# Immersive Prototyping for Robot Design with 3D Sketching and VR Acting in Reconstructed Workspace


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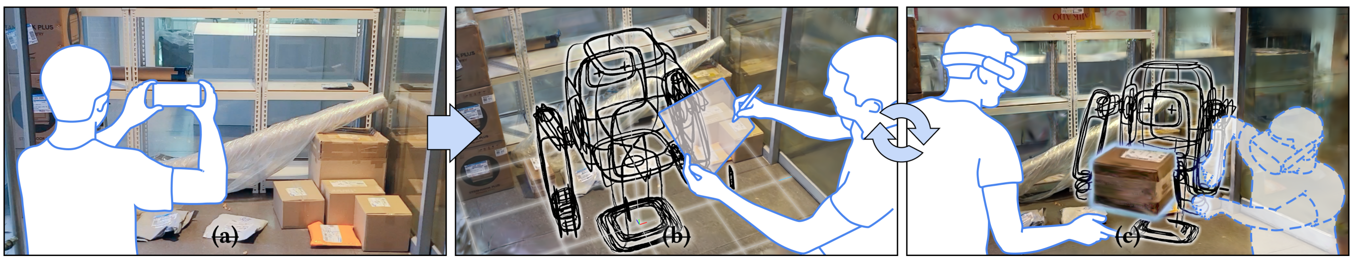


**Figure 1: In the proposed system and workflow, robot designers (a) visit and record a video of the target environment, (b) create the shape and structure of a new robot using 3D sketching within the reconstructed workspace, and (c) simulate human-robot interaction through collaborative role-playing within the same workspace in VR. Prototyping both the form and function of a robot in a realistic setting enables designers to iteratively improve their designs based on contextual insights.**


## Abstract

Rapid advances in robotics and AI technologies are opening the possibility of a wide range of commercial robot products with diverse shapes, sizes, and structures specialized for various environments, contexts, and roles. This trend calls for innovative tools and methods for designing robots as products. In this study, we propose a novel immersive prototyping system and workflow for quickly and easily creating desired robot shapes and structures through 3D sketching in target environments, realistically experiencing their movements and services through VR acting in the same environments, and iteratively improving their designs based on contextual insights. We conducted an extended robot design workshop with participants from backgrounds in robotics engineering and industrial design. The results show that the proposed system and workflow can help robot designers produce highly creative and compelling design outcomes, while also identifying areas for future improvement.



## CCS Concepts

• **Human-centered computing → Interaction techniques**.

## Keywords

Robot design, immersive prototyping, 3D Gaussian Splatting, 3D sketching, VR acting

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## 1 INTRODUCTION

Recently emerging multimodal AIs are capable of processing visual, audio, and tactile information for language, reasoning, and behavior. Combined with rapidly improving robotics components, including sensors, processors, actuators, batteries, and networks, these advances suggest a near future where robots providing valuable services to people become increasingly commonplace. In addition to familiar bipedal humanoid robots and quadrupedal animaloid robots, we may see the commercialization of a wave of new robot products with diverse shapes, sizes, and structures, specialized for

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various environments, contexts, and roles, in what can be described as a robotic Cambrian explosion [13].

However, designing new robots as products presents challenges not encountered in traditional product design:

- Unlike traditional products, robots feature complex shapes and structures composed of various joints, making it difficult for designers to express their ideas through sketches.
- Moreover, even after prototyping a life-size physical mockup, designers cannot test the robots' movements or services they are expected to perform autonomously and intelligently.
- As a result, the assessment of user experience provided by robots is often delayed until the final stages of development, making design iterations both risky and costly.

In this study, we propose an immersive prototyping system and workflow for robot design, addressing these challenges using state-of-the-art technologies in computer vision, 3D sketching, and VR. Robot designers can acquire photorealistic representations of environments, create robot shapes and structures suited to these environments through 3D sketching, experience robot movements in real time and at real scale through VR acting, and iteratively refine them to align with user requirements (Figure 1). We conducted an extended design workshop with robotics engineers and industrial designers, which resulted in creative and compelling robot concepts, demonstrating the potential usefulness of this novel bodystorming method.

## 2 RELATED WORK

In this section, we review previous work on bodystorming and the latest technologies enabling immersive bodystorming for robots.

