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Immersive Coaster Creation: Real-Time VR Table Design with CAVE-Based User Feedback

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***Abstract*—The design of roller coasters is a complex and iterative process, theme parks are consistently looking to find ways to improve the way they approach this phase of development. Traditional methods for development involve reliance on pre-visualization tools, simulations, and physical models to build out attraction layouts before they are constructed. However, these methods lack real-time feedback from riders, leading to an extended development cycle as modifications are done post-modeling. This paper proposes a novel approach for a virtual reality (VR) based roller coaster design system which integrates a VR Table for interactive development and a Cave Automatic Virtual Environment (CAVE) for riding the coaster and offering real-time feedback. The bi-directional data flow introduced improves the current process of design by allowing for dynamic adjustment, reducing production cost, and revision of roller coasters based on user feedback prior to physical development. This system streamlines the development pipeline of rides within the themed entertainment industry, highlighting the possibility for VR based solutions to attraction development.**

***Index Terms*—Virtual Reality, Cave Automatic Virtual Environment (CAVE), Modeling and Simulation, Roller Coaster Design, Themed Entertainment**

I. Introduction

Roller coaster design and development is a complex iterative process that involves an extensive amount of testing to optimize user experience, safety, time management, and resource allocation. Traditional methods of coaster development involve reliance on pre-visualization tools, allowing designers to iterate attraction layouts prior to construction, in coordination with simulation software and physical models to refine designs before construction [1]. However, due to the inherent lack of real-time informative feedback within the pipeline, direct rider experience is not influencing modifications while the design process is occurring; therefore, when feedback arrives after the modeling is done, it results in more time being added to the production timeline. To resolve these issues, among others, the themed entertainment industry is continuing to explore new mediums to enhance this framework for development [2]. This paper introduces a virtual reality (VR) based roller coaster design system which leverages a multi-display method for immersive development and real-time rider feedback.

Integrating VR into roller coaster design allows for creating an immersive environment to stimulate the creative processes of stakeholders, giving developers a heightened sense of immersion into the stories they are bringing to life. VR is an increasingly growing area of interest in the themed entertainment industry, where adopting cutting edge technology allows for improved design and evaluation [3]. By leveraging these technologies, the process for developing attractions within theme parks can be streamlined in a way that reduces cost and delivers more engaging guest experiences [2]. However, these approaches are rather underexplored in the literature, where focus involves showing how users experience virtual environments rather than a practical case for integration of VR into the design process [3]. By enabling roller coaster designers to experience their experiences from a guest's perspective, our system for development highlights a more innovative solution than the currently explored cases for implementing VR in the themed entertainment industry.

Our proposed system utilizes a Virtual Reality Table (VR Table) for an interactive environment creation, including development of a custom track and surrounding environment for the coaster's theme, and a Cave Automatic Virtual Environment (CAVE) system for immersive real-time rider feedback. This process introduces a bi-directional data flow, where designers can modify elements of their roller coasters while simultaneously observing real-time user reactions from ride testers experiencing the design within the CAVE. Our proposal is an enhancement to the current methodology by improving the iterative design process, improving user experience analysis, and streamlining the production pipeline for themed entertainment attractions. By demonstrating a real-time VR roller coaster development with CAVE-based feedback, this paper presents a novel approach to immersive ride design that enhances efficiency and user-centered engineering within the themed entertainment industry.

II. Related Work

A. Virtual Reality Solutions For Themed Entertainment

Implementing VR based experiences has played a pivotal role in the evolution of themed entertainment, where virtual environments allow for the immersion of guests into worlds which they have grown to love through their original interactions with them in a variety of different mediums such as books and movies. Mine [4] introduces the science behind DisneyQuest, a pioneering VR theme park in Orlando, Florida, where Disney's Virtual Reality Lab developed their own head-mounted display (HMD) based environments and multi-screen theaters to immerse guests into short experiences which demanded simple user-interfacing.

