VISTA3D: Visualizer for Interactive Sketching and Tagging in 3D

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ABSTRACT

The study investigates the transformative potential of interactive 3D visualizations in educational and design contexts, leveraging advanced web technologies like WebGL and WebGPU for real-time rendering. By examining the impact on user engagement and comprehension, this research highlights the significant advantages of 3D tools over traditional 2D methods. It addresses technical and usability challenges, explores the contributions of open-source development models, and emphasizes the importance of designing accessible user interfaces. The findings underscore the effectiveness of interactive 3D tools in enhancing learning outcomes and the sustainability and innovation fostered by open-source collaboration, suggesting broader adoption and integration in educational and professional settings.

KEYWORDS

Systematic Literature Review, 3D Visualization, Interactive Learning, WebGL, WebGPU, Open-Source Software, Educational Technology

1 INTRODUCTION

In contemporary education and data analysis, 3D visualization plays a crucial role in enhancing understanding and engagement. As educational paradigms shift towards more interactive and immersive learning environments, the integration of 3D visualization technologies becomes increasingly significant. These tools offer innovative ways to represent complex concepts, making them more accessible and comprehensible to diverse audiences. Traditionally, educational resources such as textbooks and static images have been limited in their ability to fully engage learners and convey intricate information effectively [15]. This is particularly evident in subjects that inherently involve spatial and multidimensional data, such as anatomy, engineering, and architecture. In these fields, 3D visualization provides a dynamic and interactive alternative that can significantly improve the learning experience. Several projects and initiatives have emerged to harness the potential of 3D visualization in education [5]. These range from virtual reality (VR) and augmented reality (AR) applications to web-based platforms utilizing advanced technologies like WebGL and WebGPU for real-time rendering. Such technologies facilitate the creation of interactive 3D environments where learners can explore, manipulate, and engage with educational content in ways that were previously unattainable.

A prominent example in this domain is the VISTA3D project, which focuses on developing an open-source 3D sketching and tagging visualizer [7]. Although VISTA3D represents a significant advancement, it is part of a broader movement towards leveraging open-source web technologies to enhance educational processes. By providing tools that are freely accessible and adaptable, these initiatives aim to democratize education, ensuring that learners from various backgrounds can benefit from advanced visualization capabilities. The benefits of 3D visualization in education extend beyond traditional classroom settings. They empower self-guided learners, support professional training programs, and enhance remote learning experiences. The ability to visualize and interact with 3D models helps learners to better understand complex structures, processes, and data sets, thereby improving retention and comprehension [14].

This paper will explore several key themes related to the use of 3D visualization in education and data analysis, including:

- **Interactive 3D Sketching:** The development and application of tools that allow users to create and manipulate 3D models interactively.
- **Labelling Visualizers:** Techniques for tagging and annotating 3D models to enhance knowledge transfer and data interpretation.
- **Augmented Knowledge Transfer:** How 3D visualization can facilitate deeper understanding and retention of complex concepts.
- **Open-Source Web Technologies:** The role of open-source platforms in advancing educational technologies and making sophisticated tools widely available.

By examining these themes, this paper aims to provide a comprehensive overview of the current landscape of 3D visualization in education, highlighting its potential to transform learning and data analysis through innovative, interactive technologies.[7]

2 BACKGROUND

The evolution of digital learning tools has been marked by significant advancements, yet existing technologies often exhibit limitations in delivering fully interactive and immersive educational experiences. Traditional 2D visualization tools and e-learning platforms, while beneficial, cannot fully capture the complexity and spatial relationships inherent in subjects requiring 3D comprehension [4]. These tools often lack the interactive elements that foster deep understanding and engagement, leading to a gap in educational outcomes. Furthermore, accessibility and universal design principles are not always prioritized, limiting the reach and impact of these educational resources. The need for VISTA3D arises from these challenges, proposing a solution that leverages the latest web technologies to provide an open-source, interactive 3D visualization platform[7]. This platform aims to enhance knowledge transfer by making complex concepts more accessible and engaging through intuitive 3D sketching and labelling features, addressing the critical limitations of current educational tools and setting a new standard for digital learning resources.

What is Interactive 3D sketching ?

Interactive 3D sketching is a cutting-edge technology that allows users to create and manipulate three-dimensional models in a virtual environment. This technology often integrates with virtual reality (VR) or augmented reality (AR) systems, providing an immersive experience where users can interact with their sketches as if they were tangible objects [6]. Here are some key aspects of interactive 3D sketching:

Immersiveness: Unlike traditional 2D sketching, interactive 3D sketching immerses the user in a virtual environment where they can sketch in three dimensions. This provides a more intuitive and natural way of creating and visualizing objects in space.