### 2.1 Bodystorming

Bodystorming is a design method that emphasizes active engagement with physical prototypes and role-playing in target environments to gain contextual insights [4]. . This approach fosters creativity, user empathy, and high-bandwidth communication among designers [3, 11] and can be particularly valuable for designing highly dynamic and interactive robots [7]. Since actual sites may not always be accessible, designers may also conduct bodystorming in staged environments. However, these environments may not accurately reflect reality, potentially biasing design outcomes toward designers' preconceptions [11].

To address this limitation, in our system and workflow, robot designers first visit and record videos of the actual environments the robots are intended to interact with, which are used to set up an immersive workspace. This approach supports unlimited bodystorming activities, preserves contextual insights gained from real observations, and enables effective and efficient design reviews using virtual robot assets that can be prototyped quickly and easily.

### 2.2 Supporting Technologies

We integrate 3D Gaussian Splatting (3DGS), 3D sketching, and VR acting technologies into an immersive bodystorming method, which to our knowledge is the first of its kind.

**3DGS for photorealistic representation of environments.** 3DGS represents 3D scenes as sets of differentiable Gaussian primitives, such as ellipsoids, by iteratively optimizing their parameters, such as pose, scale, and color, to match input images [8]. Once trained, it can generate photorealistic images of the environment even from viewpoints not explicitly captured during training, in a process known as novel view synthesis. Researchers have leveraged its high visual fidelity and fast rendering speed for browser-based remote collaboration [14]. We use it to build an immersive workspace for design activities.

**3D sketching for quick and easy creation of robot shapes and structures.** Sketching is essential for exploring form and function during the early stages of product design. Notable developments in 3D sketching allow designers to quickly visualize products [2] and their kinematic structures [9] as 3D curve networks using intuitive pen and multi-touch gestures. Building on recent work adapting this approach for robot design [10], we facilitate rapid exploration and improvement of robot concepts. Once created, these 3D robot sketches can be viewed at real scale and manipulated in real time within the immersive workspace.

**VR acting for realistic experience of robot movements and services.** Researchers have explored the use of VR to enhance design communication, enabling designers to interact with prototypes in virtual environments while their peers simulate prop movements and provide multimodal feedback [1, 17]. However, these approaches often rely on manually modeled 3D scenes and assets, which can be unrealistic and time-consuming to create. We address this limitation through efficient acquisition of 3D scenes and assets using 3DGS and 3D sketching.

## 3 SYSTEM

Our system is built around three core activities that robot designers perform. These activities allow designers to iteratively explore and improve the form and function of robots to align with user requirements:

1. **Workspace building:** Efficiently acquiring environments and props that provide design context through 3DGS (Figure 2).
2. **3D sketching:** Quickly and easily creating robot shapes and structures through pen and multi-touch gestures (Figure 3).
3. **VR acting:** Realistically experiencing robot movements and services through collaborative role-playing (Figure 4).

### 3.1 Workspace Building

To ensure the designed robot is well-suited for its target environments, our system integrates the acquisition of photorealistic representations of physical environments and props as a core step in the design process. Designers begin by selecting and visiting a location, then recording a video of the location using a smartphone (Figure 2a). The 3DGS pipeline [8] processes the video by extracting frames, aligning camera poses for each frame, and training the 3DGS model to generate a 3D representation of the environment (Figure 2b). Additionally, designers can isolate objects within the environment [12] to create interactive props for making human-robot interaction scenarios richer and more natural.

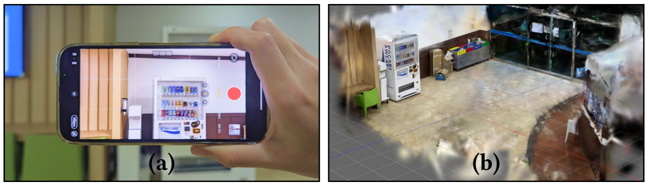


**Figure 2: During workspace building, the robot designer (a) observes a site and records a video, and (b) produces a 3D Gaussian Splatting (3DGS) model of the environment.**