Eddy et al. [3] analyzes the role of augmented reality (AR) in enhancing theme park engagement to create immersive stories. Their research highlights key developments within the AR space, such as creating mobile applications to extend park experiences beyond rides. This includes Disney's applications for their Galaxy's Edge area of Disney's Hollywood Studios, where guests can interact with missions that trigger physical interactions in the park through their mobile applications by completing missions and other activities. Their research argues that AR-driven applications are redefining the way theme parks are designing their business models, focusing on an evolving environment for fantasy environments which immerse users, encouraging deeper engagement into the venues as opposed to attending for just visiting attractions.

B. CAVE Systems for Collaborative Workspaces

The CAVE creates an interactive space for interacting with a virtual environment in a shared setting. This setup allows for physical communication among a variety of users in the same virtual environment at the same time, facilitating collaboration. This synergetic nature makes CAVEs particularly advantageous in applications targeting product design, engineering analysis, and complex data visualization [5], [6]. Ishii et al. [7] explore the integration of CAVE systems for designing collaborative public experiences in the VR domain. Their study introduces a method for reducing isolation in VR experiences, which is an issue for public applications which aim to immerse many people into the experience at a time. Their research finds that CAVE-based solutions significantly enhance spectator engagement and social interaction among players and spectators within a virtual world, suggesting that CAVE environments are suitable solutions for transforming isolated VR experiences into interactive spaces for collaboration.

In further evaluation of CAVE performance in collaborative workspaces compared to traditional HMD-based development methods, Pogmore et al. explore the impact of CAVE environments for collaborative analysis tasks compared directly to an HMD-based solution [8]. Their findings suggest that collaboration efforts within CAVE environments are preferred to HMDs due to their low levels of cyber-sickness and increased spatial awareness. Although participants show a lower sense of presence within the CAVE system compared to HMDs, they highlight that decision-making and design evaluation are improved within CAVEs, suggesting a relevant trade-off for development focused applications.

Likewise, CAVEs have been evaluated on their effectiveness in learning environments to determine how well they enhance collaborative learning. Research conducted by de Back et al. [9] demonstrates the effectiveness of CAVE-based learning environments for improving the retention of learning as opposed to traditional textbook based learning. Their findings indicate that utilizing CAVE environments for collaborative studying resulted in students outperforming those who studied through standard learning, showcasing that the capability to produce engaging and interactive settings for educational situations in a CAVE resulted in increased collaboration and participation among students.

III. Proposed System

Our proposed VR-based roller coaster design system implements a Unity Engine based application integrated with real-time network communication to provide immediate rider feedback to designers in an immersive development environment. The implementation for network communication involves setting up a Photon Unity Network (PUN), this network architecture is described within Figure 1 The system is built with two key hardware components to enhance the iterative nature of the traditional roller coaster design and evaluation process in a collaborative space:

- **VR Table:** An interactive workspace for creating and modifying roller coaster layouts and their scenery.
- **CAVE:** An immersive real-time riding experience environment designed to collect user feedback on roller coaster designs immediately.

The following subsections define the two components in greater detail with their respective implementations, purposes, and functionality.

A. VR Table

A VR Table is an immersive VR system of four integrated 3D commercial televisions in which users wear 3D glasses and are equipped with head-tracking technology which allow for the system to adjust the visuals in real-time based on user position and orientation [10]. This allows an overhead view of a system, in the case of the proposed system it operates as a command center for roller coaster design. Unlike traditional VR headsets, this design allows for a large space for physical interaction and collaboration, all while immersing users into a virtual environment. Handheld controllers are used for input, allowing users to select and modify elements within the scene.

The VR Table provides a space for designers that operates as a command center, by tracking the position of the user in real time, they can get an overarching view of the coaster, allowing for an intuitive environment to create and refine the layouts and scenery of roller coasters. Unlike traditional VR headsets, which isolate the user and limit spatial awareness, the VR Table design allows for a shared workspace with a collaborative interface, using controllers to interact with the environment all in one setting. By choosing this method of display for integration of the software, designers can easily construct, adjust, scale, alter, and or delete track segments and themed assets with enhanced hands on control, allowing for rapid experimentation.

