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Article

Developing Virtual Reality Visualizations for Unsteady Flow Analysis of Dinosaur Track Formation using Scientific Sketching

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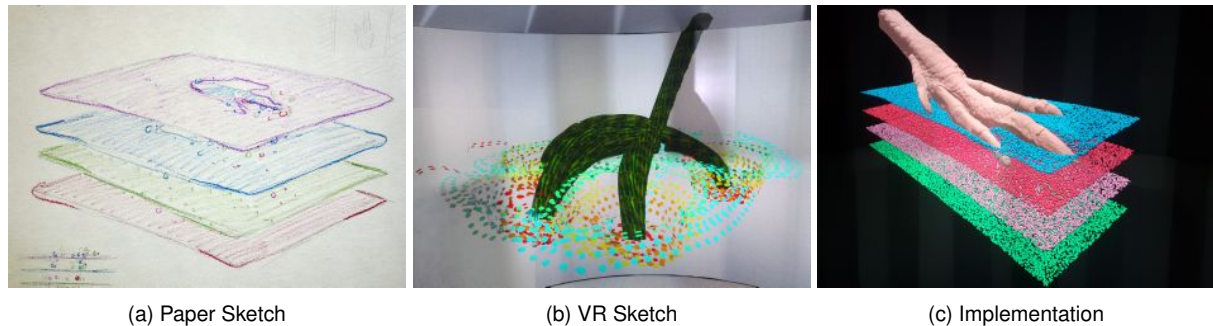(a) Paper Sketch   (b) VR Sketch   (c) Implementation

Fig. 1: An example of results from different stages of our collaborative visualization design process: from paper (a) and VR sketches (b) created by art students to the interactive data-driven implementation (c).

Abstract—We present the results of a two-year design study to developing virtual reality (VR) flow visualization tools for the analysis of dinosaur track creation in a malleable substrate. Using Scientific Sketching methodology, we combined input from illustration artists, visualization experts, and domain scientists to create novel visualization methods. By iteratively improving visualization concepts at multiple levels of abstraction we helped domain scientists to gain insights into the relationship between dinosaur foot movements and substrate deformations. We involved over 20 art and computer science students from a VR design course in a rapid visualization sketching cycle, guided by our paleontologist collaborators through multiple critique sessions. This allowed us to explore a wide range of potential visualization methods and select the most promising methods for actual implementation.

Our resulting visualization methods provide paleontologists with effective tools to analyze their data through particle, pathline and time surface visualizations. We also introduce a set of visual metaphors to compare foot motion in relation to substrate deformation by using pathsurfaces. This is one of the first large-scale projects using Scientific Sketching as a development methodology. We discuss how the research questions of our collaborators have evolved during the sketching and prototyping phases. Finally, we provide lessons learned and usage considerations for Scientific Sketching based on the experiences gathered during this project.

Index Terms—Virtual Reality, Scientific Visualization, Flow Visualization, Design Study

✦

1 INTRODUCTION

We present a design study of using virtual reality (VR) visualizations to analyze dinosaur footprint formation. Large-scale simulations of substrate flow have recently been used to explore the relationship between track morphology and foot movement by combining data from modern birds and fossilized specimens found in the field. However, the spatial complexity of these unsteady flow datasets make it difficult to analyze them using off-the-shelf visualization tools. We designed multiple VR visualizations that help paleontologists explore their simulation data with visual metaphors tailored to their specific research questions. The iterative development process spanned a period of two years with frequent progress meetings. An integral part of the development was the inclusion of students in a VR visualization design course. These students sketched potential visualization and interaction techniques in VR, guided by our collaborators using the *Scientific Sketching* design methodology described below [16].

We hypothesize that the engagement and immersiveness virtual reality offers can be leveraged to help knowledge workers, including analysts and scientists, with higher-level cognitive tasks. Several properties of VR environments, such as the feeling of presence of users in immersive 3D scenes, improved spatial cues, and the use of spatial movements to interact with data have potential benefits for users in complex data analysis tasks. These properties have been used in training and education applications, as well as VR games, but not as much for higher-level knowledge retrieval tasks.

Experimental evaluations have shown significant advantages of VR visualizations in exploring spatial relationships [20, 28], 3D paths [26], and 3D shapes [6]. These benefits make VR an excellent environment for the analysis of flow datasets. Examples of practical applications can be found in medical data visualization, where immersive visualizations are used to analyze blood flow within vessels [7, 13, 33] and to examine diffusion tensor images of brain scans [34]. Another practical application is the use of VR within the automotive industry to visualize vehicle designs, with fluid flow simulation as an explicit desire [21]. Based on these promising examples, we test our hypothesis with a design study to develop effective VR visualizations tackling the substrate flow visualization questions of our collaborators.

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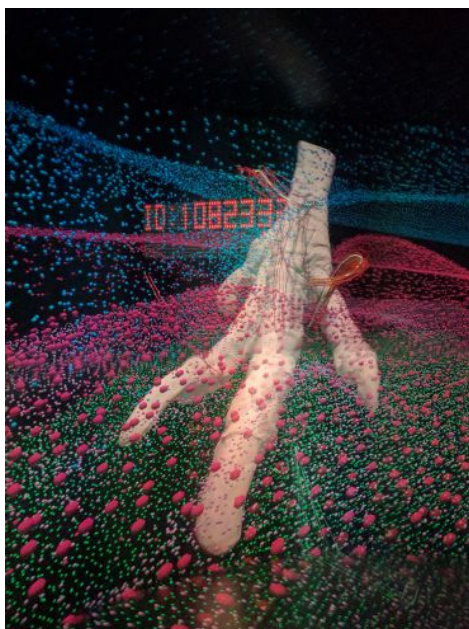
Fig. 2: Example visualization of particle flow during dinosaur track creation. To avoid visual clutter we only show four thin layers of simulated particles, color coded based on their initial depth (from blue on top over red and magenta to green on the bottom). A tooltip display indicating selected particle ID's can be seen in the background.

Developing an effective set of visual codings and metaphors to answer specific research questions is one of the core challenges in visualization research. The main research questions are, however, rarely finalized at the start of the visualization development. They often evolve and change alongside the iterative development process of a visualization application. Better understanding of their data allows domain scientists to give effective feedback and steer the development process in the right direction. Immersive virtual reality is a relatively recent visualization medium and few domain scientists have experience in using it to its full effect. It was therefore important for us to provide our collaborators with an overview of possible visualization styles in VR.

