Development of Virtual Learning System for Baja Racing Vehicles

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Abstract: To address challenges in Baja racing event training, including spatial-temporal constraints, high resource requirements, and low learning efficiency among novices, this paper designs and develops an intelligent learning system based on virtual reality technology. The system integrates core modules including racing introduction module, system learning module, tool learning module, Baja process learning area, racing car showroom and quiz module. It enables team members to engage in self-directed learning during fragmented time periods, significantly reducing human and material costs associated with offline training. The system assists novice drivers in systematically mastering competition rules, vehicle component structures, and overall racing frameworks, while familiarizing them with tool selection logic and disassembly/maintenance procedures, thereby facilitating efficient pre-race technical preparation. Experimental results demonstrate significant effectiveness of the system in enhancing learning efficiency and lowering training costs, providing a cost-effective digital solution for technical training in Baja competitions.

Keywords: Baja Racing; Virtual Reality; Training System; 3D Modeling; Autonomous Learning

1. Introduction

The Baja SAE China is a national engineering practice competition for university students, designed to cultivate innovation capabilities and teamwork spirit through designing, manufacturing, and testing single-seat off-road racing vehicles. During preparation, participants often face challenges such as insufficient understanding of competition rules, unclear grasp of structural principles, unfamiliarity with testing methods, and difficulty providing feedback on their comprehension levels. Teams typically enhance students 'theoretical knowledge and practical skills through internal theoretical assessments and vehicle disassembly/assembly exercises. However, theoretical testing methods remain limited in comprehensively evaluating students' ability to address complex engineering problems, while practical testing is constrained by venue availability, cost and safety concerns, making it difficult to conduct frequently. There is therefore an urgent need for an efficient, repeatable auxiliary training approach to address these shortcomings. Virtual Reality (VR) technology, with its low cost, high safety, and repeatability, has emerged as an ideal solution. At present, this technology has been extensively applied to the virtual simulation of electromechanical equipment. Research objects cover electro-hydraulic switch machines [1], general industrial equipment [2], automatic transmissions[3,4], automobile structures [5], Forged Structural Components for Automobile Chassis [6] and electromechanical products [7]. Meanwhile, Tan et al. conducted research on automotive human-computer interfaces [8], offering references for the design of interaction logic and interface layout in virtual disassembly and assembly scenarios. IdeaVR [9], Unity 3D [10] and Virtual Universe Pro [11] are the mainstream platforms for developing virtual reality systems.

By incorporating the technical merits and design experience of the above VR systems, this research develops a dedicated virtual learning system for Baja racing vehicles, which covers functional modules including competition rule learning and vehicle component training zones as well as a vehicle exhibition hall. With the proposed system, students can systematically learn competition rules, structural principles of vehicle components and the overall vehicle architecture, and become proficient in tool selection matching logic together with disassembly, assembly and maintenance procedures. By creating high-fidelity digital models of Baja vehicles, students can complete theoretical learning, hands-on practice, and testing in virtual environments, allowing them to repeatedly hone key skills under safe conditions while deepening their understanding of competition rules, vehicle structures, and manufacturing processes.

2. Baja Racing Vehicle Virtual Learning System

To enable users to learn Bahha Racing in a progressive manner, we adopts the design philosophy [12], (progressive layered content design) to build the virtual labtory. The Layout of the Virtual Laboratory are shown in the Figure 1, and the virual lab includes three main modules, which are racing car introduction module, four system learning modules, test modules. Learners should first enter the racing car introduction module to consolidate basic theories of Baja competitions, and carry out standardized tool training with the support of the adjacent tool learning module. They then move to the system learning module to realize the layered transition from theoretical knowledge to practical operation. Afterwards, learners get familiar with the complete manufacturing process of the whole vehicle in the Baja process learning area; visit the racing car showroom to observe the 3D full-vehicle model and perform virtual assembly and disassembly of components, and enter the quiz module to verify learning effectiveness.

The whole learning pipeline forms a closed loop of "learning–practice–feedback", enabling quantitative evaluation of learners' learning outcomes.

