GeneratiVR: Spatial Interactions in Virtual Reality to Explore Generative Design Spaces

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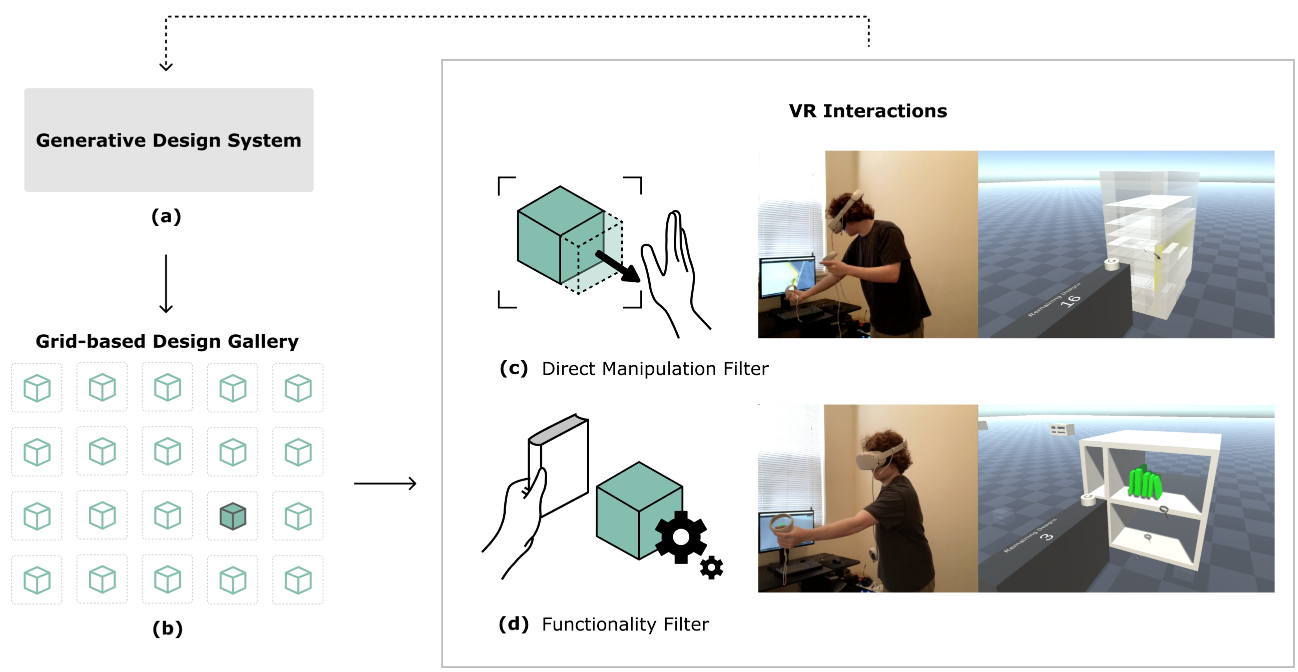

Figure 1: We introduce novel spatial interactions to explore generative design spaces. (a) A generative design system outputs a large design space. (b) The designs are grouped and displayed in a grid view. (c) Users can directly manipulate the design geometry to show their preferences. (d) Users can filter designs by demonstrating desired functionality.

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ABSTRACT

Computational design tools can automatically generate large quantities of viable designs for a given design problem. This raises the challenge of how to enable designers to efficiently and effectively evaluate and select preferred designs from a large set of alternatives. In GeneratiVR, we present two novel interaction techniques to address this challenge, by leveraging Virtual Reality for rich, spatial user input. With these interaction methods, users can directly manipulate designs or demonstrate desired design functionality. The interactions allow users to rapidly filter through an expansive design space to specify or find their preferred designs.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

virtual reality, generative design, design solution exploration

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1 INTRODUCTION

While 3D modeling and CAD software have been critical in the design process for years, more recently developed generative design systems have given designers the ability to easily explore thousands of candidate designs [1, 7, 14]. These systems also allow designers to utilize optimization methods to explore and evaluate the generated designs with a lower time overhead than what was possible in the past [16]. With generative design systems, designers provide high-level specifications and constraints, receiving many geometries that satisfy these goals as outputs. At the same time, the creation of an expansive design space drives a need for designers to efficiently navigate through the vast quantities of options now available. Additionally, the top-down approach of generative design can make it difficult for designers to conceptualize an iterative process where they can adjust both high-level goals and lower-level geometries to reach their desired outcomes. Therefore, it is imperative to develop interaction methods that allow designers to incorporate the benefits of generative design seamlessly into their workflows.

