Chameleon: Unobtrusive Substitution of Real-World Obstacles in VR with Risk-Level-Aware Adaptation

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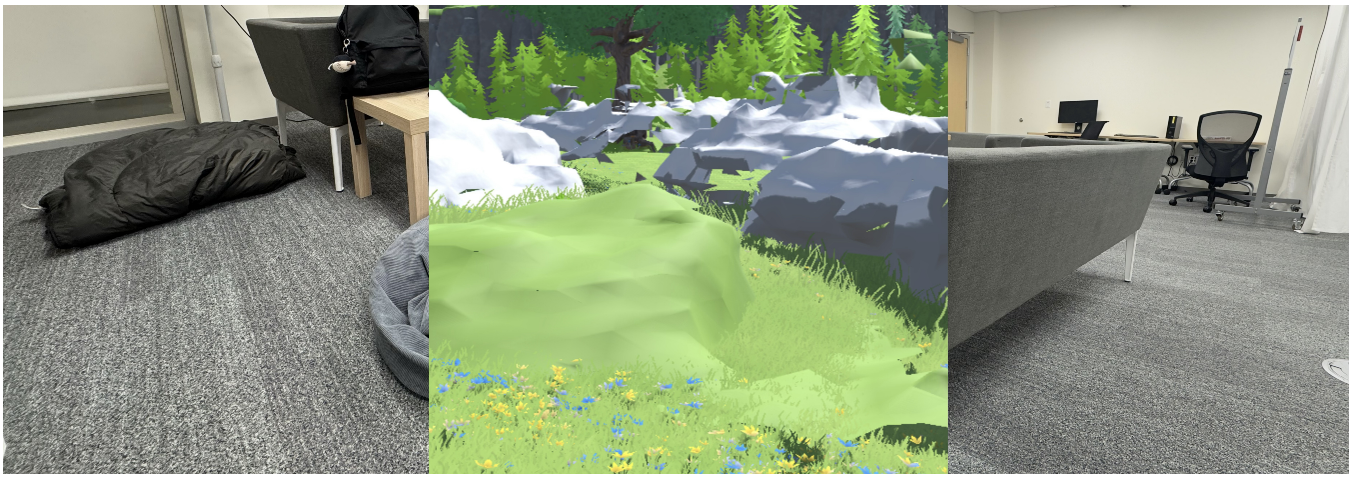

Figure 1: Visualization of obstacle substitution in a VR environment, where real-world objects are overlaid with risk-based textures to enhance safety and immersion.

Abstract

In VR environments, free movement in real space enhances immersion but increases the risk of collisions with real-world obstacles. Prior solutions investigated using substitute obstacles with context-related digital objects in VR but often treat all obstacles uniformly without considering their varying levels of risk. This oversight might result in reduced awareness for high-risk obstacles and a missed opportunity to utilize low-risk objects to enhance haptic feedback and interactivity in VR. In this study, we propose Chameleon, a system that classifies real-world obstacles by their varying risk levels and substitutes them with context-related virtual objects in VR. The substitutions are designed to align with the obstacles' real-world risk levels to ensure both safety and immersion. A preliminary heuristic evaluation assessed the usability of using visual textures to implicitly represent obstacle risk levels.

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CCS Concepts

• **Human-centered computing → Virtual reality**; **Mixed / augmented reality**.

Keywords

Virtual Reality, Obstacle Avoidance, Cross-reality System, Safety

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1 Introduction

Virtual Reality (VR) immerses users in simulations that can be experienced through sight, sound, and physical motion. Compared to traditional computer interfaces, VR offers a heightened sense of presence and engagement, especially when users are allowed to navigate the virtual world by physically walking around a tracked play area [22]. However, natural walking in a cluttered environment introduces new safety dangers [3, 7, 12, 13]. Real furniture like tables, chairs, or cabinets may cause collisions if the user is unaware of their presence while wearing a VR headset.