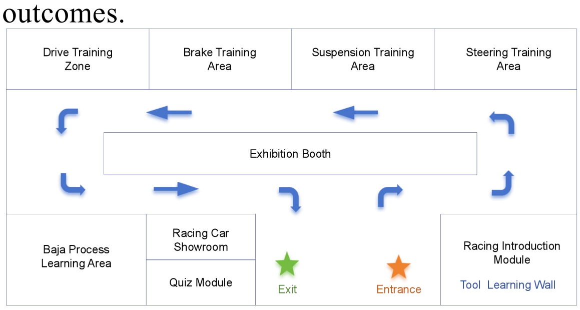

Figure 1. The Layout of the Virtual Laboratory

3. Design of Theoretical Cognition Module

To address the problems encountered by new participants in Baja competitions, such as insufficient awareness of competition rules, unfamiliarity with the vehicle development process, lack of understanding of complete vehicle structures and absence of systematic guidance for preliminary competition preparation, this system enables beginners to learn about Baja events through four dimensions: racing introduction module, Baja process learning area, racing car showroom and tool learning module.

3.1 Design of Racing Introduction Module and Baja Process Learning Area

The racing introduction module as shown in Figure 2 provides comprehensive event-related contents, including general event overview, promotional videos and official competition regulations. A dual information presentation mode integrating videos and texts is adopted in this zone. Combined with textual descriptions, videos convert abstract and complicated written rules into intuitive visual experiences through vivid footage and logical narration, allowing learners to gain an in-depth understanding of the distinctive features and technical requirements of Baja events.

Figure 2. Racing Introduction Module

Multiple thematic display panels are arranged inside the Baja process learning area as shown in Figure 3, abandoning the traditional form of pure text enumeration. Key manufacturing links, including structural design, vehicle disassembly, assembly and commissioning, as well as finished vehicle inspection, are displayed in separate modules with comic illustrations. The content is easy to understand with clear hierarchies, conforming to the cognitive rules of novice learners. In addition, virtual guiding arrows are embedded in the exhibition space. The browsing route is planned according to the visiting logic and actual vehicle manufacturing procedures to guide users to view the comic contents in sequence. Within the immersive virtual environment, learners can sort out the complete vehicle development logic and fully master the full manufacturing procedures and core technical points of Baja racing vehicles.

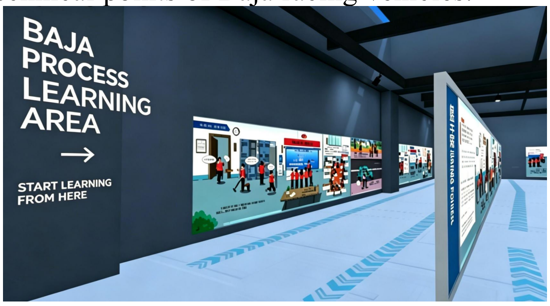

Figure 3. Baja Process Learning Area

3.2 Design of Racing Car Showroom and Tool Learning Module

The vehicle model as shown in Figure 4 displayed in the exhibition hall is established in strict accordance with the technical regulations of the SAE-China Baja Competition. The overall vehicle dimension is limited within 1620 mm in width and 2740 mm in length, and a clearance of no less than 13 mm is maintained between the linkage assembly of the engine throttle and governor and the nearest non-engine components. The basic vehicle parameters are listed as follows: aluminum sheet body, curb weight of 205 kg, overall length of 2039.14 mm, overall height of 1506.08 mm, wheelbase of 1500 mm, minimum ground clearance of 207 mm, front track of 1290 mm and rear track of 1250 mm, rear-wheel drive layout, and Kenda AT tire specification 21*7-10. The suspension adopts unequal-length double A-arm pushrod layout at the front and trailing arm layout at the rear. The transmission system is equipped with a CVTech-IBC continuously variable transmission without differential, matched with a Jietian Precision reduction gearbox, and the braking system applies front and rear disc brakes.

The tool learning module as shown in Figure 5 is embedded with 3D models of frequently used manufacturing tools. Cutting machines, electric welding machines, angle grinders, electric drills, pipe benders and bench grinders are selected as core demonstration tools with matching picture displays. Meanwhile, video modules are integrated to present standard application scenarios and standardized operation specifications for each tool.