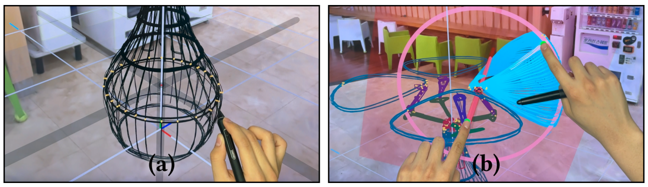


**Figure 3: During 3D sketching, the robot designer creates (a) robot parts consisting of 3D curves and (b) joints connecting them using intuitive pen and multi-touch gestures.**

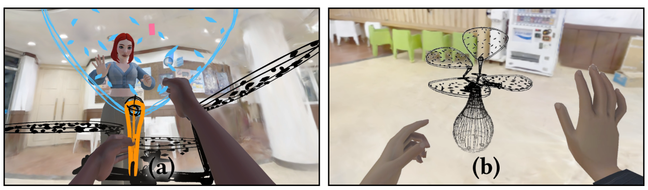


**Figure 4: During VR acting, (a) one robot designer invisibly controls the robot, moving and rotating parts using bimanual grab gestures, (b) while another designer immersively experiences the robot's services.**

### 3.2 3D Sketching

Unlike traditional 3D sketching systems, which typically provide empty canvases, our system allows designers to use the reconstructed workspace as a backdrop for 3D sketching. This approach enables the design of robots with shapes, sizes, and structures that are contextually appropriate for their target environments.

Following the method proposed by Lee et al. [9], designers can create position anchors by tapping on grid lines or existing 3D curves. Doing so creates a sketch plane, which can be moved freely in six degrees of freedom. Designers can then draw 2D curves on this sketch plane, which are projected into 3D space to form 3D curves (Figure 3a). These curves can be segmented into multiple parts by performing crossing gestures similar to coloring. The segmented parts can be repeatedly dragged along with the sketch plane to define desired movements. Based on these movements, the system generates joints, such as hinge, linear slider, curved slider, or ball joints, at appropriate positions and orientations (Figure 3b), providing a kinematic structure to the sketch so that it can be articulated as intended.

### 3.3 VR Acting

After 3D sketching is completed, designers wear a VR headset and enter the same workspace where they sketched the robot. In this immersive workspace, they can directly review the robot at real scale. Additionally, designers can manipulate the robot using the kinematic chain model [6]. With a grab gesture from the non-dominant hand, they can hold a parent part in place, while with a grab gesture from the dominant hand, they can move and rotate a child part. The system then calculates the robot's posture using inverse kinematics [16]. Designers can also grab the same part with both hands to move the entire robot.

The system also allows multiple designers to join the same workspace as either a "human actor" or a "robot actor" (Figure 4a). While human actors have visible VR avatars, robot actors have invisible VR avatars, creating the illusion that the robot is moving by itself when manipulated (Figure 4b). Additionally, robot actors can scale their avatars, allowing comfortable interaction with extremely large or small robots.

## 4 IMPLEMENTATION

We implemented the proposed system and workflow using various software and hardware components (Figure 5). We preprocessed recorded videos using COLMAP [15], which maps video frames to camera poses subsequently used as inputs for training the 3DGS model [8] on a Razer Blade 16 laptop running Ubuntu 22.04, equipped with Intel Core i9-14900HX CPU, 64 GB of RAM, Nvidia GeForce RTX 4090 GPU, and 16 GB of VRAM. After training, we used the SuperSplat editor [12] to isolate interactive props.

We implemented the 3D sketching and VR acting clients using the Unity engine, the 3DGS viewer for Unity [5], the Meta XR and Avatar SDKs, and the BioIK inverse kinematics library [16]. The clients were executed on two Lenovo Legion 5i laptops running Windows 11, equipped with Intel Core i9-14900HX CPU, 32 GB of RAM, Nvidia GeForce RTX 4070 GPU, and 8 GB of VRAM. The laptops were connected to a Wacom Cintiq Pro 24 Touch digital tablet with pen and multi-touch support and two Meta Quest 3 VR headsets, and communicated via LAN.

## 5 EVALUATION

To evaluate the proposed immersive prototyping system and workflow for robot design, we recruited robotics engineers and industrial designers as participants and conducted an intensive design workshop over an extended period. Participants were organized into teams and tasked with using the proposed system and workflow to complete robot design projects across various themes (Figure 6). Afterward, participants shared feedback on usability and usefulness through surveys and interviews.