Prior works have explored approaches such as the replacement of real-world obstacles with virtual objects aligned with the virtual environment, which improved the users' safety when using VR equipment [1, 16, 28].A significant advantage of these approaches is the increased immersion during the using, users don't have to directly face the obstacles' shape or appearance in the real world, but can naturally interact with objects in the virtual environment, thus enhancing spatial coherence [21]. However, these studies have tended to treat all obstacles the same without considering their specific characteristics. This oversight could reduce awareness of high-risk obstacles (as users treat all obstacles as equally risky), miss the opportunity to use low-risk objects to enhance haptic feedback and interactivity in VR.

In this work, we will continue to use the alternative object approach, and our goal is to develop a way to visualize these obstacles to reflect their varying degrees of risk, thus allowing for more flexibility and diversity in future designs for obstacle substitution. Our proposed Chameleon system is designed around three core elements: **dynamic obstacles detection**, **obstacles safety classification** and **risk level representations**. The system dynamically evaluates the danger of an obstacle, categorizes it as low, medium, or high risk, and assigns a visual representation based on the risk level. For example, a low-risk pillow can be rendered as a soft cloud to encourage interaction, while a high-risk table corner can be avoided with a flame or thorn texture. Chameleon enhances the safety and functionality of obstacle substitution, while increasing user interactivity and immersion, providing more possibilities for future design.

2 Related Work

In terms of protecting users' safety and collision avoidance, the most used approach is to directly replace the obstacle with another object [6, 9, 16, 24, 27]. For example, VRoamer [6] generates a virtual scene based on the layout of the room where the user is located, allowing the user to walk safely in the virtual world [6]. And also, in Metaspace II [24], the system observes the position of objects in the environment in advance and puts virtual objects into the virtual system based on different object positions and sizes to provide obstacle avoidance. In addition to object replacements, there are also ways of displaying real objects directly in the virtual world [16]. This approach is more intuitive and allows the user to understand the obstacles in a more intuitive way. These two approaches have the ability to effectively allow users to understand realistic obstacle situations, and provide a way to maintain safety during VR experiences.

Prior work has investigated representing obstacles in a dynamic and unobtrusive manner to preserve immersion in VR experiences. Research on stereoscopic interaction overlay guidance emphasizes that overly conspicuous or distracting cues can disrupt a user's "sense of presence" and diminish the unmediated illusion feeling that the user is truly "in" the virtual world rather than merely observing it. This approach is in line with HCI principles [5, 11, 29] that emphasize transparency and subtlety in design: the system should support and inform the user of hidden dangers without constantly pulling the user out of the immersive experience. Thus, achieving the highest levels of user comfort, safety, and presence in VR requires a careful balance between being unobtrusive and effectively communicating risks [10].

There are still some challenges in the previous work. The detection approach adopted in most of the current work requires pre-scanning the environment [24]. The system is unable to reflect changes in the real environment onto objects in the virtual environment in real time. The VR environment needs to be modified manually to realize the replacement of obstacles. However, the real environment is very complex, especially the real objects that will often be moved, so this pre-set approach can not be very accurate in realizing the replacement of obstacles, which will put the user in the use at risk. Meanwhile, in terms of dealing with security issues, the current work uses an approach that basically avoids all obstacles [27]. Moreover, the appearance of obstacles is often highly repetitive, and prolonged exposure to the same objects can lead to visual fatigue and lack of alertness to obstacles. The variety of obstacles means that there are different levels of risk. Most of the studies now generally do not realize that different objects have different levels of risk, and we want to take advantage of this to express different levels of risk with different appearances.

3 Chameleon System

3.1 Design Goals

Based on the research gap noted in the related work, our design goals are listed as follows:

- **Dynamic Obstacles Detection.** Continuously track changes in the user's real environment. When new objects or individuals enter the space or when existing obstacles are moved, the system should promptly update both classification and visual cues, thereby reducing collision risk and ensuring the system adapts seamlessly to shifting real-world conditions.
- **Obstacles Safety Classification.** Automatically assess and classify the risk level of physical objects to ensure user awareness. By analyzing each object's shape, geometry, and material, the system should determine its potential danger and assign an appropriate safety rating. Users can further refine this classification to match their specific needs or personal comfort levels.
- **Risk Level Representations.** Express risk messages in a subtle yet clear way to maintain immersion, rather than drawing attention with overt warnings. The system should present virtual elements overlaid on obstacle contours to visually convey varying risk levels, thereby guiding user behavior without overshadowing the VR experience.

