Sketching for Insight: Trajectory Retrieval in VR with Flotation Data

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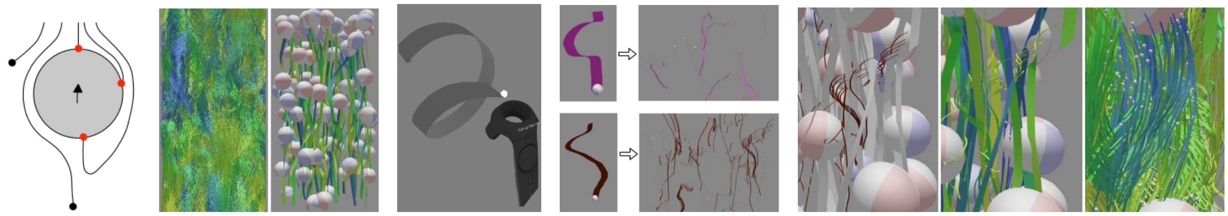

(a) Domain expert expectations of particle-bubble interactions

(b) Unfiltered dataset visualized using color-coded trajectory ribbons (time: yellow to blue) and spheres representing bubbles

(c) Sketching interaction performed using the VR controller

(d) Sketch of planar C-shape path (purple) with a few retrieval results and a refined 3D spiral-like sketch (brown) revealing additional results

(e) Detail of retrieval result for spiral-like sketch (left). Time-encoded views and alignment with bubble trajectories confirmed that the retrieved patterns were caused by rising bubbles (middle), previously obscured in the dense dataset (right).

Figure 1: Illustration of an exploration scenario in a flotation dataset.

Abstract

We explore sketch-based trajectory retrieval in virtual reality (VR) as a method for analyzing dense 3D motion data. Using a flotation simulation—an industrial particle separation process in which rising air bubbles collect material in fluid mixtures—as a challenging testbed, we investigate how immersive sketching can support visual querying and hypothesis exploration. Our tool allows users to sketch query paths directly in 3D space to retrieve similar motion patterns. Structured tasks and expert feedback reveal both the potential of this approach for exploratory trajectory analysis and its current limitations in precision and adaptability.

Index Terms: Trajectory Retrieval, Temporal Data, Interaction Design, Sketching, Data Analysis, Virtual Reality, Flotation.

1 Introduction and Motivation

Analyzing motion in three-dimensional space is a common challenge in scientific visualization [2]. Trajectory data—such as particle paths in fluid simulations—are often dense, complex, and difficult to interpret using traditional 2D visualizations or static views due to heavy occlusions. Shape-based retrieval mitigates occlusion by filtering trajectories according to geometric similarity, allowing analysts to focus on relevant motion behaviors [3]. While automated techniques such as clustering can reveal general patterns, they often lack flexibility for exploratory analysis.

In this work, we explore immersive 3D sketching as an input modality for interactive trajectory retrieval. Prior research has shown that mid-air sketching in VR supports the expression of conceived shapes [4], making it a promising method for visualizing hypotheses about motion and using them as query inputs. While trajectory analysis in VR has been studied, existing approaches have not leveraged sketching as a direct input technique. VR environments enable embodied navigation and natural spatial interaction—features that are particularly well-suited for reasoning about complex 3D motion, where spatial structures are often difficult to interpret on flat displays due to clutter and occlusion.

We evaluate sketch-based trajectory retrieval in VR using a flotation simulation—a challenging real-world case from mineral processing—to assess how immersive sketching supports pattern discovery, hypothesis exploration and where its limitations arise.

2 Methods Overview

We developed an immersive analysis tool for exploring 3D trajectory data using sketch-based retrieval. Users draw motion patterns in space using a VR controller, and the system retrieves similar segments from a dataset based on shape similarity, shown in Figure 1.

Visual Representation. Trajectories are rendered as ribbons to enhance spatial perception compared to lines with less occlusion than tubes. Time is color-coded from yellow to blue, offering perceptual clarity through a brightness gradient from bright to dark while providing better distinguishability than single-hue shading.

Spatial Interaction Design. Users can freely navigate the VR environment by rotating, translating, and scaling the dataset. The interface is designed for embodied spatial interaction, enabling direct engagement with both the data and the retrieval process, following principles of immersive analytics [1]. Filtering options such as trajectory length or spatial origin help narrow the dataset, but due to its density, this filtering alone does not sufficiently reduce visual clutter to reveal overall motion patterns. Although flotation-specific filters were included to support the use case, the interaction design remains domain-independent.

Sketch-Based Retrieval. To define a query, users sketch a trajectory in 3D by moving the VR controller through space as shown in Figure 1c. This direct spatial input allows users to express motion intent in the same space as the data, improving alignment between the query and visual interpretation. The system encodes both the sketch and dataset trajectories using symbolic representations and computes similarity via a normalized weighted edit distance [3], supporting partial matches and invariance to translation, rotation, and scale.

In addition to freehand sketches, users can extract segments from existing trajectories and reuse them as query inputs. This approach leverages actual motion data and supports iterative refinement during exploration.