### 5.1 Participant

We recruited a total of 16 participants, comprising robotics engineers and industrial designers (ages 22-45, 4 female, 12 male). Among them were 5 robotics engineers and 11 industrial designers (P1–14). All but two had prior experience with VR, and none had prior experience with 3DGS. Additionally, two of the authors of this paper (P15, P16) participated in the study.

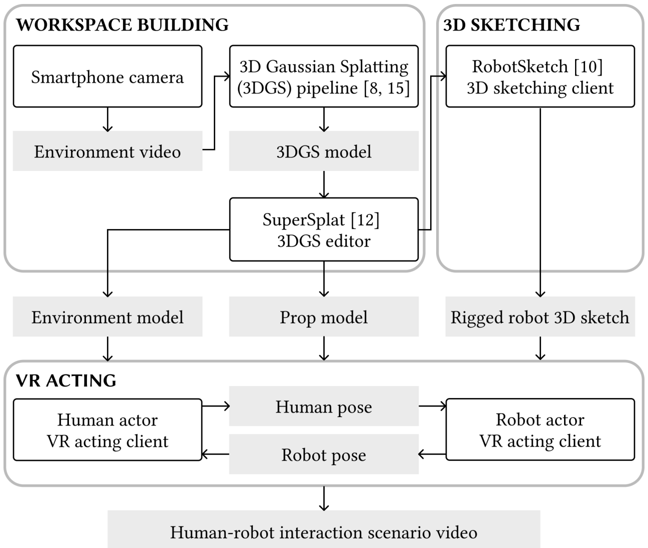


**Figure 5: Data exchange diagram of our implementation.**

The robotics engineers had expertise in robotics AI, bipedal and quadrupedal robot design, and factory automation, with backgrounds ranging from undergraduate students to field experts with over 10 years of experience. Similarly, the industrial designers had expertise in UI/UX, product, and automotive design, with backgrounds also ranging from undergraduate students to field experts with over 10 years of experience.

## 5.2 Project

Each team consisted of four members, including at least one robotics engineer and one industrial designer. To complete a single project, each team participated in four weekly workshops, each lasting three hours. Each team completed projects covering three themes: "Robots for Office," "Robots for Home," and "Robots for Community." Each team was provided with one set of the aforementioned equipment. After completing each project, we shuffled the team members.

## 5.3 Workshop

In the first workshop, the teams brainstormed robot concepts aligned with the assigned theme. The results were drafted as paper posters, outlining each robot's approximate shape, structure, and service scenarios through simple sketches and text (Figure 6a). At this stage, each team also selected and visited environments for training their 3DGS models (Figure 6b).

In the second, third, and fourth workshops, the teams engaged in 3D sketching within the reconstructed workspaces, prototyping the shape and structure of their robots (Figure 6c). They then participated in VR acting to collaboratively bodystorm robot services among them (Figure 6d). Through iterative cycles of 3D sketching and VR acting, the teams improved their robot designs and recorded final scenarios as video clips. At the end of each workshop, the teams shared their progress and exchanged feedback. By the conclusion of the fourth workshop, the teams finalized and presented their multimedia posters.

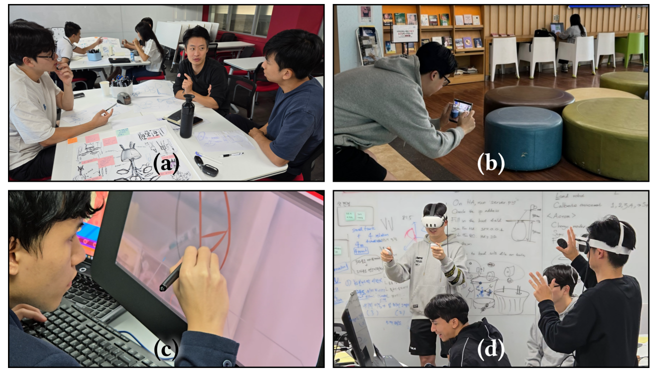


**Figure 6: For each project in the workshop, robot designers: (a) brainstormed robot concepts, (b) visited target environments to acquire their 3DGS models, (c) created robot designs through 3D sketching, and (d) role-played human-robot interaction scenarios through VR acting.**

## 5.4 Survey & Interview

Follow-up surveys and interviews were conducted with 14 participants, excluding the two author-participants. The survey included nine 5-point Likert scale questions assessing the usability and usefulness of our system and workflow. During the interviews, participants reviewed the intermediate and final outputs of the three projects they had contributed to, as well as their responses to the survey questions. Each interview lasted approximately 45 minutes, providing detailed insights into their experiences and thoughts.