We based our design process mainly on the Scientific Sketching methodology proposed by Keefe et al. [16]. This required us to introduce a third discipline to our development process, artists from the Rhode Island School of Design (RISD) with a background in visual design. Scientific sketching aims to combine the individual expertise of scientists, visualization experts and artists to create novel solutions to visualization problems. It is separated into four phases that are inspired by artistic work processes; *Paper Sketching*, *VR Sketching*, *VR Prototyping* and finally *Implementation of visual specifications*. We realized these stages by recruiting students (visual design and computer science majors) through a course on immersive scientific visualization design that we offered two separate semesters.

This work contributes to the field of scientific VR visualization in multiple ways:

- Implementation and qualitative evaluation of multiple VR visualization methods for unsteady flow visualization. Out of a wide range of potential methods, the visualization techniques selected by our collaborators might be applicable to other flow visualization applications.

- A case study of Scientific Sketching and its effectiveness as design methodology in a long-term visualization project.

- Insights and best practices for the effective use of Scientific Sketching.

This paper is organized as follows: Section 2 provides an overview and related work about the scientific problem of our collaborators and 3D flow visualization in general. Section 3 introduces the individual stages of the design process, the simulation data used for the final implementation, and CAVE VR environment used for visualization sketching and development. Sections 4 and 5 summarize and discuss the findings of our two-year development process. Finally, we present conclusions and potential guidelines for the development of future VR visualizations.

2 RELATED WORK

In this section we introduce prior work related to our visualization research and the scientific problems we are attempting to address. We provide details about dinosaur track analysis and how 3D particle flow simulation is used to infer foot motion from fossilized tracks. We then list established 3D flow visualization techniques and how they are linked to our visualization metaphors.

2.1 Dinosaur Track Analysis

Dinosaur tracks are relatively common records of Earth's fauna during the Mesozoic Era. Unlike a fossilized skeleton, a track is evidence left by an animal while it was alive. Such trace fossils can often be attributed to different species or groups, providing insights into population distribution and paleoecology. Even a single track holds potentially valuable information about an animals movement and behavior. However, extracting reliable inferences from a footprint's final morphology is rarely straightforward [8].

Tracks are not static molds of the foot, but rather the result of a dynamic interaction among anatomy, movement, and substrate. As a dinosaur contacts malleable ground, it deforms not only the exposed surface, but sub-surface layers as well. On very soft mud the foot can sink quite deeply, passing through multiple layers as it moves through the sediment volume. Displaced material can pass around the toes and collapse, or be dragged along with the motion. The amalgamation of all these events reorganizes the particles in the fossil's volume, which can be split open to reveal track surfaces at multiple levels. An understanding of sediment flow during formation is thus critical to the correct interpretation of these specimens.

Analyzing interactions below ground is hindered by foot and substrate opacity. Experiments using model indenters have been fruitful, as have observations of extant animals like birds, which have very similar feet to those of predatory dinosaurs [1, 11, 24]. Recently, sub-surface imaging of foot motion by multiple X-ray cameras has been combined with discrete element simulation to reproduce track formation sequences in substrate volumes [8]. The resulting datasets, consisting of millions to tens of millions of dynamic particles as well as a moving foot model, present challenges to visualize, explore, and interpret. Our work aims to visualize the particle flow within these datasets, providing paleontologists with insights about dinosaur locomotion and the origin of a tracks morphology.

2.2 3D Flow Visualization

The analysis of 3D flow data is a common task in a wide range of scientific fields and numerous methods to visualize internal flow structures have been proposed so far. Survey papers by McLoughlin et al. [23], Brambilla et al. [4] provide a comprehensive overview of the state-of-the-art in flow visualization. The methods used in our VR application are based on geometric flow visualizations which represent the flow data as discrete geometric objects.

Our dinosaur track simulation data is defined as time-varying flow field using the Lagrangian specification. This allows us to directly visualize particles in 3D (see Fig. 2) and show their movement as animation. To visualize particle movement over the entire simulation in a static way we use integral curve representations similar to those introduced by Zöckler et al. [35]. In particular we utilize 3D pathlines, which connect particle positions of subsequent simulation timesteps.

To gain insight into particle movements over the whole volume of a flow dataset, it is necessary to visualize the relative movement of multiple particles and particle groups. Our visualization approaches
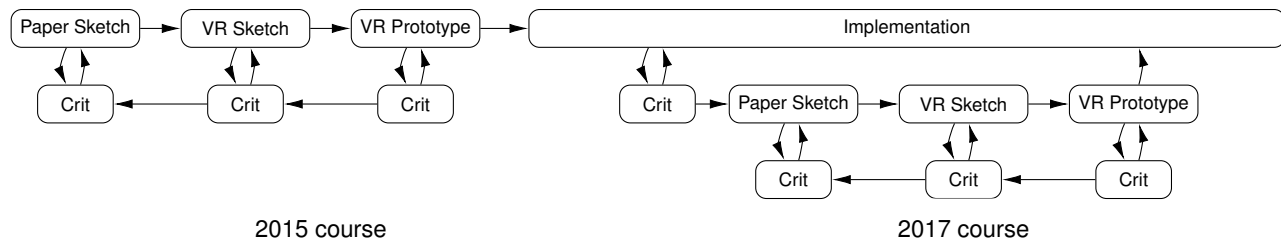
Fig. 3: The project development timeline showing how students of two VR visualization design courses contributed to our visualization outcome. Our implementation stage started directly after the completion of the 2015 course. Insights found during the implementation stage led to improved feedback during the 2017 course. Finally we combined the outcomes of two Scientific Sketching projects into our collaborative flow visualizations.

are based on the concepts of 3D path and time surfaces. Pathsurfaces, as discussed by Schafhitzel et al. [27], are the integral 3D surface created by following the movement of a connected line of particles through time. We use a similar method to visualize the movement of foot geometry during the simulations. To analyze relative particle movement between two subsequent timesteps we use time surfaces, introduced by Krishnan et al. [19]. Their method defines a surface of connected particles in a single timestep of the dataset and then follows this surface through time. This effectively visualizes local changes in particle neighborhoods as surface deformations. This visual metaphor is particularly effective, since it shows similarities to the deformed substrate layers found in fossilized dinosaur tracks.

3 APPLICATION DESIGN METHODOLOGY

In this section we introduce the research questions of our paleontologist collaborators and the design methodology we used to address them. We combined the collaborative efforts of students, faculty and scientists in an interdisciplinary VR design course to create effective VR visualizations. Our design process is based on the Scientific Sketching methodology introduced by Keefe et al. [16], which we describe in detail in the remainder of this section. This application development approach aims to efficiently coordinate the work of artists (in our case, RISD and Brown students), visualization experts (visualization majors and faculty) and domain scientists (paleontologists) in VR visualization projects. The development process is split into four successive stages; *Paper Sketching*, *VR Sketching*, *VR Prototyping* and *Implementation of visual specifications* (see Fig. 3). In each stage the three participating groups have a different set of responsibilities to fulfill.

