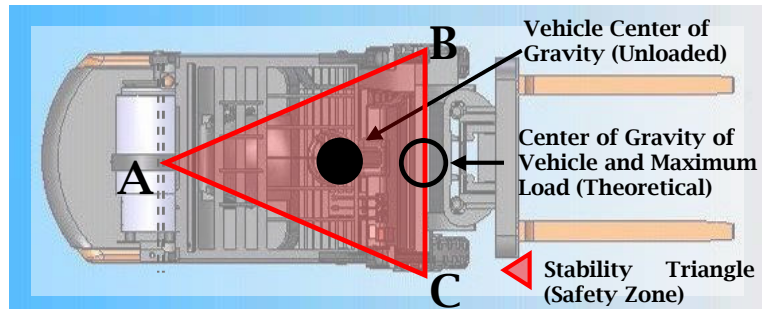


Fig. 9: Centre of gravity and stability triangle of forklift truck.

4.1 Scenario 1 – Slopes



Fig. 10: A slope at the back of a warehouse.

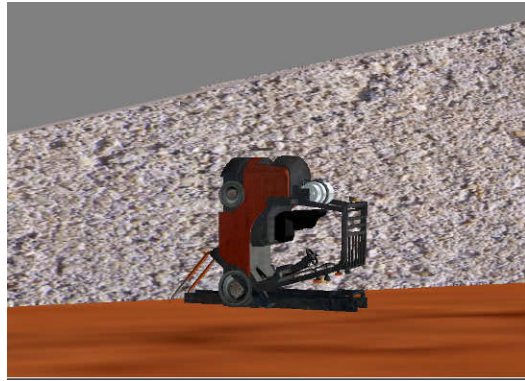


Fig.11: Simulated accident – a forklift truck fell off a slope.

Slopes are commonly found in warehouses or other logistics facilities, as shown in Fig. 10. Though driving up a slope may seem easy, tip-over can happen if a driver is not skilful enough. For example, the driver should never turn on a slope, keep a safe distance from the edge, and travel on slope in accordance with the manufacturer's recommendations. Moreover, the driver should drive in reverse when travelling down slope with a load [15]. A virtual slope has been built and tested in the simulator. When the virtual forklift truck accelerates, it climbs up the slope slowly; and falls back when the pedal is not triggered. In Fig. 11, a forklift truck had fallen from the side of a slope.

4.2 Scenario 2 – Sharp Turns



Fig. 12: An overturn forklift truck.

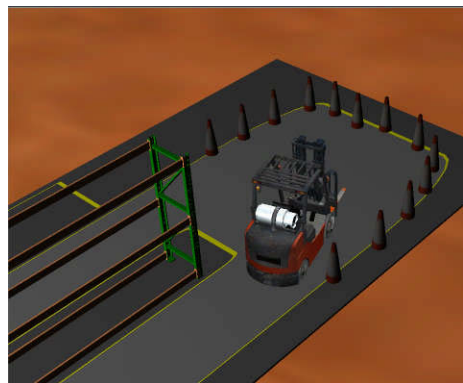


Fig. 13: A sharp turn for simulation.

When making turns, the COG of a forklift truck shifts outwards due to centripetal force. If this is smaller than the friction of the tires against the floor, the forklift remains stable. However, as the velocity of truck increases, the centripetal force increases correspondingly until the friction force is no longer large enough to hold it and the forklift truck starts to skid, side tip, and even overturn as shown in Fig. 12. For this simulation scenario, the forklift truck is put into an oval track with traffic cones lining along a side, as in Fig. 13. The forklift truck is then operated at different speeds in making turns. In simulations, the forklift truck remains in lane when making turns at slow speeds, but at some higher speeds the forklift truck begins to lose control and crashes into the traffic cones.

4.3 Scenario 3 - Overloads

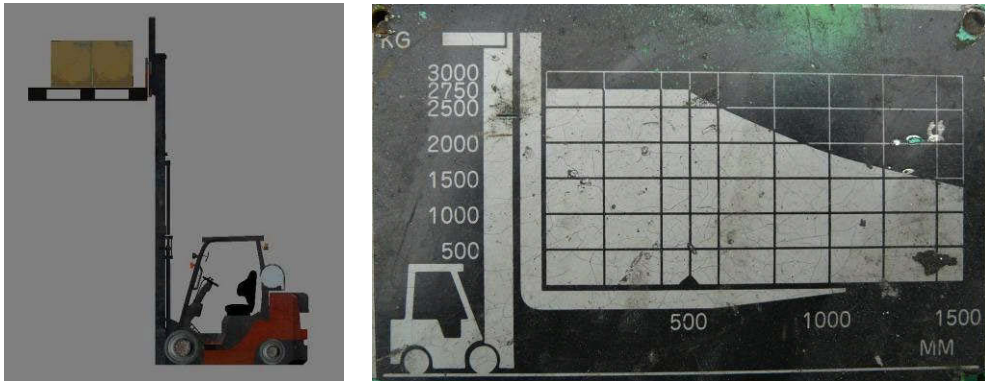


Fig. 14: A typical capacity chart of a forklift truck.

A forklift truck has a maximum load limit [15, 16]. In most cases, the load limit is shown on the data plate of the truck body, as shown in Fig. 14. Overloading may bend the forks or even result in accidents. Also, truck drivers should be aware that the load limit decreases as the load centre is raised. Therefore, they should make sure the loads are kept low and closed to the front wheels when moving [15]. Three types of weights, light, medium and heavy were prepared to choose in the menu. During simulation, a driver can change the weight of the loads among the three anytime during simulation. As the load is lifted high up for loading, the mast may sway back and forth about its original position. Oversized, irregularly shaped loads will be included afterwards to test the effect of different load centre distance to the stability of forklift truck.

5 CONCLUSIONS

A prototype system for simulation of forklift truck operations with an intuitive human-machine interface has been built in a CAVE to provide a full-immersive virtual reality environment to train drivers and to involve them in “virtual” accidents. By visualizing the impact of such “accidents”, drivers would become more vigilant and sensitive to hidden dangers in their workplaces. Hence, they would gradually improve their safety mentality and become more skilful in handling adverse conditions. It is hoped that forklift truck accidents could be reduced as a result, thus benefiting the entire logistics industry and supply chains.

Nevertheless, the system currently has two main limitations. Firstly, the imseCAVE has only four views (front, right, left, floor), and it cannot simulate the top view and the back view. This would diminish the sense of immersion as the driver cannot see the back view for reversing or the top view for manipulating pallets at a height. Secondly, simulation of complex mechanical and dynamic behaviours of a forklift truck with the built-in physics engine of Virtools™ seems quite difficult, and this remains an issue to be addressed.

6 FUTURE WORK

The prototype simulation system is a feasibility study of building a forklift truck simulator in CAVE. Currently, no industrial data of forklift truck engines or warehouses have been incorporated. For in-depth study on the dynamic behaviours in accidents scenarios, factual information like friction, weight, inertia, elasticity, damping, and suspension etc. should be gathered. In the long run, the simulation system can be further developed into a practical tool for training forklift truck operators; with standardized training rules or guidelines, the system can help users to get rid of bad driving habits that are likely to cause accidents. In addition, the system together with the behavior model can be ported into other similar VR simulations of other industrial vehicles, like truck cranes, stackers, bulldozers, and excavators. Another essential development is to explore possibilities of incorporating more powerful physics engines, such as Open Dynamics Engine (ODE) that scored the best performance in a recent test of several free and commercial physics engines [17], to supplement or replace that of Virtools™.

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