Many efforts to address the challenges of exploring a high-dimensional design space (e.g., from a generative algorithm) focus on automatic sorting and clustering algorithms or interactive visualization tools. For example, designers can choose parameters and a similarity measure to reduce the candidate designs to a manageable, but differentiated, set [4]. However, this method requires the designers to explicitly define the 3D model parameters they deem important. Alternatively, systems like Dream Lens allow designers to use an example-based approach, without having to express what the desirable features are. To avoid relegating designers to a purely passive evaluator role, Dream Lens also introduces selection tools that allow designers to actively interact with the design geometries [12]. Systems like Forte begin to incorporate human guidance by allowing users to modify inputs and outputs of generative design through sketching [3].

Notably, these interactions take place in traditional 2D environments as is typical for 3D modeling and CAD software. However, virtual reality (VR) provides a relatively untapped medium for allowing designers to interact with generative design systems and outputs, which we address in this work. VR interfaces have been promising for design because of their ability to facilitate spatial interaction with 3D objects and simulate environments in which designs might operate in the real world [20]. The V-Dream system begins to tackle the exploration of large-scale design spaces through visualization within VR, allowing users to cluster and inspect designs spatially [8]. Calliope, on the other hand, utilizes VR in generative design by allowing mesh manipulations, mutations, and combinations, focusing on allowing the user to update the design's geometry [19].

In this paper, we focus further on the particularly unique benefits of interacting with generative design in VR, including the ability to manipulate objects with gestures and the ability to enact scenarios in which a design might be used [18, 20]. As our key contribution, we present prototypes of spatial interaction techniques in VR that allow users to actively interact with designs to explore the design space and narrow down candidate designs to their preferred style and function. These interactions, shown in Fig. 1, include 1) gesture-based direct manipulation to indicate preference for design features and 2) action-based demonstrations of desired design functionality. The interactions are explored through the example of designing storage shelving. Here, direct manipulation can be used to explore attributes such as width, height, or shelf location, while items can be directly placed in the shelves to ensure that the design functions as desired (i.e. supports the items). These spatial interactions can assist humans in navigating a large design space and getting a better sense of how their designs might function in the relevant environment.

2 RELATED WORK

Emerging machine learning techniques have facilitated advancements in the field of generative design, yet their application can depend on whether performance measures can be defined quantitatively. In the case of complex, multi-objective design problems (e.g. the design of a consumer product) human judgement may also be needed. While generative algorithms can be implemented to find many possible design solutions, it is then necessary to reduce the number of options to a subset that is feasible for a human to evaluate [9]. Subsequently, how the human explores the remaining design space becomes increasingly important. The key components to consider for our work, therefore, are the way in which humans explore the generated designs and the relevant VR interaction space.

2.1 Design Space Exploration

There have been many studies to visualize a design space and allow designers to explore multiple design alternatives in the generative design literature. This section outlines methods that have been developed to review both whole designs and specific design dimensions.