In the initial paper sketching stage, for example, the scientists' role is to provide background that explains their scientific problem. The other two groups need to be able to understand the problem and the characteristics of the underlying data, such as relationships between data variables and their relative importance [16]. The artists' role is to take the provided information and come up with a large quantity of visual ideas, exploring the problem from a variety of different angles. The visualization experts join the sketching effort, but also mediate the discussion between artists and scientists to keep track of the overall visualization goals. In this early stage, the focus lies on covering a wide range of visualization concepts without regard for implementation complexity.

An important tool throughout all stages is the artistic critique, as used in art and design education. It is a careful and critical group discussion evaluating specific aspects of visual artworks. Any feedback given in a critique session needs to be well founded and explained in detail (i.e. "I do not agree with this color choice, because [...]") to serve as a starting point for a constructive discussion [32]. Within the scope of this project, critiques were used to argue about the effectiveness of individual sketches and prototypes. Involving all three participating groups into these critiques ensured that each proposed visual concept was discussed from artistic and scientific viewpoints.

3.1 Paper and VR Sketching

We developed our VR visualizations over the course of two separate semesters of the Virtual Reality Design course offered by Brown Uni-

Table 1: Group Compositions during course the two iterations of the Virtual Reality Design course.

	Course 2015	Course 2017	Total
Scientists	2	2	2
Art/Vis Faculty	2	2	2
Brown Students	8	6	14
RISD Students	5	6	11

versity and the Rhode Island School of Design. A total of 11 RISD art students, 14 Brown University computer science students, and one faculty member from each school participated in the design of the application. Two paleontologists from Brown University presented the scientific problem, using data from their collaboration project with Liverpool John Moores University. Before starting the Scientific Sketching projects, all students participated in introductory exercises covering basic 2D and 3D visualization methods as well as core VR drawing techniques.

In both iterations of the course, the paper and VR sketching stages were part of mandatory class assignments. The assignment started with an interactive lecture by the science collaborators to provide students with the background knowledge needed for the research questions at hand. The underlying data were introduced through media presentations using images and videos rendered with their desktop-based visualization tools Ovito [31] and Autodesk Maya [2]. Actual dinosaur footprint fossils and cast duplicates were used as physical examples of the visualization subject. The initial research questions posed by our collaborators were the following:

- Can we work backwards from a track surface to determine the original configuration of its particles in the starting plane? Where did each particle come from?

- Alternatively, can we trace the fate of particles in the starting plane forward in time? Which particles will descend, ascend, move forward, or collapse to form the features of the final track?

- How do foot-particle and particle-particle forces move sedimentary particles? When and where do compression (push), tension (pull, cohesion), shear, or gravity dominate?

- How can dynamic, simulated data of moving particles be compared to the static final morphology of a real fossil dinosaur track?

After the introduction lecture, students were given one week to create paper sketches for the first critique session with collaborators. To encourage creative designs, a wide range of visual and physical art-forms were permitted as potential hand-ins (e.g., digital art, 3D printing, and sculpting). Intermediate results of this stage can be found in the results section (e.g. Fig. 4a). After two critique sessions in which each sketch was discussed at least once, students had to realize at least one of their paper sketches as 3D VR sketch. To complete their assignment, students used a VR painting application called Cave-Painting [15] in a high-resolution CAVE-like display room called the
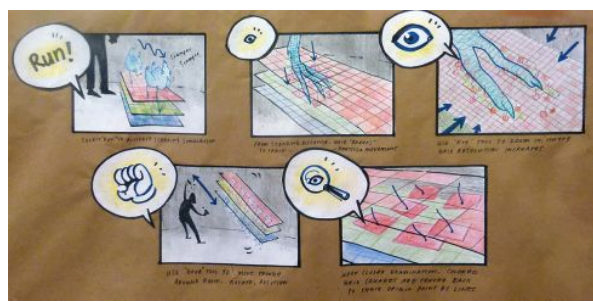
(a) Paper Sketch

(b) VR Sketch
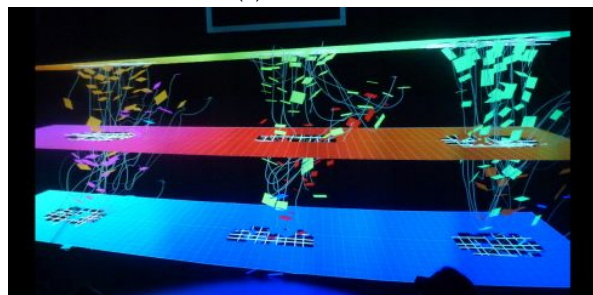
(c) VR Prototype

Fig. 4: Example of the evolution of a student idea for visualizing the deformation of different substrate layers during track formation. The paper sketch (a) includes proposed visual representation and interaction techniques. The VR sketch (b) is used to discuss the visual concept with science collaborators before creating a high quality VR Prototype (c).

YURT (see Sect. 3.5). The application allowed students to draw simple textured primitives like tubes, planes, and text using an easy to understand wand-based interface. This allowed them to create and test immersive sketches of their proposed visualization within a short timeframe. Loading of 3D models created in external applications was prohibited, which forced students to complete the design task within the VR environment. This constraint ensured that students understood the interaction concepts and UI challenges of working within an immersive display.

The resulting VR sketches were discussed in a second round of critiques which took place directly in the YURT display room. In these sessions the paleontologists also acted as users of the sketched visualizations, and gave feedback on how they would interpret them in their current form and whether they reflected their understanding of the data. Results of the VR sketching stage are shown in Fig. 4b, and the results section.

3.2 VR Prototyping

A VR prototype, as defined by the Scientific Sketching method, is a highly refined mock-up of the developed application. This includes more carefully drawn visuals, but also the use of animations to simulate interactive usage scenarios of the prototyped applications. CavePainting supports this prototype development by offering drawing layers to switch between visualization views and an animation frame system.

Scenarios can then be played out by simulating the application behavior through Wizard-of-Oz interaction techniques [5]. In practice, students realized this by creating a set of static scenes. During the presentation they stood in the back and switched scenes in response to users interacting with their prototypes to showcase their proposed interaction concepts inside the YURT.