3.2 System Deign

In order to meet the design goals, we designed the system through the real-time obstacles detection and recognition, adaptive safety classification, and unobtrusive risk level representation features. The system automatically analyzes an obstacle's risk and applies an appropriate texture, using common sense [19, 23] to inform the user of potential dangers. Meanwhile, users remain free to interact with, achieving a balance between personal comfort, situational awareness, and immersive exploration. These interactions can also extend naturally to future work involving multi-user or remote collaboration scenarios.

3.2.1 Dynamic Obstacles Detection and Recognition. As the user moves through the virtual environment, the system updates the virtual representation of obstacles in real-time to ensure that the virtual world is always consistent with real space. The process involves continuous tracking of the user's position while monitoring changes in the physical environment, such as the movement, disappearance, or addition of obstacles. When a change in the environment is detected, the system immediately adjusts the display of the virtual obstacle so that it accurately reflects the current reality. And perform object recognition on these obstacles.

3.2.2 Adaptive Safety Classification. To ensure a more intuitive and user-centered approach to managing obstacles in virtual reality, our system employs an adaptive safety classification framework.

For AI recommended safety classification, the system analyzes it with the help of AI by combining the information about the shape, material, and surface properties of the obstacle. The obstacles are categorized into three levels so that classification rules [2, 4] can be adopted for different levels of potential dangers. These classification rules are based on the classification of household products, especially children's furniture considered the material and appearance of the objects. These classification rules are relatively strict and are better suited to provide maximum security when users wear VR devices. The classification rules are used in the system as follows:

- **Low Risk.** Obstacles have no sharp edges or protrusions and are made of relatively soft materials, the possibility of user's injury after a collision is extremely low. For example, sofas and pillows. Users can co-exist with them in the virtual environment with little or no interference, and an accidental collision will result in only a minor or negligible impact.
- **Medium Risk.** Obstacles that do not have sharp protruding parts, but are made of hard materials that may cause mild to moderate impact or pain upon impact. For example, plastic tables and chairs and tables. Although users can interact with them by simply touching, grasping, pushing, or pulling, care should be taken to avoid excessive collisions.
- **High Risk.** Obstacles with sharp protrusions or in high-speed motion that do not support user interaction and need to be actively avoided are defined as high risk. The shape of such obstacles has obvious sharp edges or tips or is in high-speed movement, impact or contact will lead to greater risk, and may even cause serious injury. For example, knives and fans.

Considering that each individual may have different perceptions and standards of dangers, we also provide customize safety classification to provide the option to personalize the settings prior to operation, allowing the user to adjust the safety classification according to personal needs and safety standards. Users can modify the level of certain specific types of dangers based on the default safety classifications provided by the system.

3.2.3 Unobtrusive Risk Level Representation. In order to maximize the immersion of the user in the virtual environment, the system automatically selects the most suitable texture style for the obstacle based on its material, shape, and risk level. We chose texture-based adaptation because it provides a more natural and intuitive approach to risk communication than color-coded warnings because textures themselves carry perceptual cues that are consistent with real-world expectations [20]. In addition, maintaining a consistent size between real-world obstacles and their virtual counterparts helps users accurately judge distances and avoid collisions, thus preventing disruption of immersion. The system has a rich texture library, covering different styles and colors of virtual materials, and the AI module automatically selects the texture that best combines the risk warning and aesthetic effects based on the characteristics of the obstacle (e.g., size, shape) and the level of danger. The following is an example of the system following classification rules [2, 4] in a virtual forest environment(see Figure 2):