# 6 RESULT

The 16 workshop participants, over the course of 36 hours (3 hours × 4 weeks × 3 projects), produced a total of 12 high-quality multimedia posters detailing their robot concepts and 48 video clips illustrating their human-robot interaction scenarios. These projects showcased diverse and innovative robot designs for offices, homes, and communities, some of which are presented (Figures 7-12). Additionally, the scores for each of the 5-point Likert scale survey questions are provided (Figure 13).

# 7 DISCUSSION & LIMITATION

We identified several key benefits and shortcomings of the proposed system and workflow from the surveys and interviews.

**Reviewing robots after quick prototyping.** Participants quickly learned how to use our system (Q1: 3.7 ± 0.4, mean score ± 2 standard errors) and efficiently created desired robot shapes and structures (Q3: 4.3 ± 0.4) suited for intended tasks and functions (Q7: 3.8 ± 0.6). Specifically, the ability to directly manipulate the postures of robots sketched in 3D with their hands in VR allowed designers to easily check their kinematic viability.

For example, P12 discovered that *PenGuard*'s shoulder required a ball joint instead of a hinge joint so that the arm could fold to the side (Figure 11). Similarly, after some trial and error, P3 successfully designed a complex mechanism for *SilboTown*, enabling it to transform from a two-armed robot into a scooter by extending its body, neck, and ears (Figure 12).

## 6.1 Robots for Office


**Figure 7: (a) *Positibo*, the smart Post-it meeting assistant robot, (b) dynamically rearranges Post-it notes at users' requests, (c) stores and restores layouts from previous meetings to maintain continuity, and (d) supports voice-based note search.**

**Figure 8: (a) *ConnecTree*, the elegant networking assistant robot, (b) detects and approaches conversations during meetings and casual gatherings, (c) serves coffee and refreshments with minimal disruption, and (d) uses its display and robotic arms to connect on-site and remote attendees.**

## 6.2 Robots for Home


**Figure 9: (a) *DormBot*, the meticulous dorm supervisor robot, equipped with a pair of manipulators that function as both arms and legs, (b) sorts trash for recycling, (c) organizes incoming delivery packages, and (d) removes outdated bulletin board postings to maintain cleanliness in shared spaces.**

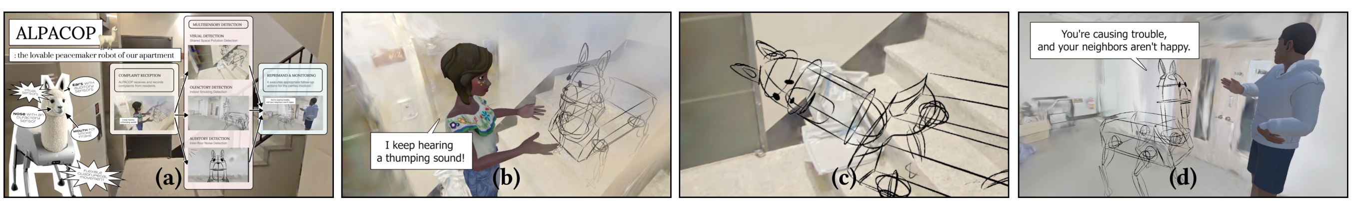


**Figure 10: (a) *AlpaCop*, the charming peacemaker robot for apartment neighborhoods, (b) listens to and registers residents' complaints, (c) monitors its surroundings using advanced sensors, and (d) gently but firmly warns specific residents about inappropriate behaviors.**

## 6.3 Robots for Community


**Figure 11: (a) *PenGuard*, the vigilant crossing guard robot supporting safe commutes for children, (b) assists children at crossings by directing traffic, (c) delivers forgotten school supplies to children on their way to school, and (d) facilitates video calls between lost children and their parents.**