Creating the VR prototype was the four-week final project in both classes. Students were free to pick a specific hypothesis to explore in their prototype. The assignment was to design one or more VR visualizations including a step-by-step scenario of how they would be used by scientists. To ensure that students developed their ideas in fruitful directions, the two sketching stages were repeated in the first two weeks of the final project, focusing on the interaction storyboard. Critique sessions continued during class time and students had the option to return to earlier sketching stages (e.g. paper sketches) for idea refinement. A majority of students picked hypotheses addressing research questions in dinosaur track simulation, leading to several high-quality prototypes. Examples are shown in Fig. 4c, and the results section.

3.3 Implementation

The final projects of the 2015 course provided us with several detailed prototypes of potentially helpful VR visualization concepts. We implemented a subset of these concepts in an interactive data-driven application for exploring their most recent simulations. To keep the development on track, progress meetings with our paleontologist collaborators were scheduled multiple times every month. This tight feedback loop allowed us to extensively test and refine visualization ideas from the VR prototypes. The results of this stage with the corresponding sketches and prototypes are discussed in section 4.

During the Implementation Stage, the VR Design course was offered a second time, bringing in a new group of art and computer science students. Based on their experience with the VR application and new data from fossil tracks, scientists were able to provide clearer, more refined, research questions to the class. Resulting VR prototypes of that course were focused more closely on sediment and foot movement in dinosaurs as well as birds. This allowed us to use the student projects as inspirations for further refinements to the ongoing implementation process.

In the next two sections we provide details about the datasets and VR environments used during the implementation stage.

3.4 Dinosaur Track Simulation Data

The flow data used in our study was obtained through a combination of physical experiments, animation, and particle simulation. To study track formation in a living bird, the sub-surface walking kinematics of a chicken-like species (guineafowl) were recorded with a biplanar X-ray system as they walked through radiolucent artificial muds of varying depth and hydration, as well as a dry sand analog (poppy seeds). The recorded foot motion data were then processed using the X-Ray Reconstruction of Moving Morphology (XROMM) technique [3, 10] to obtain an animated 3D model of the foot geometry. To simulate the sedimentary particle flow during footprint formation, one footfall was recreated using the discrete element method (DEM) [8]. The simulation was computed using LIGGGHTS [18]. The resulting simulation data (9.5 million particles, 523 frames) was initially visualized in Ovito [31], which was used for cropping and downsampling (370 thousand particles, four slabs).

To test our hypotheses of fossil dinosaur track formation, four specimens from the Beneski Museum of Natural History, Amherst College (ACH-ICH 31/51, 31/57-59; Fig. 5) were chosen for imaging and analysis. These four slabs, collected in the mid-1800s from the Early Jurassic (200 million years ago) rocks of Wethersfield, Connecticut, form a stack bearing a deep dinosaur track [14]. Specimens were CT scanned to visualize internal deflected laminations, which were reconstructed in 3D with Amira. Using these fossil data as a constraint and current understanding of guineafowl subsurface kinematics as a guide, an articulated dinosaur foot model was animated in Autodesk Maya. A LIGGGHTS DEM simulation (33 million particles, 174 frames) was

Fig. 5: Paleontological motivation. (Top) Early Jurassic dinosaur tracks chosen for visualization (scale bar equals 10 cm). (Lower left) Interpretive illustrations of the four surfaces from this track volume highlight changes in morphology with depth [14]. (Lower right) Deformations of the internal laminations are visible in a rendered section of the second slab based on CT scan data.

Fig. 6: (top) A student in our YURT display room, working on a VR sketch using the CavePainting application. (bottom) The wand and active stereo glasses used in the YURT. The constellations of reflective balls attached to each tool allows the optical tracking system to determine their 3D during runtime.
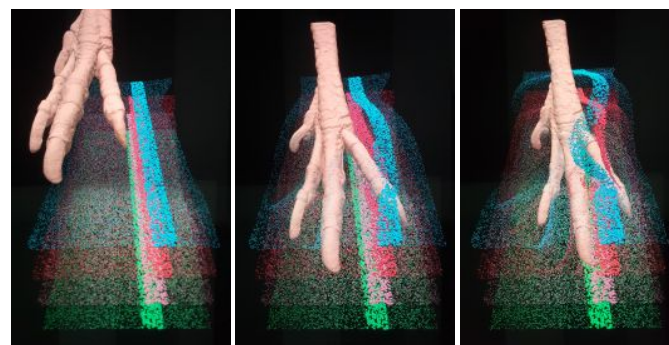

Fig. 7: An example of the Slice-tool, highlighting the particles of a thin user-controlled slice of the dataset. Substrate deformation is visualized by keeping particle highlighted based on their location in the first simulation timestep.

first cropped (4.2 million particles) before further downsampling (70 thousand particles, four slabs) in Ovito.

3.5 Virtual Reality Environment

Our visualization uses the YURT (YURT Ultimate Reality Theater) VR display room located at Brown University [17] shown in Fig. 6. It is equipped with 69 high-definition stereo projectors that use rear projection to illuminate a curved wall, curved doors, a conical ceiling, and a 135 ft^2 floor. When standing in the center it effectively provides retina resolution on its 190-degree front wall (1 pixel per arcminute). In that position, the YURT covers 95% of the users field of regard.

Stereo is provided using Volfoni 3D active stereo glasses with a shutter frequency of 120Hz. Users interact with the VR environment using an Aimon PS wireless wand controller. Glasses and wands are tracked by a OptiTrack Prime 13W optical tracking system with an array of 8 infrared cameras mounted in the ceiling of the YURT (Fig. 6).

We developed our VR application in C++, based on the MinVR 2.0 framework [25]. This allows our application to work with a variety of different VR systems including the YURT, other CAVEs, the HTC Vive and the Oculus Rift. It is also possible to run it as a regular desktop application with reduced functionality, due to the lack of 3D input devices in that mode.

4 RESULTS

This section summarizes the outcomes of the initial three Scientific Sketching stages and discusses the iterative implementation process of selected VR prototypes. Stepping from hand-drawn sketches to interactive data-driven visualizations is a significant development effort. At the same time it is not guaranteed that sketched visualization methods work as effectively as planned once they are tied to actual data. During our implementation stage we went through several iterations to refine the resulting visualizations. Since this is an integral part of the Scientific Sketching method we not only present the final results, but also intermediate implementation stages and the original prototype visualizations they evolved from.

4.1 Particle Visualization

To start the VR application development stage, we implemented geometry based particle visualization, similar to the methods available in our collaborators' Ovito environment. The goal was to provide a baseline visualization of the data as a comparison point for the upcoming VR prototype implementations. The baseline included the ability to manually step through simulation time-steps, to visualize the 3D foot models used to create the datasets, and to color particles based on their location.

To visualize a high number of particles at interactive framerates we rendered particles on quad-billboard primitives, using OpenGL geometry and fragment shaders to create accurate sphere representations.