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3 USE CASE: FLOTATION ANALYSIS

To evaluate the practical utility of sketch-based trajectory retrieval in VR, we applied the method to a complex dataset from a flotation simulation—a particle separation process where air bubbles rise through fluid to collect valuable particles, resulting in intricate 3D motion patterns shaped by turbulence, gravity, and collisions.

Dataset Characteristics. The dataset, generated through direct numerical simulation [5], includes 135 bubble trajectories (3D position and orientation) and over 4 million particle trajectories in a periodic 3D domain simulated for 560 time steps over 0.5 seconds. These unfiltered trajectories are shown in Figure 1b.

The trajectories vary in length and complexity, presenting a rich and challenging case for interactive exploration. Their inherently three-dimensional nature makes them particularly well-suited to analysis in an immersive VR environment.

Analysis Tasks. Together with a domain expert, we defined four exploratory tasks to guide the use of sketch-based retrieval, reflecting common goals in trajectory analysis for flotation data:

- **T1:** Characterize typical bubble motion (e.g. straight paths),
- **T2:** Identify common particle motion patterns,
- **T3:** Locate regions of similar particle motion,
- **T4:** Analyze particle–bubble interactions.

4 EXPLORATION INSIGHTS

To gain initial insights into how immersive sketch-based trajectory retrieval can support practical analysis, we conducted exploratory sessions with a domain expert in fluid mechanics using the flotation dataset. The expert performed the analysis in person, while the developer observed without intervening. A follow-up semi-structured interview provided additional insights into the user experience.

Example Scenario. To illustrate how the system supports insight generation, consider the scenario shown in Figure 1. The domain expert began with a planar C-shaped sketch, drawn in a single plane rather than utilizing the full 3D space. This sketch reflected a 2D expectation of particle deflection around rising bubbles (T4), as shown in Figure 1a. The initial retrieval confirmed this behavior, validating this hypothesis. To explore more complex motion, the developer refined the sketch into a 3D spiral path that fully utilized 3D space, revealing additional instances and regions with coordinated particle behavior (T3) shown in Figure 1d. Time-encoded views confirmed that rising bubbles caused these patterns, which had been obscured in the dense dataset shown in Figure 1e. This scenario highlights how 3D sketching can uncover spatial motion behaviors that are difficult to isolate through planar input or filtering alone.

Retrieved Motion Patterns. Sketch-based retrieval revealed interpretable motion types, including C-shaped paths around bubbles, spirals indicating turbulence (T2), and V-shaped turns linked to wake entry (T4). Straight or curved lines reflected undisturbed paths (T1). These patterns aligned with domain expectations, supported hypothesis-driven analysis, and uncovered additional behaviors such as group motion (T3).

Interaction Behavior. In the analysis sessions, different sketching strategies emerged based on user experience. The domain expert primarily sketched simple, planar shapes, reflecting expectations grounded in 2D representations. Despite the availability of full 3D input, planar sketches were often sufficient to retrieve relevant motion patterns. The option to refine queries by selecting segments from retrieved trajectories proved especially valuable for precision. The developer, more comfortable with immersive interaction, used 3D sketches to explore more complex spatial patterns. This approach revealed motion behaviors that planar sketches had missed, illustrating the potential of 3D sketching for spatial reasoning.

5 LIMITATIONS AND CHALLENGES

While the sessions demonstrated the system's potential, several limitations emerged. First, freehand sketching in mid-air lacked precision, often resulting in approximate rather than exact matches. Second, in some cases, it was unclear why certain trajectories were retrieved, highlighting the need for clearer visual feedback on similarity to the query. Additionally, the retrieval algorithm would benefit from greater adaptability to specific datasets; for instance, incorporating spatial sensitivity to orientation of the sketch in world space would make semantic sense in our use case. Finally, our findings are based on a limited number of analysis sessions with only a few users. While they suggest that immersive sketch-based retrieval holds promise for exploratory trajectory analysis, broader validation through a comparative user study is needed to generalize these results.

6 CONCLUSION AND IMPLICATIONS

This work presented insights from applying immersive sketch-based trajectory retrieval to a complex scientific dataset involving particle and bubble motion in a flotation process. The flotation domain served as a challenging testbed, but the tool is adaptable to other datasets and well-suited for dense 3D motion data.

Our analysis sessions showed that immersive sketching supports visual hypothesis exploration. Simple planar sketches were often sufficient to retrieve meaningful patterns, which could then be refined through 3D sketches or by selecting trajectory segments from the results. This workflow facilitated the discovery of motion behaviors that would be difficult to isolate using filtering or static views alone due to heavy occlusions.

The analysis sessions also revealed limitations: 3D sketching lacked precision, retrieval results were sometimes hard to interpret, and the algorithm would benefit from more adaptability to domain-specific requirements such as the direction of motion.

Our findings suggest that immersive sketching is a promising interaction technique for exploratory trajectory analysis. Future work should focus on improving sketching guidance, enhancing retrieval interpretability, and evaluating the method through comparative user studies.

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