Figure 4. 3D Model of the Baja Racing Vehicle

Figure 5. Tool Learning Module

4. Design of Chassis System Learning Module

Following the concept of personalized autonomous learning and the progressive principle of cumulative cognition, the Baja vehicle is decomposed into four core subsystems: transmission, brake, suspension and steering, with an independent learning zone configured for each subsystem as shown in Figure 6. Basic working principles of each subsystem are illustrated via graphic materials and instructional videos in corresponding learning zones. Two types of disassembly and assembly training modules are provided for practical consolidation. The automatic disassembly and assembly function serves as a demonstration of standardized operation procedures, while the manual disassembly and assembly mode allows learners to conduct independent practical exercises. Combined with observation demonstration and hands-on operation, this dual-mode design deepens learners’ comprehension of subsystem structures and assembly logic.

4.1 Design of Automatic Disassembly and Assembly Module

The automatic disassembly and assembly module focuses on the disassembly sequence of mechanical structures as well as the three-dimensional spatial position of each component. Two core functions, automatic disassembly and automatic assembly, are developed in this research. After creating primary tasks in IdeaVR, visual programming is adopted to realize the human–computer interaction logic of the two functions.

Figure 6. Internal Scene of the Learning Zone

Clicking the functional buttons on the menu bar triggers animation playback to demonstrate the whole disassembly and assembly processes. This function mainly relies on button-based human–computer interaction as well as animation configuration and production.

Actual disassembly operations in manufacturing consist of translation, rotation followed by translation, translation followed by rotation and other compound motions as shown in Figure 7. To restore real industrial operation logic authentically, such motion details are strictly considered during animation development. For instance, the adjusting nut of the tie rod in the steering system needs to be translated first and then rotated for removal; by contrast, the connecting bolt of the tie rod must be rotated loose with a wrench before translational extraction. According to the standard disassembly sequence of the four subsystem learning zones, the animations of individual parts are integrated into a complete disassembly animation in chronological order. Corresponding translation parameters, rotation parameters and disassembly duration are configured for each single component.

The automatic assembly animation is generated by reversing the playback sequence of the pre-produced disassembly animations, which will not be elaborated repeatedly here.

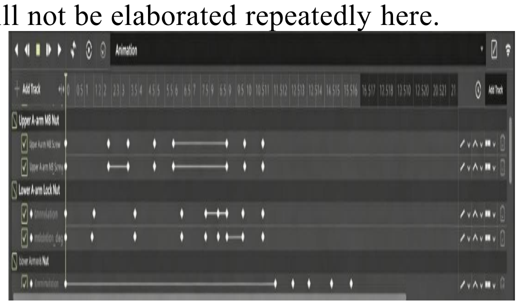

Figure 7. Animation Parameter Configuration

4.2 Design of Manual Disassembly and Assembly Module

A manual disassembly and assembly module is developed to help users get familiar with the structural composition and disassembly-assembly procedures of the transmission, brake, suspension and steering subsystems of Baja racing vehicles.

Clicking the practice disassembly and assembly buttons on the menu bar activates the corresponding scripts, which are pre-programmed for the buttons via visual programming to launch interactive operations. A virtual prompt board pops up to notify users of the target component for the current operation step. If users try to disassemble or assemble parts out of the standard sequence, the system will send intuitive error prompts as shown in Figure 8. Users need to select the correct component to carry out subsequent operations as shown in Figure 9. After all parts are completely disassembled or assembled, the prompt board will display text messages marking the completion of disassembly or assembly. Compared with physical disassembly training, this virtual module saves much time and labor. In addition, it eliminates common drawbacks of physical training including component wear and potential safety hazards.

Figure 8. Wrong

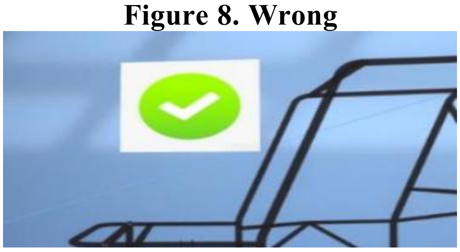

Figure 9. Correct

5. Quiz Module

To accurately evaluate learners' mastery of knowledge, theoretical assessment and practical operation assessment modules are designed in the quiz module.