The particle visualization implementation went through several iterations to fit our collaborators' needs. Showing the full volume of particles in the dataset, for example, caused occlusion problems. Particles in the outer regions of the dataset would block the view of those close to the foot geometry. To uncover the moving particles of interest within the volume, we sub-sampled the data and visualized thin horizontal particle slabs as representatives of the substrates unsteady motion. The empty space between these horizontal slabs is critical for unobstructed views of both top and bottom surfaces within the volume as they deform. This reduction of the dataset greatly improves the interpretability of visualized particle motion. Another early feature request was an interactive way to adjust the diameter of all particles to control the trade-off between occlusion and particle legibility.

Even with subsampling and particle size adjustments, our collaborators wanted to explore smaller regions of known initial position. Based on their particle selections requirements we designed a slice tool to highlight a subset of particles of interest. With it users can control and place a 3D slice inside the dataset. Particles sizes outside the region of the slicing tool are reduced to effectively highlight selected particles
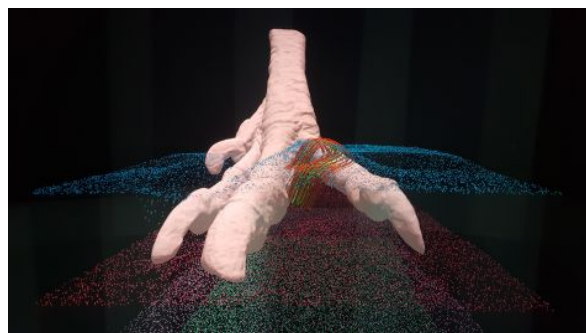
(a) Narrow pathline clustering between two toes.
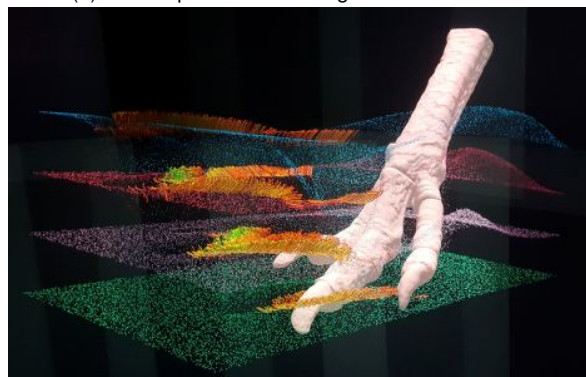
(b) Wide pathline clustering showing multiple similar pathlines on all particle slabs.

Fig. 8: Examples of implemented final pathline visualization. (a) Clustered pathlines of particle movement between two toes of the dinosaur foot. (b) A widely extended selection of pathlines at the borders of the dinosaur track. The relatively simple path shape is found in multiple particle slabs.
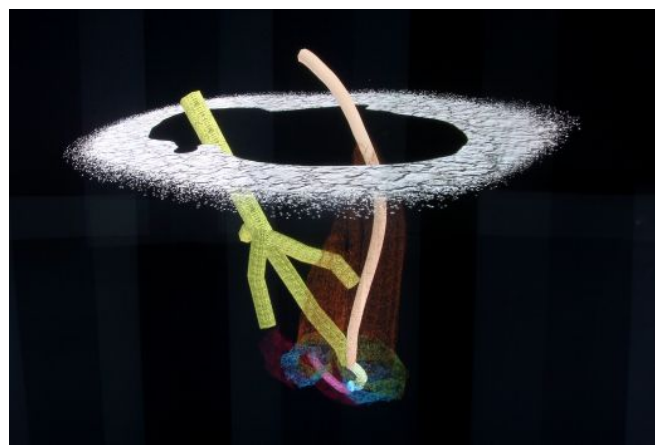

Fig. 9: A VR prototype outlining the idea of pathline clustering around a single selected path. The student sketched out two clusters next to a selected seed pathline following the center toe tip. Pathline and clusters are colored to highlight different parts of the step sequence (foot descent, step, and foot retraction).
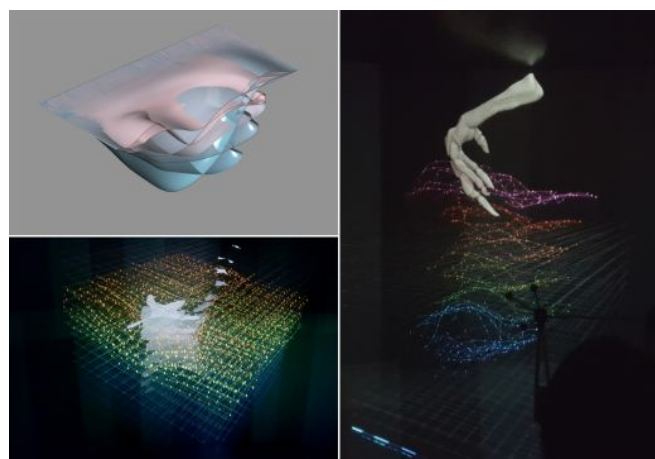

Fig. 10: Paper and VR sketches of ideas to visualize overall substrate deformations by showing surface representations at varying depths of the particle volume. Implementation results based on that idea can be found in Fig. 11.

and make them easier to follow throughout the animation. The slicing tool selects particles based on their starting position, which highlights their displacement over multiple simulation timesteps (Fig. 7). Alternatively, users can highlight particles within the slice during the actively shown timestep.

The first VR prototype implementation was particle filtering based on their total movement distance throughout the simulation. Particles that are not moving are of little interest to the research questions of our collaborators and we initially removed them from the visualization, as proposed in the VR prototyp. However, these unmoving particles provided important context for moving particles, by representing the surrounding substrate. They were therefore visualized as small, neutral-colored particles in later visualizations.

Particles alone, however, were not able to capture larger-scale particle movement patterns. Out of the numerous visualization ideas created by students during the prototyping stage in Scientific Sketching, two were of particular interest to our science collaborators: Pathline visualizations emphasizing similarity in substrate particles movement (see Fig. 8) and visualizing thin layers of particles as deformable surfaces, comparable to what is seen in fossil dinosaur tracks (see Fig. 10 and Fig. 11).

4.2 Pathline Visualization and Clustering

Following the motion of individual particles throughout the simulation is a frequent exploration task in our collaborator's datasets. Several students proposed VR prototypes based on pathlines to aid users in the analysis of substrate movement. We have subsequently implemented pathline visualizations that can be activated by selecting any particle with the wand tool. However, single pathlines are rarely enough to gain insights into substrate movements as a whole.

