Title	VR Space Drawing with Adjustable and Directional Brush
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Citation	
Issue Date	2026-03
Type	Thesis or Dissertation
Text version	author
URL	https://hdl.handle.net/10119/20500
Rights	
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VR Space Drawing with Adjustable and Directional Brush

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Virtual reality (VR) offers a promising platform for three-dimensional shape modeling, providing immersive environments where users directly manipulate objects in spatial contexts. Unlike traditional desktop modeling restricted to two-dimensional screens and mouse/keyboard inputs, VR enables intuitive 3D modeling through six-degrees-of-freedom (6DOF) interaction. Users can reach into virtual space, manipulate creations from any angle, and receive immediate visual feedback, closely mirroring real-world sculpting and drawing experiences.

Existing VR spatial drawing tools, however, face limitations. Line-based methods produce simple strokes lacking volumetric structure, while curve network approaches require post-processing that may not preserve intended surface details. Ribbon-alike brushes generate surface geometry immediately but are restricted to line-segment cross-sections. Furthermore, these brushes require simultaneous control of trajectory and orientation through wrist rotation. Due to anatomical constraints, the wrist cannot rotate continuously, and the distance between the drawing point and wrist amplifies tremors. Achieving smooth, precise control over cross-section orientation remains extremely challenging.

From a geometric perspective, ribbon-alike strokes are a special case of generalized cylinder generation, where a line segment is swept along a trajectory. The generalized cylinder paradigm creates 3D surfaces by sweeping arbitrary 2D profiles along paths. While widely adopted in desktop CAD, no existing VR system adequately applies this to enable manipulation of both arbitrary cross-sections and curve trajectories in immersive environments. This research addresses three questions: extending cross-section flexibility beyond line segments to support arbitrary shapes and real-time deformation; improving brush drawing control without requiring simultaneous real-time wrist control; and developing intuitive VR interfaces for direct manipulation of these components.

To address these challenges, this thesis presents a VR spatial drawing system applying the generalized cylinder paradigm. The system extends ribbon-alike brush approaches by supporting user-definable cross-sections and real-time morphing. The core methodology comprises shape and path definition.

For shape definition, profile curves utilize a graph-based structure. Each brush shape is a 2D graph where vertices carry coordinate attributes and edges define connectivity. This supports open polylines, branching structures, and non-manifold configurations. For smooth transitions, linear blend shapes interpolate between a base shape and multiple morph targets, computing vertex positions as weighted combinations of displacement vectors.

Path definition utilizes sequences of control points interpolated using Catmull-Rom splines to form smooth C^1-continuous curves. Each point stores position, unit quaternion orientation, local scale, and morph weights. Catmull-Rom splines provide interpolation (passing through points) and locality (segment influence limited to four points) without excessive computational overhead. At each point, cross-section orientation is specified through rotation angles, particularly rolling, allowing precise control over how the profile twists along the path.

The proposed system provides three integrated interfaces. The drawing interface allows the creation of 3D strokes via a trigger-based workflow. When the trigger is pressed, a control point is placed at the controller position; rotating the controller during placement sets the rolling angle. This approach separates trajectory definition from orientation control, solving the difficulty of mastering simultaneous control in continuous drawing. The base shape editor provides tools for defining cross-section geometry through vertex placement, snapping, and branching. The morph editor enables the definition of deformation targets for real-time interpolation during drawing.

Real-time mesh generation is achieved through synchronized multi-parameter interpolation. Position uses Catmull-Rom splines, orientation uses spherical linear interpolation (Slerp), and appearance/morph parameters use linear interpolation. Final world-space vertices are computed by transforming morphed local coordinates using the interpolated parameters. Triangulation derives directly from the cross-section graph, naturally handling non-closed topologies and branching forms.

Two experiments evaluated the system. Experiment 1 assessed usability and creativity support with 12 participants completing tasks at three difficulty levels. Participants used the Creativity Support Index (CSI) and System Usability Scale (SUS) questionnaires. Experiment 2 was a comparative study where 4 participants compared the proposed system with two reproduced baseline ribbon-alike brushes: one using direct wrist pose mapping and one with modified orientation handling. Neither baseline allowed custom cross-sections, providing a controlled comparison.

Quantitative results from Experiment 1 showed the system provides strong support for creative work, with a CSI score of 77.10/100 and a SUS score of 67.29/100. CSI subscale analysis revealed high ratings for immersion (4.50/5) and quality (4.33/5), with satisfactory scores for exploration, intuition, and playfulness. The pattern of high CSI and moderate SUS scores suggests a higher barrier for operational mastery but strong creative capabilities once users are familiar with the interface.

In Experiment 2, participants showed a 100% preference for the proposed system over both baseline ribbon brushes, with a mean preference rating of 4.25/5 compared to 2.13/5 for baselines. Qualitative feedback emphasized that 3D modeling fundamentally requires volume rather than just surfaces. The ability to define arbitrary cross-sections enables greater creative expression and more predictable modeling results. Participants reported an initial learning cost but noted substantial efficiency gains after practice, describing the modeling logic as clear. Suggestions for improvement included precision aids like grid snapping and direct parameter control through thumb-sticks.

This thesis demonstrated a VR spatial drawing system applying generalized cylinder modeling. By controlling brush drawing through user-definable cross-sections, real-time morphing, and separated orientation control, the system significantly expands geometric expressiveness. Evaluation results show the approach provides considerable creativity support with acceptable usability. Primary contributions include the development of a unified framework bridging CAD-like modeling with immersive drawing, the expansion of expressiveness via graph-based representation with separated control, and empirical validation of user preference over traditional ribbon-alike approaches. The key insight is that volumetric control addressing limitations of ribbon-alike brushes, combined with separated trajectory/orientation control, offers a new direction for VR-creative modeling and prototyping.