5.1 Design of Theoretical Assessment

The theoretical assessment is realized via a built-in question bank module of IdeaVR. This native examination module of IdeaVR is imported into the virtual laboratory environment. Through communication with professional instructors and sorting of teaching materials, nearly 100 test questions as shown in Table 1 are compiled and imported into the module as the question bank, covering single-choice questions, multiple-choice questions, true-or-false questions and other question types. When learners start the test, the system randomly extracts 10 questions from the question bank as shown in Figure 10. Upon finishing all 10 questions, the system automatically displays the final score and the total time consumed to complete the test as shown in Figure 11.

Table 1. Display of Partial Test Questions

Question Type	Question Stem	Answer	A	B	C	D
Single Choice	When was the first BAJA Competition held?	C	Apr-13	Apr-14	Aug-15	Sep-16
	Where was the first BAJA Competition held?	A	Weifang, Shandong	Beijing	Xiangyang, Hubei	Guangzhou
Multiple Choice	How to remove the hub bolts when disassembling wheels?	AC	17# socket wrench	vise	tighten diagonally	tighten clockwise
	Which of the following time intervals will affect the automobile braking distance?	CD	Driver reaction time	driver foot movement time	brake actuation time	continuous braking time
	What factors should be considered in the frame design of BAJA racing cars?	ABCD	Strength	Stiffness	Lightweight design	Manufacturing process
	Which of the following components may be used in the power system of BAJA racing cars?	ABC	Engine	Gearbox	Drive shaft	Windshield wiper
Judgment	The free travel of the steering wheel refers to the angle that the steering wheel can rotate freely when the front wheels remain stationary.	TRUE				
	The student BAJA racing competition only focuses on speed without paying attention to safety.	FALSE				

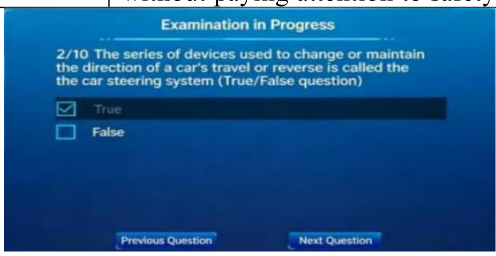

Figure 10. Examination in Progress

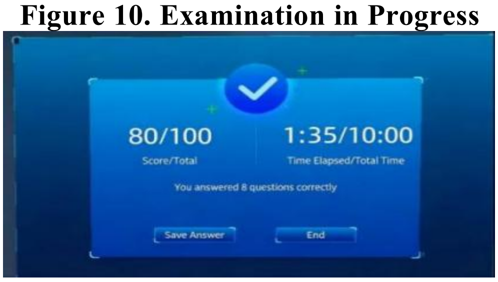

Figure 11. Assessment Results

5.2 Design of Practical Operation Assessment

The practical operation assessment as shown in Figure 12 is conducted within each subsystem learning zone. After learners finish studying the disassembly-assembly procedures of the transmission, brake, suspension and steering subsystems, and complete relevant practice training, they can start the assessment by clicking the buttons of manual disassembly and manual assembly on the operation panel, so as to evaluate their mastery of disassembly and assembly skills learned in this session.

During the assessment, users must follow the standard disassembly and assembly sequence demonstrated in the automatic disassembly and assembly module. A check mark will pop up if the component is operated in the correct order; otherwise, a cross mark will be displayed as an error reminder. Once all components are fully disassembled or assembled, the panel will present the total operation time consumed and the corresponding letter grade. The grading standard is determined by the total operation duration as follows: Grade A for operations completed within 120 seconds, Grade B for 120–240 seconds, Grade C for 240–360 seconds, and Grade D for operations exceeding 360 seconds. The final letter grade serves as a reference indicator to judge learners' proficiency of the relevant content.

Figure 12. Practical Assessment Interface

6. Conclusion

As a lightweight self-learning platform oriented to new team members, our Baja racing virtual learning system fills the learning gap before offline centralized training. Riders can utilize fragmented spare time to thoroughly learn official competition regulations, master the working principles of core vehicle mechanisms and key points of disassembly and assembly operations, helping new participants clarify their technical development orientation within the team. This virtual platform effectively reduces labor and material costs for offline team training and standardizes the entry training process for newcomers. It supports Baja teams in accumulating technical reserves for members and consolidating the overall technical capacity of the whole team.

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