Tools and Techniques: Interactive 3D sketching often utilizes specialized tools such as VR headsets, styluses, and motion tracking technology. These tools enable precise control and a realistic sketching experience, making it easier for users to translate their ideas into 3D models.

Applications: This technology has wide-ranging applications, especially in fields like architecture, design, engineering, and education. It allows for rapid prototyping and visualization of concepts, which can enhance creativity and efficiency in the design process.

User Experience: The user experience in interactive 3D sketching is significantly different from traditional sketching. Users need to develop a sense of spatial awareness and get accustomed to sketching in a virtual 3D space which can be challenging.

Advancements and Challenges: The field is continually evolving, with ongoing research focused on improving the accuracy, usability, and accessibility of these systems. Challenges include making the technology more user-friendly and affordable, as well as enhancing the fidelity of the sketches. [19]

What is labelling visualizer ?

Labelling visualizers are tools or software used to annotate or tag visual data, such as images or 3D models. These tools allow users to add labels or markers to specific parts of the visual content, making it easier to identify, categorize, or explain certain features or elements within the data. In educational or data analysis contexts, labelling visualizers are particularly useful for enhancing understanding by providing clear, interactive ways to highlight and explain complex visual information [8].

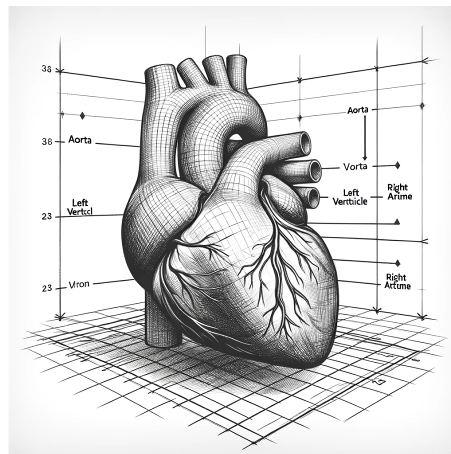

Figure 1: Sketch of the hart with various tags.

What is augmented knowledge transfer?

Augmented knowledge transfer refers to the enhancement of traditional knowledge sharing and learning processes through the use of advanced technologies, particularly those that add layers of digital information to real-world environments. This can include augmented reality (AR), virtual reality (VR), and mixed reality technologies. These tools provide immersive, interactive experiences that can make learning and information exchange more engaging and effective [12]. They allow for a more hands-on approach, where learners can interact with digital content in a way that closely mimics real-world interactions, thereby augmenting the overall learning experience. [13]

Target audience

The target audience for VISTA3D spans a broad spectrum, including educational institutions such as schools and universities, researchers, data scientists, and professionals across various fields such as engineering, medicine, and environmental science. It is also designed for self-learners and hobbyists interested in 3D visualization. This wide-ranging audience reflects the versatility of VISTA3D, aiming to serve anyone seeking to enhance their understanding or presentation of complex data and concepts through interactive 3D visualization.

3D technologies for educational purpose

Some widely recognized 3D technologies used in education:

- Virtual Reality (VR): Immerses students in a completely virtual environment, enhancing engagement and understanding of complex subjects by simulating real-life scenarios.
- Augmented Reality (AR): Overlays digital information onto the real world, enriching the learning experience by bringing textbook diagrams and models to life.
- 3D Printing: Enables students to create tangible models of objects they're studying, facilitating hands-on learning and creativity in subjects like engineering, biology, and arts. [10]

VISTA3D aims to complement existing 3D educational technologies by focusing on embedding interactive 3D sketching and labelling co within digital documents and notes. Unlike other tools that primarily offer pre-made 3D models or environments, VISTA3D allows users to create and customize their 3D content directly in educational materials. This approach facilitates a deeper interaction with 3D models and concepts, enabling learners to visualize and understand complex information in a more hands-on manner.