2.1.1 Exploring Design Galleries. One method of exploring the design space focuses on the visualization of multiple designs holistically. An early work by Marks et al. proposes a gallery-based

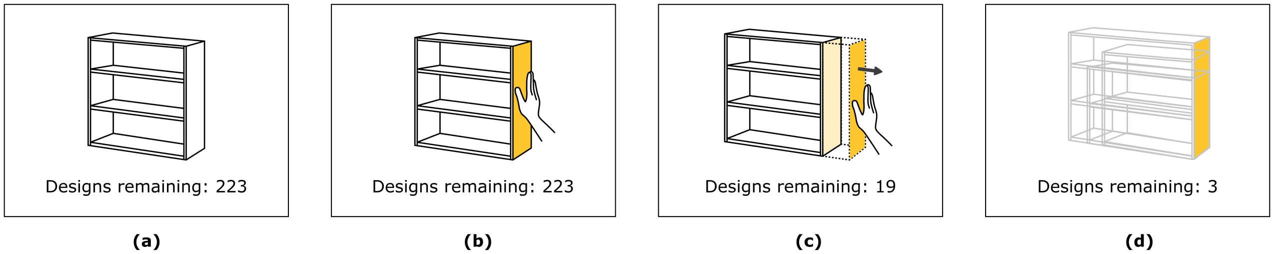

Figure 2: Direct manipulation filter: (a) Users first select an example design from the grid. (b) They select the part of the design they would like to modify. (c) They drag the feature to demonstrate their preferred position, and can see how many designs fulfill their preference in real-time. (d) When they let go, only designs that satisfy the preference remain and are shown as ghost shelves.

interface which displays a selection of representative designs using a dispersion and arrangement algorithm, allowing users to easily and intuitively browse through complex design spaces [11]. Following research on assessing design alternatives frequently applies this idea of a "Design Gallery." For instance, Erhan et al. develop a method for designers to select and reduce the gallery of design solutions by filtering based on similarity measures and visualizing the reduced design space in clusters [5]. Similarly, GEM-NI adopts a design gallery interface for parameter range exploration and design generation, enabling users to create additional alternatives using the designs in the gallery [21]. Dream Lens uses a grid-based gallery view, which we adopt in this work, to display the design space, allowing users to visualize and sift through alternate designs [12]. While visualizations such as design galleries target only one of the sensory experiences available in VR, they remains critical for the exploration of generative design outputs. To this extent, researchers have created a generative design solution space visualization specifically in VR. Using V-Dream, users can navigate, organize, and cluster a solution space to locate or narrow down potential ideal design solutions from the generated outcomes [8]. A major challenge this paper tackles is mapping these general exploration methods to interactions that leverage the advantages of VR.

2.1.2 Exploring Design Parameters. Another common strategy for design space exploration is to allow the designer to interact with design parameters instead of full designs. A straightforward approach to this strategy is to represent the parameters as a series of sliders, or "interactive parallel coordinates" and let the designers drag the sliders around to test out designs. Mohiuddin et al. propose several interactions that can improve parallel-coordinate-based exploration such as sketching lines to select points on multiple sliders at once [13]. Bao et al. offer an alternative to parallel coordinates by sampling the parametric space for several discrete designs and then representing the design space as a 2D "navigation polygon" [2]. However, when exploring design spaces, it can be necessary to distinguish whether a design fulfills an intended function, rather than simply exploring form. Design parameters can affect the design's function, but not all combinations of parameters lead to a design that satisfies the desired function. Fab Forms addresses this challenge by allowing the designer to interactively change parameters while automating checks for functionality, preventing designers from navigating into invalid regions of the design space [17]. Bao et al. address the dimension of function in a different way by allowing design performance measures that can be measured algorithmically (e.g. weight, material cost) to be treated as additional parameters that designers can explore. Furthermore, this method allows designers to directly manipulate the parts of a design those parameters relate to. If one design is worse than another in every performance metric, then it can be excluded from the design space [2]. Schulz et al. then describe an algorithm for approximating and visualizing the set of remaining designs, called the "Pareto Front," where switching from any design to another will cause a tradeoff between performance metrics [15]. The Dream Lens system also allows users to select and filter the design options to explore the relationships between parameters and design performance, particularly along the Pareto Front [12]. These works highlight the importance of exploration using a design's specific features as well as the relationship between design parameters, design function or performance, and the resulting design, which we incorporate into our VR interactions.