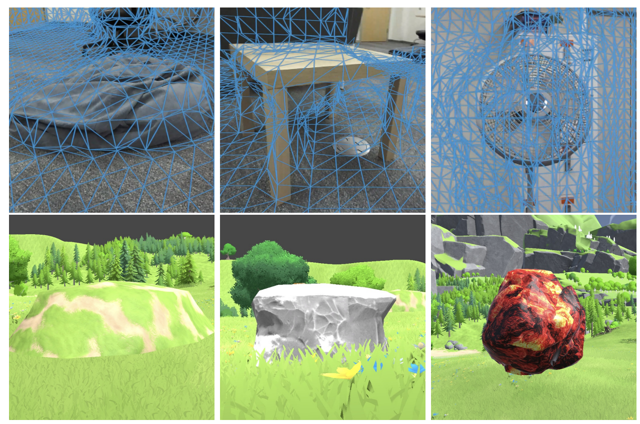

Figure 2: Examples of Safety Representation in different Levels with Sofa, Table, and Fan

- **Low Risk.** Obstacles with no sharp protrusions or soft materials, the system overlays soft textures that match the surrounding woodland environment, such as light-toned bushes, grass patches or moss.
- **Medium Risk.** Obstacles that are harder in shape, but have no obvious sharp edges, the system uses a bark or vine texture that contrasts somewhat with the background to differentiate their risk. There is a slight increase in color saturation compared to low-risk textures.
- **High Risk.** Obstacles with sharp edges or risk of high-speed movement, the system overlays high-contrast textures, such as flames. These textures have more significant brightness and vibrant colors compared to low and medium-risk textures, helping users to quickly identify potentially high hazards from a distance so they can avoid them in time.

Since the objects in the original VR scene are also characterized by polygons, this makes the texture-covered obstacles appear less obtrusive. With three different representations, the system can effectively utilize human common sense to express the results of safety classification in a virtual environment.

3.3 Implementation

We use ZED Camera and Meta Quest 3 to implement our system. Firstly, we use ZED Camera to capture the RGB and depth data in the real environment, generate a real-time updated 3D mesh through spatial mapping, and combine it with the YOLO[1] object recognition model to obtain information about the objects in the environment. These data are imported into Unity as a real-time stream and integrated with the virtual scene. After Unity's rendering, we integrate the real obstacles with the virtual environment and dynamically interact with them on Meta Quest by continuously acquiring the real data through the ZED Camera. The system is capable of rendering different materials for objects in the virtual environment according to their risk level, such as providing soft effects for low-risk objects and warning effects for high-risk objects, thus balancing the immersive user experience with safety [25].

4 Heuristic Evaluation

We conducted a heuristic evaluation with three lab members to check the usability of the system and gather early feedback for iterative design improvements. We chose this method because it allows for a cost-effective and structured evaluation of the prototype to identify usability issues without the need for a large number of participants. All the participants had at least two years of experience designing or using VR applications, also with HCI and design background. We focused on principles such as **visibility of system status** and **match between system and the real world** which we deemed most relevant to VR obstacle substitution [17].

4.1 Procedure and Tasks

Before the study we briefly introduce participants to the functionality of our system and allow them to make changes to the object's risk level. Then each participant spent 10 minutes performing three tasks in a small room: 1) Naturally walking from one end to the other to encounter and avoid obstacles. 2) Intentionally interacting with the low-risk obstacles to observe haptic alignment. 3) Moving some selected medium-risk objects to see how the system updates risk classification in real-time. Afterwards, each person rated: 1) Rate the accuracy of the system in detecting obstacles. 2) Rate the correct categorization of the disorder or the rate of meeting participants' mental expectations. 3) Rate the appropriateness of the presentation of the obstacle and the level of risk expressed. All ratings use the Numeric Rating Scale. And all participants will be interviewed individually for 15 minutes. During the interview the participants will explain the reasons for the scores they given, as well as system deficiencies and other constructive comments.

4.2 Findings and Discussions

Most participants praised the timely updates when they repositioned objects, though P1, P2 noted a 5-second lag in mesh re-rendering, causing minor disorientation. The AI's categorization of objects as low, medium, or high risk generally matched participants' expectations, but P3 evaluator suggested a manual override system for edge cases (e.g., a small plastic fan incorrectly labeled as high risk). Participants appreciated the "subtle yet visible" textures for most obstacles, stating that it maintained immersion. However, P2 found the flame texture is not bright enough and recommended replacing the texture with a brighter one. P1 thought it was actually counterintuitive when some things were set to be movable. For example, objects that were replaced with stone materials should not be moved easily, which defies common sense.