To overcome this issue, several students have proposed to investigate multiple pathlines throughout the entire dataset at the same time or to cluster multiple pathlines into an aggregate visualization (see Fig. 9). We implemented both methods and evaluated them with our collaborators. To create meaningful overview visualizations with moderate levels of occlusions it is necessary to reduce the overall number of visualized pathlines. We implemented several well known sampling techniques to select pathlines that captured critical substrate motion while still providing legible visualizations. These techniques included similarity measures based on curve properties such as critical points [22], Poisson disk sampling to select a series of non-overlapping pathlines [12], and using PCA to summarize the pathlines and then select dissimilar ones [9]. However, the resulting visualizations still contained many pathlines that our collaborators were not interested in, while lacking detail in areas of critical substrate movement.

To give them better control over pathline exploration, we implemented an adaptive selection technique that allowed them to extend a chosen "seed" pathline to an interactively-sized group of pathlines with similar shape characteristics (see Fig. 8). We define pathline similarity as the least-squares distance between point pairs of two paths. To make the metric translation and rotation invariant, we align the paths using the rigid transformation that minimizes pathline similarity. The transformation is calculated using the method introduced by Sorkine-

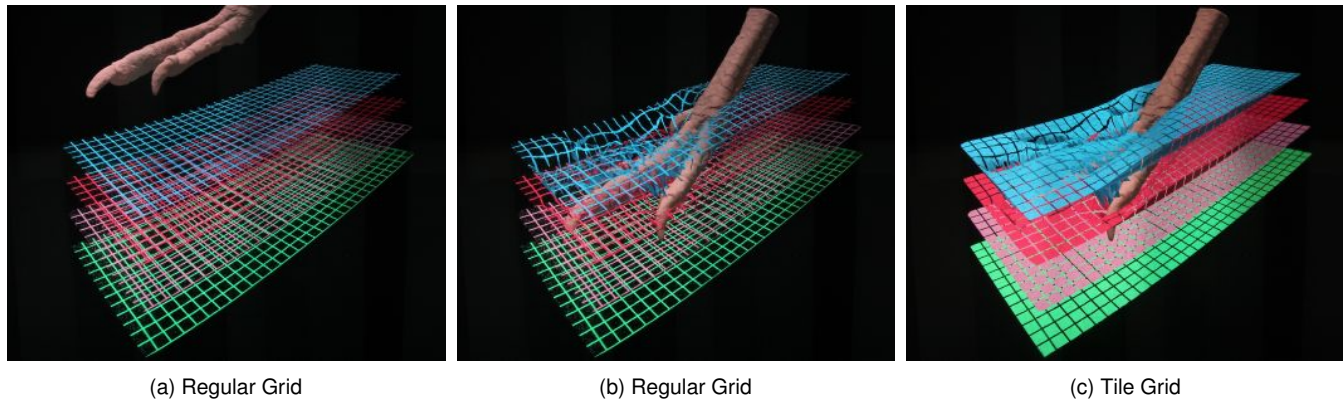(a) Regular Grid   (b) Regular Grid   (c) Tile Grid

Fig. 11: Example views of the horizontal time surface visualization with a regular grid (a,b) and a tile grid (c) texture. The tile grid offers a more legible representation of surface deformation, at the cost of increased occlusion of the foot model and underlying surface layers.

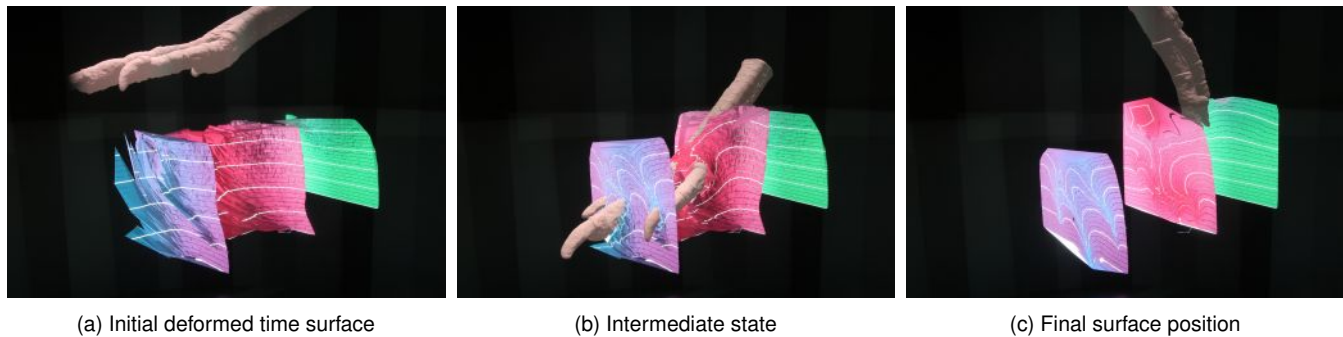(a) Initial deformed time surface   (b) Intermediate state   (c) Final surface position

Fig. 12: Example views of the vertical time surface visualization with horizontal guidelines. The deformed time surface in (a) and (b) gradually converges to a flat surface in the final timestep (c), visualizing the origin of all particles on a surface in a way that mimics natural fossil cross sections (Fig. 13).

Hornung et al. [30]. This metric is the result of empirical testing and fine-tuning over the course of multiple development cycles to fit the needs of our collaborators. It captures similar particle movement in multiple regions of the dataset and is time-dependent to avoid clustering substrate movements of different track creation stages (e.g. entry vs exit motion of the foot). We visualize the similarity of pathlines to the original selection as a color gradient from green (highly similar) to red (least similar).

Our collaborators report that this method of pathline visualization has enabled them to 'learn' the dataset and explore expected and novel patterns of particle motion. The color gradients have been noted to be a particularly effective and non-overwhelming means of representing a large amount of pathline similarity among the data.

4.3 Time Surface Visualization

Another important analysis task in track simulation data is to investigate and compare substrate deformations within particle regions of the volume throughout the simulation. Particle visualizations in distinct slabs give a rough overview of the total deformation, but information about initial neighborhoods is often lost in the complex particle motion paths. To address this problem it is helpful to think of slabs as continuous surfaces instead of individual particles. This representation is referred to as time surface [19]. Several students have proposed and sketched visualization ideas based on virtual surface deformation (see Fig. 10). Our paleontologists were intrigued by the concept, since it effectively mimics the thin layer structures found in many fossil samples (see Fig. 5). This provides a direct comparison between simulation outcomes and field data.