2.2 Mixed Reality Interactions for Design

Compared to other traditional 3D design and modeling tools, VR elevates immersion and spatial awareness for users, allowing designers to interact with virtual objects utilizing a wider range of senses [20]. The exploration of large-scale data and the ability to perform spatial navigation tasks while analyzing design instances is a promising step for future generative design systems. However, currently, systems like V-Dream feed static solution sets into the VR scene for exploration [8]. Thus, while whole designs can be visualized, specific design dimensions cannot be explored. Dream Lens addresses direct interaction with design geometry in a traditional software environment, letting users use tools like a "chisel" to select areas of geometry to remove from 3D models [12]. However, a key interaction type that has been explored for design in mixed reality is gesture, which can also allow the exploration of designs along specific parameters. Specifically, prior research has focused on the detecting of gesture-based interactions in VR for design operations [6]. This gestural capability is leveraged by Urban Davis et al. to allow users in VR to inspect visual elements of results from

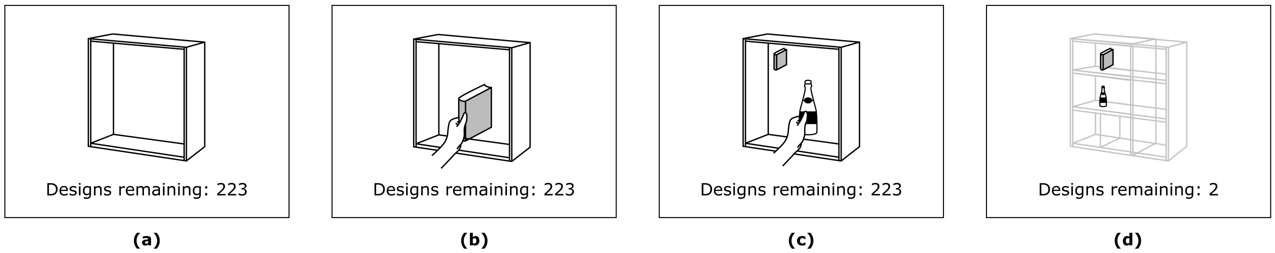

Figure 3: Functionality filter: (a) Users see a bounding box based on the space of remaining designs. (b) They create objects of desired sizes. (c) They place the objects in their preferred positions. (d) They are shown the designs that satisfy their demonstrated function (i.e., supporting the items in the specified locations).

generative design systems and sculpt or manipulate meshes in real-time. Combining a visualization system with gestural manipulation, this work sets the stage for embodied interactions with generative design spaces [19]. Furthermore, in augmented reality, researchers have created the process of "Situated Modeling." Situated modeling introduces shape-stamping methods where a user models with tangible primitive 3D shapes such as cubes or cylinders [10]. In our work, we utilize these principles, for instance, by allowing users to stamp virtual shapes in 3D space that correspond to physical shapes that might interface functionally with the design in reality. We also incorporate gestural interactions that facilitate lower-level exploration along design parameters. These VR interactions allow users to play a more active role in exploring generative design spaces as opposed to conveying high-level intent and letting the system do the rest.

3 GENERATIVE DESIGN SETTING

For the sake of exploring different interactions, the sample domain of shelving design, where human judgements are necessary, is used. For example, preferred designs may vary based on the necessity to store specific items or based on available room space. A six-dimensional model is created in Rhino 3D and Grasshopper, a common toolchain in parametric industrial design and architecture. The model is a simple shelf with width, height, depth, wall thickness, shelf location, and support location parameters and is used to create hundreds of designs for the VR evaluation. A two-way connection is established between Rhino and Unity 3D, the engine with which the VR application is developed, using C# and the RhinoCommon API[1]. The VR user experience is intended for a stationary user, perhaps sitting or standing at a desk. For the purposes of remaining controller-agnostic, each tool uses at most the grip and trigger buttons and all other user input (e.g. an undo button) is done using virtual physics buttons that the user must physically reach out and press. In the GeneratiVR workflow, the designer starts with the large list of generated shelf designs, supported by a gallery-like visualization that allows them to explore several designs at once. The designer can then narrow down and choose designs or design parameters. To this end, we explore two key spatial VR interactions: a direct manipulation filter and a functionality filter, both discussed below and shown in Figs. 2 and 3.