**Figure 12: (a) *SilboTown*, the transforming robot designed for senior lifestyles, (b) encourages physical activities such as ping pong, (c) promotes cognitive activities such as reading, and (d) engages scooter mode to enhance mobility.**

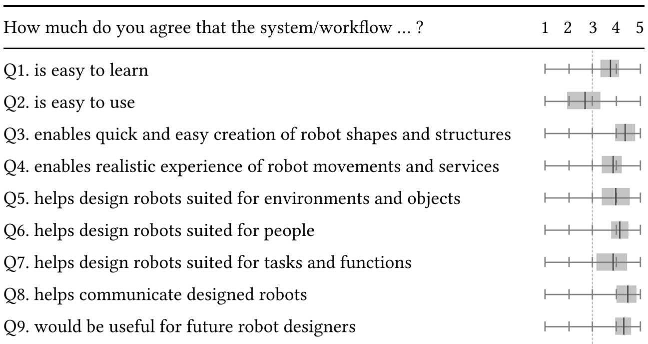


**Figure 13: Results of the 5-point Likert scale survey on usability and usefulness, assessing participants' agreement with the following statements (1: strongly disagree, 2: disagree, 3: neutral, 4: agree, 5: strongly agree, bars: mean score ± 2 SE). An average score of 3.9 indicated an overall satisfactory experience.**

**Improving robots based on contextual insights.** Participants could realistically experience the movements and services of their robots using our system (Q4: 3.8 ± 0.4) and design robots better suited for interacting with target objects in intended environments (Q5: 3.9 ± 0.6). Specifically, by sketching robots and performing immersive role-playing within reconstructed workspaces, designers gained valuable contextual insights that improved their designs.

For example, P2 identified that *DormBot* needed an additional joint in its shoulder to lean over trash bins (Figure 9). Similarly, P9 determined the optimal arm length for *Positibo* to navigate between and collect Post-it notes on a whiteboard (Figure 7).

However, some issues related to immersion were reported. P10 noted that visualizing robots as curves reduced believability. Others noted that the current IK implementation struggled with long chains of complex joints, and that they were unable to grab and move more than two parts simultaneously when both hands were occupied, hindering acting of some concurrent behaviors (P3, 4, 6, 9, 14).

**Infusing robots with human-like interactions.** Participants reported that the system facilitated close communication and empathy-building (Q8: 4.4 ± 0.4), helping them design more human-friendly robots (Q6: 4.1 ± 0.4).

For example, P4 observed that *ConnecTree*'s branch gestures, such as waving for greetings or serving food and drinks, felt organic and natural because they were performed by humans rather than manually keyframed (Figure 8). Similarly, P5 described making eye contact with *AlpaCop* in VR and gaining confidence in its friendly yet authoritative role (Figure 10).

**Seamlessly integrating multiple system modules.** Despite these strengths, participants found the system and workflow relatively challenging to use (Q2: 2.6 ± 0.7), likely due to the implementation of the 3DGS pipeline, 3D sketching, and VR acting as separate modules (P2-4, 6, 9, 13, 14). Addressing this limitation could make the system and workflow more accessible to future robot designers (Q9: 4.2 ± 0.3).

Moreover, the robot shape and structure data created using our system can be exported in the URDF file format, commonly used in robotics, as a reference for detailed engineering. Furthermore, the video and motion data of human-robot interaction scenarios can be utilized to teach and guide robots' services in subsequent development stages.

## 9 CONCLUSION & FUTURE WORK

In this paper, we proposed a novel immersive prototyping system and workflow for robot design, integrating real-world environment acquisition and object segmentation using 3DGS, 3D sketching and rigging of robots with various joint types through pen and multi-touch interactions, and collaborative role-playing and bodystorming in VR using two-handed mid-air gestures.

A total of 16 participants, including robotics engineers and industrial designers with diverse expertise and professional experience, participated in our 12-week workshop, using the proposed system and workflow for a total of 36 hours. Through team projects, they designed new robots for offices, homes, and communities, resulting in 12 creative and compelling robot concepts and 48 human-robot interaction scenarios.

Participants reviewed robots after quick prototyping, improved them based on contextual insights, and infused their designs with human-like interactions. Their feedback highlighted several directions for future research, including improved visualization using 3D surfaces, simultaneous manipulation during locomotion, and the ability to perform 3D sketching directly within VR [10].

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