3 STUDY DESIGN

3.1 Research Goal

The research goal spans multiple 3D visualization projects, including VISTA3D, various 3D educational tools, and SecondSkin. Each project aims to enhance knowledge transfer and education through innovative use of 3D visualizations. The primary objective is to develop user-friendly interfaces that support interactive 3D visualizations, integrating technologies like WebGL/WebGPU for efficient rendering. The scope includes ensuring these tools are accessible and engaging for diverse audiences, from students and educators to professional artists and designers. Deliverables for these projects comprise fully developed software platforms, comprehensive documentation for both users and developers, and a set of example visualizations demonstrating the capabilities of each tool. Ultimately, these projects aim to provide tools that enhance learning and design processes through intuitive and interactive visual experiences, making complex data and concepts more comprehensible and engaging. This includes improving the accessibility and effectiveness of educational content and facilitating creative workflows in design and architecture.

The scope inclusion [I] and exclusion [E] criteria are listed as follows:

- I1 Sketch with a stylus pen, finger, or mouse
- I2 Zoom and Panning canvas
- I3 Embed the VISTA3D Visualizer via iFrames
- I4 Export and Import artwork in an open file format in JSON
- I5 Build a library of example models
- I6 Import third-party models
- E1 Able to create multiple pages in the visualizer
- E2 Create animated cameras
- E3 Full note-taking application, just the visualizer

3.2 Research Questions

The research questions for our comparative study explore critical areas across various 3D visualization projects, aiming to optimize WebGL/WebGPU for enhanced 3D rendering, design user interfaces for broad accessibility, assess the educational impact of interactive 3D visualizations, tackle scalability challenges in educational platform integration, and examine the role of open-source development in tool sustainability and innovation. These questions address technical, user experience, and systemic challenges in developing and implementing advanced 3D visualization tools, laying the groundwork for a comprehensive investigation into making educational and design content more engaging, accessible, and effective.

- **RQ1:** How does the integration of interactive 3D visualization in web-based educational and design tools impact user engagement and comprehension of complex subjects compared to traditional 2D methods?
- **RQ2:** What are the technical and usability challenges in implementing WebGL/WebGPU for real-time 3D rendering in educational and design applications, and how can these be effectively overcome?
- **RQ3:** In what ways can open-source development models contribute to the sustainability and innovation of web-based 3D visualization tools?
- **RQ4:** How can user interfaces be designed to ensure broad accessibility and usability for diverse user demographics, including students, educators, and professional designers?
- **RQ5:** What scalability challenges arise when integrating interactive 3D visualizations into educational platforms, and what strategies can be employed to address these challenges?

3.3 Methodology

The knowledge acquired for this study was done with the help of the following resources:

(1) Foundational Papers from Supervision: These initial documents, provided by an academic advisor or supervisor, serve as a primer on the subject matter. Their analysis helps to define the trajectory and to formulate specific research questions.
(2) Exploration via Online Scholarly Databases: Utilization of academic search platforms such as IEEE Xplore, Google Scholar, ScienceDirect.
(3) Snowballing Technique: This strategy begins with a core collection of articles or papers, expanding the search to encompass further works cited within the original selection. The process iteratively continues, incorporating articles cited within newly discovered papers.
(4) Professional Networks and Forums: Engagement with professional online networks and academic forums. This involves participation in discussions, seeking recommendations from peers.

3.4 Threats to Validity

When evaluating the threats to validity in studies involving 3D visualization tools in education and design, it is crucial to consider various dimensions:

3.4.1 External Validity: This pertains to the generalizability of the study's findings beyond its specific context. A key threat is the diversity of educational settings, technological infrastructures, and user demographics where the tools might be implemented. Ensuring that the results are applicable across different environments and audiences is a significant challenge.

3.4.2 Internal Validity: This focuses on establishing causal relationships within the study. It is vital to ensure that any observed improvements in learning outcomes or user engagement are directly attributable to the tool itself and not confounded by external variables such as prior knowledge, teaching methods, or environmental factors.

3.4.3 Construct Validity: This concerns the degree to which the tools measure what they are intended to measure. Accurately assessing their impact on educational effectiveness and user engagement is essential. Ensuring that the metrics and methods used in the studies genuinely reflect the tools' intended educational and creative benefits is critical.

3.4.4 Conclusion Validity: This addresses the reliability and soundness of the conclusions drawn from the study. Ensuring that the research design is robust enough to avoid Type I (false positive) and Type II (false negative) errors is crucial for confidently asserting the tools' effectiveness. This involves rigorous experimental design, appropriate statistical analyses, and thorough consideration of potential biases and confounding factors.

In summary, addressing these threats to validity is essential for ensuring that research on 3D visualization tools in education and design provides reliable, generalizable, and accurate insights into their impact.

4 COMPARATIVE ANALYSIS

This subsection explores a range of projects and research studies related to 3D visualization in education.