[1]Connection between Rhino and Unity3D is based on code from https://github.com/jhorikawa/GrasshopperPlayerWithRhinoInsideUnityTemplate

4 INTERACTION TECHNIQUES

4.1 Direct Manipulation Filter

The direct manipulation filter aims to allow gesture-based interactions so that a user can explore along various design dimensions and "show" the system their preferred designs. Designers can drag physical parts of designs into desired positions, filtering out the remaining designs whose physical parts do not match the given positions. For example, suppose a designer wants shelves whose height matches the designer's waist level or shelves that look more like a square. After navigating to the direct manipulation filter, the designer is shown a set of semi-transparent shelves from the current set of potential designs. These "ghost" shelves give an at-a-glance summary of what the current design space looks like, and serve the dual purpose of acting as handholds for the designer to manipulate. The designer can use the controller to grab the top of one of the ghost shelves, and drag it up or down to their preferred level. They can also drag the side of the shelf to extend or reduce the shelf width. As shown in Fig. 2, the selected portion of the design turns into a slider representing the design dimension of interest. As the designer drags the selected portion of the shelf, the evaluation system continuously updates the ghost shelves to reflect the current list of shelves that match the new filter. Once the designer is satisfied with the width of the shelf, for example, they have a few options for subsequent actions. They can view the new subset of the design space, filter based on another dimension, use a different filter, or undo the filter. In this way, the user can narrow down the design space as well as build a better spatial understanding of the design's dimensions.

4.2 Functionality Filter

The functionality filter aims to allow designers to represent constraints or desired function without having to explicitly modify the design's geometry. In the general case, the functionality filter allows the user to act out a desired physical interaction with an object as it were there. Then, data from that interaction is used to filter out object designs that would not have allowed the recorded actions to take place. In our shelf demo, the physical action is placing an

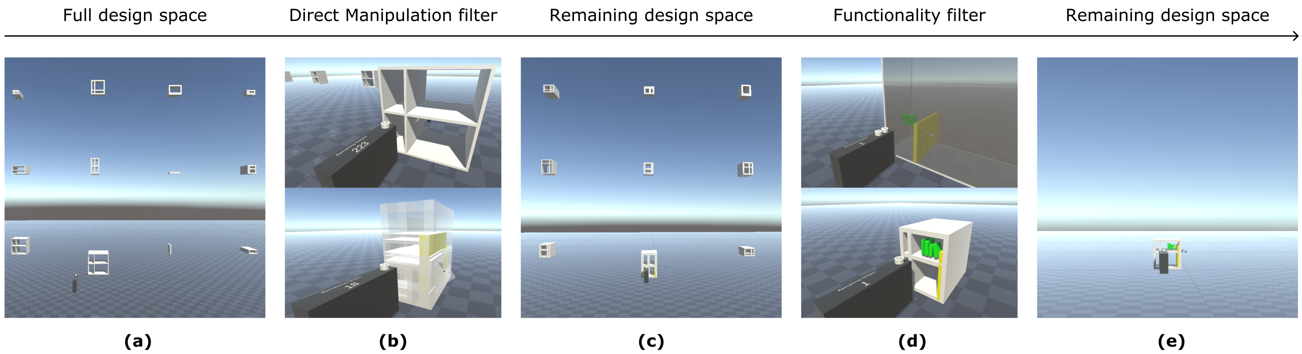

Figure 4: Interaction workflow in our implemented system: (a) Users view the grid gallery of designs. (b) They select a starting design and apply a direct manipulation filter to show preference for physical appearance or a design parameter (e.g. width). (c) They explore the gallery of the new design space with fewer alternatives. (d) They apply the functionality filter by placing objects (e.g. books) where they would like them to be. e) They are left with a remaining design space that fulfills their demonstrated preferences.