4.3.1 Horizontal Time Surfaces

To implement this visualization concept, we reconstructed slab surfaces by using Delaunay triangulation on particles within thin horizontal

slabs. Opaque flat-shaded rendering of these surfaces proved to be not effective. Each slab covered a wide area within the volume and often occluded lower layers and the foot geometry itself. Additionally, the lack of a geometric pattern on the surface made it difficult to follow more complex deformations. To solve this problem we applied a semi-transparent horizontal grid texture to the surface. Locking the texture coordinates during the initial animation step ensures that the grid deforms while following the particle motion. Overall substrate deformations can then be analyzed by observing the distortions of grid cells (see Fig. 11). The size and line thickness of the grid texture impacted the legibility of the visualization. More transparent grid layouts often allowed too much view on underlying surface slabs and made it harder to follow individual grid cells.

Based on promising prototypes developed during our courses, we inverted the grid texture to give it a tile-like design (Fig. 11). This gave us better control over the visibility of underlying surfaces and made the visualization of deformations more legible. Our collaborators found this to be a very accessible visualization technique that provided them with new insights into patterns of substrate movement within the horizontal plane of the slab.

4.3.2 Vertical Reverse Time Surfaces

Based on the successful implementation of time surfaces in horizontal slabs, we attempted to apply the same method on vertical slabs through the particle volume. We found that in this case, our collaborators were interested in the origin of particles within vertical slabs at the last timestep of the simulation. We implemented this by triangulating the surface in the final timestep, while selecting grid texture coordinates and color based on the particle location in the first frame. This results in a "reverse" time surface, that starts in a heavily deformed state and gradually approaches the vertical plane over the course of the simulation (Fig. 12). The deformed horizontal gridlines on the final flat surface
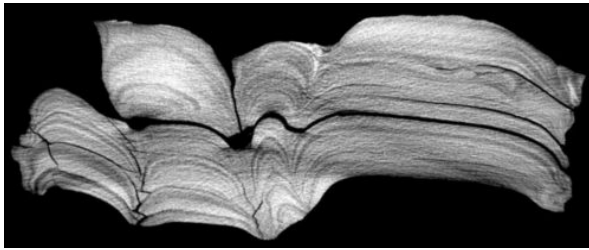
Fig. 13: Cross-section of a fossilized track showing deformed horizontal material layers at regions the dinosaurs toes passed through. Our vertical time surface visualizations mimic this effect through surface color and horizontal guidelines.

correspond to layer structures found in cross-sections of fossils. This makes it an intuitive metaphor for paleontologists and allows them to effectively analyze the sediment movement that lead to the final state of the fossil. It also provides another effective comparison point between simulation outcomes and real world fossils (Fig. 13).

4.4 Foot Motion Visualization

The difference between actual foot motion and the shape of the final track is another research question of our collaborators. Critical points in a track, like toe entry points, often shift in position during substrate deformations. To gain insights into these offsets, students have prototyped visualizations of pathsurfaces created by tracking the central axis of each bone in the geometric foot model throughout the simulation (see Fig. 14). This visualizes the entire foot motion sequence as simplified static 3D model. In combination with the previously introduces particle and time surface visualizations, this data representation allows researchers to explore the offsets between actual foot motion and substrate deformation in great detail (Fig. 14c).

5 DISCUSSION

In this section we discuss our results and experiences with the Scientific Sketching design process. These include advantages and disadvantages of using a large group of students to represent the artists, the overall results of the project and lessons learned from employing this design methodology.

In the early sketching stages, as students began to explore the problem space, they came up with a large number of potential visualization concepts. The relatively large group size allowed us to cover a wide range of visualization ideas. However, this came at the cost of significant overhead. The artistic expertise of course participants varied and critique discussions had to include basic introduction sessions to bring everyone closer the the same level of understanding. The process of evaluating and critiquing all sketches also required a considerable time commitment by our scientific collaborators.

While each student created multiple sketches for each stage of the project, only a select few sketching results were unique visualization ideas. In many cases there was significant overlap between student designs during paper and VR sketching stages. However, thanks to the critique sessions, students were able to coordinate their works and focus on their own distinct visual concepts during the VR prototype stages.

At the end of each course we collected feedback questionnaire from our students, with positive results in both cases. Students commented that the course helped to promote "creativity and understanding of virtual reality science visualizations" and taught "the importance of legibility and how to creatively display data".

5.1 Influence of Scientific Introduction

We observed that the initial presentation of the scientific problem had considerable influence on the outcomes of the sketching stages. In particular, we found differences in the variety of visual designs created by students between the two iterations of the design course. In the 2015 class, students explored a wider range of visualization ideas than in
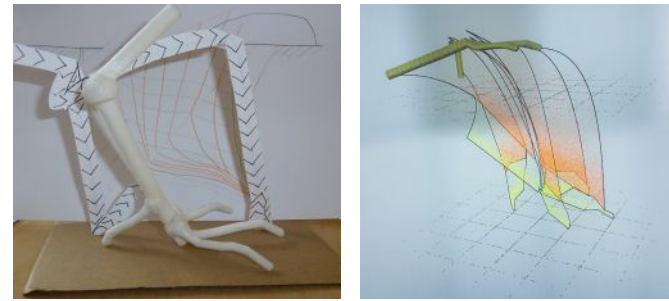
(a) Paper sketch/model

(b) VR Sketch
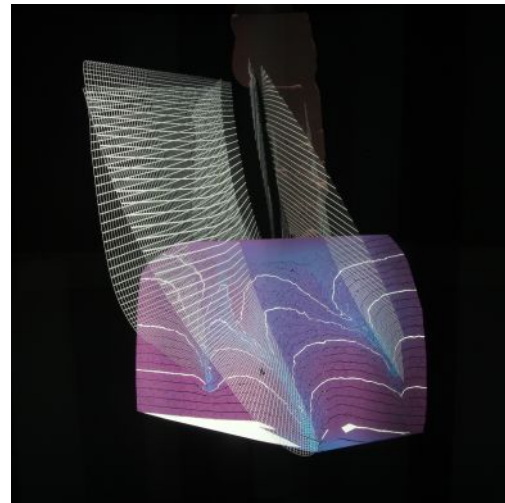
(c) Implementation

Fig. 14: A physical model (a) and VR sketch (b) of a concept to visualize the foot motion with pathsurfaces of the central axes of individual bones. An example of the implemented visualization showing the pathsurfaces trailing the foot motion trailing throughout simulation timesteps (c). Combined with vertical time surface visualizations, this highlights the offset between the actual motion of the foot anatomy and the trails it leaves behind and was one of the main take-aways of our science collaborators.

the 2017 one. This difference could have been caused by the increased expertise of the science collaborators. In 2015 the research questions presented to students were strongly exploratory, without specific expectations about the visualization outcome. In the 2017 class students were presented with more specific research questions and improved examples of the data and existing visualizations. It also contained a second dinosaur track related assignment, providing students with deeper background knowledge. Having additional information might have caused sketches and prototypes to be visually closer to the already implemented VR visualization concepts. While the second course did not result in drastically different visual metaphors, it still provided compelling ideas for improvements to our ongoing implementation stage.