HMDs have become increasingly used in practice by a variety of industry-based communities for the virtual prototyping due to their ability to provide immersive perspectives

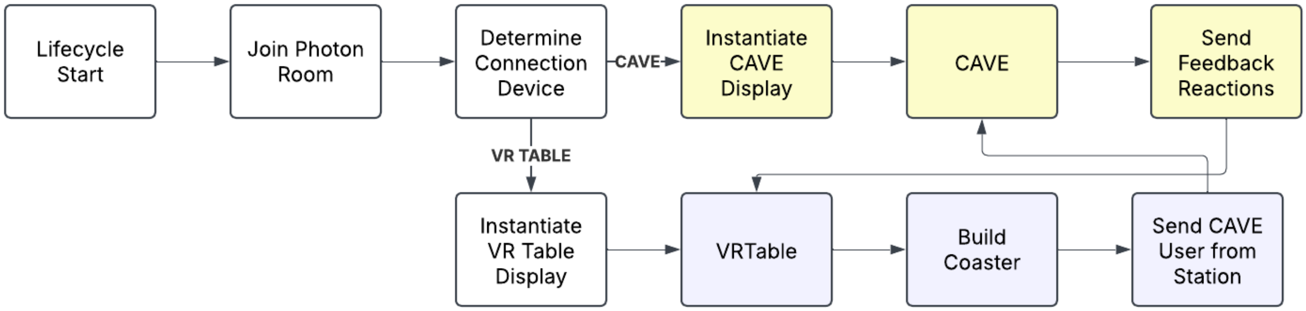

Fig. 1. System network pipeline

on simulated environments. Using the VR Table as a command center gives distinct advantages over traditional HMD approaches for collaborative spaces. The development of roller coasters involves many stakeholders working together to refine and adapt to complex themes and requirements. HMD-based systems isolate users by design, restricting real-time communication and shared spatial awareness among members of the development team [11]. The traditional methods for designing roller coasters in the themed entertainment industry rely on pre-visualization tools, simulations, and physical models, which result in extended timelines due to the sequential nature of design iterations and integration of feedback at each step [12]. The VR Table system, depicted in Figure 2, addresses this challenge by allowing for real-time visualization and change assessment, this accelerates the process by allowing different stakeholders to work within the same collaborative environment, enhancing precision in design adjustments resulting in more refined and immersive attractions.

B. Cave Automatic Virtual Environment (CAVE)

A CAVE is a VR system designed for immersing users within a 3D virtual environment projected onto walls in side-by-side 3D display mode, in the case of this system four walls (floor, left, right, and front-facing), to create an interactive space while maintaining physical presence in the real world [13]. Within the space, users wear 3D glasses with a head tracking mount for adjusting visuals in the virtual world in coordination with where users are located in the physical environment. This setup allows for having multi-user VR experiences with physical and collaborative interaction.

The CAVE is utilized to immerse the test riders in the designed environments from the VR Table, experiencing updates from the command center in real time. Within the CAVE system, as shown in Figure 3, users are given a controller to provide feedback in four different categories at any point during the rider experience: excitement, boredom, sickness, and frustration. These options for feedback display an icon on the VR Table as users offer them, allowing for immediate identification of issues in the design process. This feedback mechanism allows detailed information on improving the rider experience in a variety of factors, such as areas that require more immersion to engage riders or adjust the experience to be less intense when riders are reporting issues with illness. The real-time nature of this process allows stakeholders to make adjustments early in the process of development, speeding up the timeline for producing a final product.

Integrating a CAVE as the immersion method for the virtual environment offers advantages that HMD-based solutions struggle with. Compared to HMDs, which remove the sense of perception of the physical surroundings, CAVE systems mitigate symptoms of motion sickness, which is particularly relevant in a high-motion scenario like roller coaster riding. Likewise, the lightweight equipment setup for a CAVE creates a more realistic set-up for how riders would experience the ride in a real-world scenario, reducing physical strain and discomfort which can potentially alter the feedback a rider would provide.