object on the shelf. The designer is shown a bounding volume of the current shelf designs, seen in Fig. 3. They can use the VR controllers to create and place blocks of various sizes (representing different sizes of items that may sit on the shelf) into the volume as if their desired shelf is already there to hold the items up. Once the user places their items, they press a physics button, and each of the current potential designs is tested against the block positions using ray and cube intersection tests. If a shelf design is unable to hold the block, either because it physically intersects the item's position or does not have a surface beneath a block to hold the block up, the design is filtered out. For instance, suppose the user has a set of books to place on the shelf. The user can generate these books as virtual blocks and place them at the location they would want the books to be in their room (e.g. within an arms length from standing up). The filter then allows the user to see the subset of designs that would support the books at that location. The designer can repeat this process with other items they may want to place. Thus, the functionality filter allows the user to select designs that fulfill general requirements for use, as well as simulating what that use might entail.

5 INTERACTION WORKFLOW

The interaction techniques are used to explore the design space in VR using a design gallery view. The main method of design visualization places the designs in a two-dimensional grid in front of the user throughout the exploration and narrowing process (i.e. both before and after filtering designs). Grid views are common in other interfaces, such as photo galleries or online shopping. A familiar interface may allow the user to more intuitively navigate through the designs, motivating this choice. Previous research also demonstrates the usefulness of sorting designs into groups based on some algorithmically defined measure of "similarity." Our visualization tool supports such an approach by including a group menu, consisting of a grid of cubes representing each group. Each cube contains a representative design from the group, and can be selected when the user points and clicks their controller. When a cluster is selected, the grid of clusters translates behind the user and the grid of the selected cluster is displayed. Users can return to the inter-cluster grid by pointing and selecting it. The grid is navigated by the user grabbing and dragging the space in front of them using the VR controllers, which drags the design grid in the same direction. The design at the center of the grid, closest to the user, is pushed forward towards the user to allow examination of individual designs. This gives the user a better sense of the scale of the design, as they are able to stand directly next to the shelf. The user can begin using the spatial interaction techniques on any design that is in front of them. As shown in Fig. 4, layering the filters sequentially can reduce the designs left in the grid, though the filters can be removed at any time to allow broader exploration. As the user filters using the spatial interactions, consecutively fewer designs are shown in front of them, allowing them to narrow the design space to their preferred design types.

6 CONCLUSION AND NEXT STEPS

Large-scale solution sets obtained through generative design processes allow designers to more exhaustively search for the best possible design, but add the challenge of finding intuitive and useful mechanisms to conduct this evaluation. In this work we present spatial interactions that allow humans to actively explore a large design space in virtual reality with the ultimate goal of allowing them to guide the process of generative design. We develop the direct manipulation and functionality filters, as well as a visualization system that connects these interactions, providing a way for users to quickly narrow the design space to suitable solutions.

The current system lays most of the groundwork needed for conducting studies on how interactions in VR can be used to guide the generative design process with human feedback, although formal evaluation studies have not yet been conducted. Our immediate next steps will consist of quantitatively and qualitatively evaluating how designers might actually incorporate these types of interactions into a design process, as well as their benefit on generating desirable designs. Although not implemented yet, the outputs from the interactions can be selected as a final design or sent back to the generative algorithm as the basis for generating a new design space. The generative algorithm can also incorporate more objective performance metrics as a pre- or post-filtering step. This feedback loop will be incorporated in the future.

There are some additional points that will be considered for future work. The interactions have only been tested using the design of a shelf as an example, though there is a clear application to other furniture-like designs such as desks, tables, or cabinets. Furthermore, while the current implementation requires the programmable specification of the parametric design in Grasshopper, designers may be more comfortable using various other 3D modeling software for their initial design. Other challenges include the necessity in our system to explicitly define the parameters that map to the desired geometric manipulations. There is a tradeoff between finer control allowed by this level of specification and the ease of interaction that may come with only having to specify higher-level intent. Furthermore, it may be difficult to apply these interactions to designs with more complex geometries, as the mapping between high-level intent and lower-level design parameters may be more unclear. However, application to more complex geometry can be achieved through allowing more detailed gestural input. Thus, the spatial interactions created here will be evaluated along with other prototype interactions that show promise as mechanisms for allowing informative human feedback to enable iterative generative design.

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