5.2 Benefits of VR visualization

Our paleontologist collaborators confirmed our hypothesis that VR visualization offers significant benefits compared to their standard desktop-based analysis tools. The main advantages reported over the course of the entire project were the following:

The large interaction space of VR environments was beneficial to data analysis. Our VR system surrounds users almost entirely with screen space, as opposed to a single stationary desktop-screen. This allows our visualization to show data at a larger than usual scale. Users can inspect specific regions of the visualization simply by stepping closer, which effectively zooms into the visualization. While focused on specific details users can still connect them to the context of the entire

dataset by looking around in the immersive environment. However, this context was easily lost when users were completely surrounded by the visualization. In the YURT, and CAVE-like displays in general, this also distorts the visualization for viewers without head-tracked stereo glasses. We found that our collaborators mainly used the available screen and interaction space to physically walk around the entire dataset. As a response we scaled the visualization to comfortable allow this in our YURT display room.

The depth cues provided by stereo imagery and motion parallax greatly improved our collaborators understanding of their volumetric datasets. Interacting with their data through an intuitive 3D wand interface gave the visualization a feeling of physicality. These factors combined caused our collaborators to feel more present within the virtual environment, a feature that has been linked to increased visualization effectiveness [29]. Many of our implemented visualization techniques, would not work as effectively on a 2D display due to the spatial complexity of our visual metaphors (e.g. initial and intermediate stages of the vertical time surfaces, see Fig. 12).

The paleontologists also commented positively on the collaboration aspect in our YURT display room, which can host multiple people at the same time. Being surrounded by data visualizations minimized distractions and stimulated discussions. While only one person can *drive* the visualization at a given time, other observers were still able to follow the exploration process of the driver. This collaborative exploration sometimes discovered new perspectives by serendipity and generated valuable intuition about the structure of the datasets. Our successful visualization project underlines benefits of high-fidelity VR displays and immersive visualizations for the exploration of spatially complex scientific datasets.

5.3 Using Scientific Sketching

After observing Scientific Sketching in two separate design courses we observed several factors that could influence the effectiveness of this methodology:

- Scientific Background Information
  As previously stated, we found some evidence that the initial introduction of the scientific problem can have significant impact on the expected sketching outcomes. We suggest to consciously control the amount of detail given at the introduction phase to steer the creative process of the artists and influence the variety of expected visualization outcomes. Broadly defined research questions, for example, give artists a wider design space to work with, but might result in visualization ideas that do not directly address the scientists' problems.

- Group Size
  There are potential diminishing returns on the artist group size. Our courses had 13 and 12 student participants, respectively. In both cases we found a gathered a larger number of overlapping visualization ideas. This suggests that smaller groups could still work effectively while reducing organization overhead.

  We also found that using a single CAVE system for VR sketching leads to scheduling challenges at our group sizes. We overcame these problems by allowing students to work in groups of two. However, in order to ensure the accessibility of the drawing environment we suggest to use more VR devices, or appropriately sized groups.

- Artistic Capabilities
  Our course groups were made up of artists and computer scientists at varying skill levels. Bringing the group to a basic common level of artistic capabilities required additional teaching effort. While it might be more efficient to use a small group of well trained illustration artists, the mixed group had some distinct benefits. Learning the artists' terminology and critique style gave computer scientists the ability to articulate their questions and describe their sketches in the most constructive way. The teaching aspect of beginner critique sessions also familiarized our domain scientists to the artistic process and Scientific Sketching.

- Scientist-Artist moderation
  Keeping the dialogue between scientists and artists going throughout all stages of the design process is critical to its success. Scientists should be available to answer student questions even outside of critique sessions, to help them better understand the scientific problems and guide their visualization designs in relevant directions.

- VR Sketching Environment
  After completion of the course, several students commented that they would have preferred additional drawing features in the CavePainting VR environment, including the capability to load 3D models and animations from desktop applications. Giving the art students access to their usual design tools would most likely allow them to realize some of their designs in more detail and in shorter time. However, this would reduce their exposure to the VR environment and in turn their understanding of the specific interaction requirements for immersive visualizations.

- Importance of the Implementation stage
  While the original methodology paper of Scientific Sketching [16] mainly focuses on the initial sketching and prototyping stages, we want to stress the importance of the transition from VR prototype to implementation. We suggest that the group of visualization experts extends their role during the VR prototype phase to provide warnings about potential implementation issues with problematic visualization concepts.

- When to use Scientific Sketching
  Compared to more traditional software and visualization design methodologies, Scientific Sketching requires a very specific setup. Combining the efforts of domain scientists, artists and visualization experts to create novel visualizations involves significant organization effort. However, the outcome of a Scientific Sketching project is not just a VR visualization technique or tool. The frequent critique sessions between all three groups allow each member to gain a detailed understanding of the visualization problem at hand, since it is discussed from multiple different scientific and artistic viewpoints. Likewise, all participants gain insights in the effective use of VR user interfaces, which is helpful for the student group. This educational component sets Scientific Sketching apart from other design methodologies, even though they might yield similar visualization outcomes.

  Additionally, the sketching approach can help to engage new collaborators, by offering them a low-cost method to test whether their scientific research can benefit from VR visualizations. We therefore recommend the use of Scientific Sketching for exploratory visualization and science problems without strict initial requirements and a secondary focus on teaching/understanding VR design in general.

6 CONCLUSION

We presented results of an iterative VR visualization development process to analyze unsteady flow in dinosaur track creation datasets of our paleontologist collaborators. The visualization concepts implemented as part of this work have become effective tools for our collaborators and continue to be the base for an ongoing research partnership. The process of developing these tools with the Scientific Sketching methodology was overall successful.

Iterative sketching and prototyping stages allowed us to examine a wide range of visualization ideas and choose the most viable ones for implementation. Ultimately, we created VR tools that help paleontologists to analyze their data through particle, pathline and time surface visualizations. By actively participating and guiding the sketching processes, our collaborators gained new insights into the intricacies of their simulated flow data and drew new connections between dinosaur foot movement and substrate deformation.

Assessing the Scientific Sketching method itself, we found that it was very effective in our scenario. Over the course of our project all

three involved groups, artists, visualization experts and paleontologists gained new insights about visualization design and the effective use of VR as a medium for scientific exploration. Based on our results, we can highly recommend Scientific Sketching as design methodology for VR visualizations.

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