In addition to these points, participants also raise other points to consider. For example, some of the alternative objects do not exactly match the shape or size of the real object, which can cause a slight "hand-through" illusion. Also they suggest adding other signals such as faint pulsations, or dynamic shading effects, to enhance depth perception and provide more intuitive representations.

The heuristic evaluation validated the potential of the system to perform seamless, unobtrusive and responsive obstacle substitution in VR. However, participant feedback indicated several areas for improvement. First, reducing the 5-second lag in mesh re-rendering is critical to enable smoother interactions and enhanced spatial perception. Additionally, allowing direct manual overrides for the categorization of edge cases would prevent mislabeling errors and better accommodate individual user preferences. Finally, tweaking the flame texture either by increasing brightness or other visuals which can further distinguish high-risk objects without compromising immersion. These are the points that we can improve afterward, striving for a more perfect balance between security, realism, and user engagement.

5 Limitation and Future Work

We are working to improve the system. Although our current obstacle detection and classification methods are capable of handling a wide range of common objects, they still struggle with small or narrow objects such as poles, cables, or slender table legs. These small features are more likely to be occluded and less reliably captured by real-time RGB-D scanning, resulting in occasional misclassifications or omissions.

In addition, dynamic risk reclassification remains a complex problem because the same object may pose different risks depending on its location, motion, or user perception. Future iterations will explore the use of scenario understanding models for context-aware risk adaptation so that risk levels can be dynamically adjusted according to real-time environmental changes. Pose analysis to detect unstable or dangerous object configurations, e.g., tilted chair vs. stable chair.

The feedback from the heuristic evaluation emphasized additional user experience improvements. For example, it was counterintuitive that objects replaced by large stone materials could be moved easily. Future iterations could introduce material-physics-based constraints to better reflect real-world expectations of whether objects can move easily or otherwise behave physically. Similarly, some participants noted shape and size mismatches between virtual alternatives and real-world objects, as well as "hand-through" issue [15]. The use of more advanced mesh alignment or adaptive deformation techniques [8, 14, 18] could eliminate these discrepancies and maintain immersion.

In future iterations, we plan to explore integrating large language models (LLMs) to automatically infer the theme or setting of the VR scenario and generate context-appropriate textures. For instance, if the LLM detects or predicts a "forest" theme, it may suggest moss-covered rocks or grass-like surfaces for low-risk objects, or thorny bark textures for more dangerous elements. By analyzing object shapes and their risk properties, the LLM can intelligently

[1]https://github.com/Tianxiaomo/pytorch-YOLOv4

recommend texture overlays, making system's design pipeline more autonomous and flexible across varying narrative contexts.

Meanwhile we plan to conduct larger-scale, formal user studies to validate effectiveness in diverse real-world settings. These studies will investigate multiple factors, including the usability and comfort of risk-adaptive texture overlays, the accuracy of real-time mesh reconstruction in varying lighting conditions, and the impact of prolonged exposure on user trust and system acceptance. Participants with different levels of VR experience and different environmental constraints will be recruited to capture a broad range of use scenarios. We aim to measure both objective indices (collision frequency, route efficiency, interaction behaviors) and subjective feedback (presence, perceived safety) to comprehensively evaluate system's performance and guide iterative improvements.

6 Conclusion

In this work, we present the Chameleon system, which aims to address safety risks in the use of VR devices by dynamically replacing real-world obstacles with risk-aligned virtual objects. This is achieved by classifying obstacles as low, medium and high risk and visualizing them by overlaying them with different textures in order to visualize the risk level. Thereby Chameleon enables the user to better understand the information about the obstacle without compromising immersion. With this flexible approach, lower-risk objects can be integrated into the virtual environment to enrich haptic interactions, while higher-risk obstacles utilize human common sense to enable users to actively avoid them. This system improves user safety and also broadens the design possibilities for incorporating elements of the real world into immersive virtual reality experiences [26].

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