IV. System Workflow

Practical implementations of this system begin with the creation of a roller coaster layout using a graphical user interface with the option to raise and lower the loading zone for the ride. The user interface provides a variety of tools for altering tracks, including banking, pitching, turning, shortening, and lengthening tracks. When an interaction is selected, the process for updating the rotation ($\mathbf{R}$) and position ($\mathbf{P}$) of the end of the track occurs, interpolating the value of the start of the track to the finish to generate a new mesh for the track in real-time. The current bend components b_i (for $i \in \{x, y, z\}$) represent the track's angular components along each axis, which are updated with an incremental input e_{bi} that are scaled by a factor k_i (where $k_i = w$ for the x and z axes, where w is defined as the work direction of the track (defining whether the roller coaster cart should reverse on this track or not), and $k_i = 1$ for the y axis) before being snapped to the nearest multiple of the fixed snap angle Δ_b as defined by the user, offering flexible precision when designing. Similarly, the shim components s_i (which define the positional offsets of the track) are updated by adding incremental inputs e_{si} and snapping the results to the nearest multiple of the snap length Δ_s; a constraint is imposed on the z-component to ensure that $s_z^{\text{new}} \geq 0.5$, preventing the track from inverting. Following

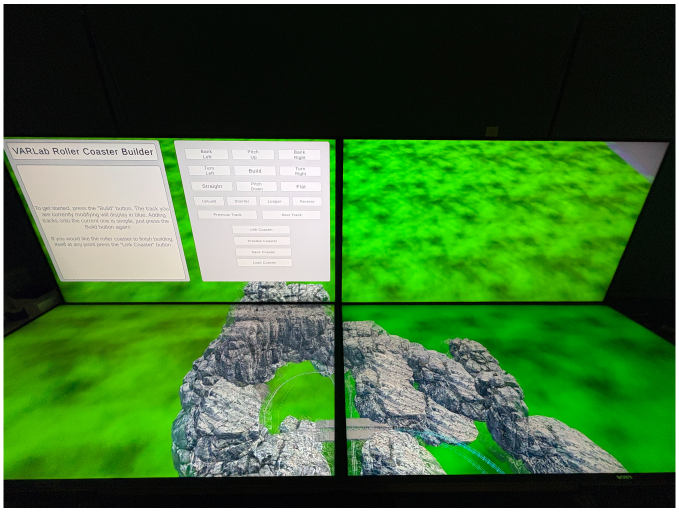

Fig. 2. VR Table display with example roller coaster

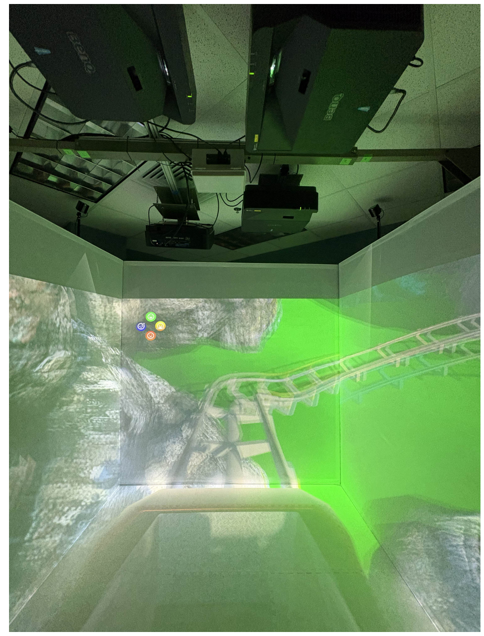

Fig. 3. CAVE display with example roller coaster

these discrete updates, the new rotation $\mathbf{R}$ is computed by converting the updated bend values into Euler angles, and the final track position $\mathbf{P}$ is calculated by interpolating between the transformed shim vector using the starting rotation R_{start} and the new rotation R, and then adding the starting position $\mathbf{P}_{\text{start}}$. This update can be mathematically defined as follows:

$$b_i^{\text{new}} = \Delta_b \cdot \text{round}\left(\frac{b_i + e_{bi} \cdot k_i}{\Delta_b}\right), \quad i \in \{x, y, z\}, \tag{1}$$

$$s_i^{\text{new}} = \Delta_s \cdot \text{round}\left(\frac{s_i + e_{si}}{\Delta_s}\right), \quad i \in \{x, y, z\}, \tag{2}$$

$$\mathbf{R} = \text{Euler}\left(b_x^{\text{new}}, b_y^{\text{new}}, b_z^{\text{new}}\right), \tag{3}$$

$$\mathbf{P} = \mathbf{P}_{\text{start}} + \frac{1}{2}\left(\mathbf{R}_{\text{start}}\, \mathbf{s}^{\text{new}} + \mathbf{R}\, \mathbf{s}^{\text{new}}\right). \tag{4}$$

When this process occurs, users in the CAVE receive an immediate update for the newest iteration of the coaster. In response, the riders can then follow up with a simple click of a controller in one of four directions as indicated by a graphical icon within the system to indicate their feeling at the current location on the coaster which allows for instant feedback. This establishes a bi-directional data flow, where command center developers are monitoring the feedback to gain insight into how their changes impact rider experience, quickly identifying areas which are problematic or beneficial to an end-user. This significantly enhances the responsiveness of the currently established design process for roller coaster development.

Use-cases for the proposed system highlight the synchronized workflow's capabilities for benefiting designers in the prototyping phase of development. Testing steep drops, tight curves, and intense speeds while designing an environment which immerses a rider is non-trivial, and requires heavy assessment of the impact of different environments in cohesion with physical interactions. By monitoring real-time feedback, designers can gain an immediate understanding of how much a specific tweak in the current iteration of the ride, such as if the environment is a greater contributing factor to sickness or boredom than the physics and vice versa. By providing a solution to fine tuning for real-time feedback, the system allows for better roller coasters which are tailored to rider expectations.

V. Discussion

Our proposed system introduces a novel VR Table and CAVE-based VR application for designing roller coasters. By establishing a bi-directional data flow, we introduce a solution for the long and iterative process of designing coasters through integrating feedback of user experience in the same phase as designing. This reduces the bottleneck of delayed user testing by providing real-time feedback of riders into the pipeline, offering designers perspective on how changes impact the ride. The system allows designers to refine both environmental factors and physical factors, testing multiple aspects such as track curvature, drop steepness, and thematic elements in real-time. By dynamically adjusting the layout of the roller coaster based on immediate feedback, rides can be enhanced to provide better comfort, excitement, and immersion in an accelerated format. This provides potential for a reduction of production cost while improving the overall satisfaction of rides before they reach the implementation phase. Although this research does not conduct formal user study evaluations, they are a primary focus on future research, which plans to assess user capabilities in collaboration within our framework compared to HMD-based methods and current industry-standard workflows.

While these advancements provide an improvement to the current process of design and development of roller coasters, challenges persist which require further research. The VR Table fosters a collaborative design environment, the effectiveness of how well users work with each other may be dependent on the familiarity of users with VR interaction paradigms. In addition to this, the CAVE based feedback system provides real-time reactions but does not account for long-term physiological and psychological factors such as fatigue and adaptation to motion stimuli. Future work should explore integration of physiological sensors such as heart rate monitoring to provide a data-driven complement to user feedback. Likewise, ride implementation currently does not physically immerse users into the movement process of roller coasters, and future integrations should move towards an approach which engages the user in a motion based way. There is also great potential to integrate AI solutions for story telling, this can lead to an enhanced process for designing immersive themes in real-time. Although this work focuses on rollercoaster development, the modular design of the VR Table and CAVE-based feedback system allows for adaptation to other attraction types and themed design challenges. Future work in this area should explore performance at scale across a variety of simulation methods and collaborative scenarios to better highlight CAVE-based design improvement in the themed experience industry. By continuing to explore these enhancements, our proposed system has the potential to become an industry-standard tool for VR driven attraction development.

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