4.1 3D Educational Tools

A variety of 3D visualization tools have significantly impacted the field of education, demonstrating the widespread benefits of this technology.

4.1.1 Google Expeditions. Google Expeditions allows students to embark on virtual reality (VR) field trips, transforming abstract concepts into tangible experiences. This tool has been particularly effective in geography and history classes, where students can virtually visit ancient ruins or explore distant ecosystems, thereby enhancing their engagement and understanding [24].

4.1.2 zSpace. zSpace combines augmented reality (AR) and VR to create immersive learning experiences across subjects like biology and physics. By manipulating 3D models of the human body or simulating physics experiments, students can gain a deeper comprehension of complex topics[25].

4.1.3 Unity3D. Unity3D, widely used in medical training, enables the creation of realistic simulations for studying human anatomy and practising surgical procedures. This application not only improves spatial understanding but also provides hands-on practice in a risk-free environment. These examples highlight how 3D visualization tools can enrich educational content, making learning more interactive and effective by providing students with opportunities to explore and interact with content in ways that traditional methods cannot offer [20].

4.2 CASSIE

4.2.1 Introduction to CASSIE. CASSIE is an innovative conceptual modelling system designed for Virtual Reality (VR) environments. It enables users to create 3D models through freehand mid-air sketching combined with a sophisticated 3D optimization framework. This framework facilitates the creation of connected curve network armatures, which are predictively surfaced using patches with C0 continuity. CASSIE's balance of interactivity and automation offers a seamless 3D drawing interface that supports freehand curves, curve networks, and surface patches [26].

4.2.2 Key Features and Functionality. CASSIE stands out for its ability to encourage and assist users in drawing consistent networks of curves, easing the transition from freehand ideation to concept modelling. The system integrates several key features:

- **Freehand Mid-Air Sketching:** Users can draw in a 3D space using natural hand movements, allowing for intuitive creation of shapes and structures.
- **Curve Network Armatures:** The system automatically optimizes 3D strokes to form structured curve networks, ensuring geometric accuracy and coherence.
- **Surface Patches:** Predictive algorithms generate surface patches from curve networks, providing a clear and detailed representation of the conceptual model.

These features collectively enable users to seamlessly transition from initial ideation sketches to detailed concept models.

4.2.3 User Study and Results. A comprehensive user study involving twelve participants, including both professional designers and amateurs, was conducted to evaluate CASSIE's effectiveness. The study focused on three main components of the system:

- **Freehand Mid-Air Drawing:** This aspect was assessed for its ability to facilitate ideation without significant constraints.
- **Armature Optimization:** The optimization of strokes into precise curve networks was evaluated for its usability and effectiveness in enhancing the modelling process.
- **Patch Surfacing:** The automatic creation of surface patches was tested for its contribution to the overall modelling experience.

The results of the study indicated that CASSIE successfully supports both freehand ideation and structured concept modelling. Participants found the system to be on par with traditional freehand sketching in terms of user experience and expressivity, while also enabling the creation of sophisticated 3D models suitable for downstream applications.

4.2.4 Contributions and Impact. CASSIE makes several significant contributions to the field of immersive design and concept modelling:

- **Integrated Ideation and Concept Modelling:** By combining freehand sketching with automatic optimization, CASSIE bridges the gap between initial design ideas and refined concept models.
- **Enhanced User Experience:** The system's intuitive interface and real-time feedback encourage creativity and precision, making it accessible to both professionals and hobbyists.
- **Diverse Applications:** The 3D models created using CASSIE are suitable for a range of applications, including sculpting, engineering, and fabrication.

4.2.5 Conclusion. CASSIE exemplifies the potential of VR technologies in transforming the design and modelling process. By offering a unified platform for both ideation and concept development, CASSIE not only enhances the efficiency and quality of 3D modelling but also democratizes access to advanced design tools. This case study highlights the system's capabilities and its impact on the field of immersive design, paving the way for future innovations in VR-based modelling [26].

4.3 Strokes2Surface: Bridging Freehand Sketching and Digital Modelling in Architectural Design

Free-form architectural design often involves two essential stages: concept design and digital modelling. During the concept design stage, designers favour freehand sketching due to its low overhead in representing, exploring, and communicating geometric ideas. This stage allows designers to tap into their intuition and achieve a state of mental flow that might be difficult to achieve otherwise. Subsequently, the digital modelling stage ensues, where the sketch serves as a visual reference for manually creating and editing a 3D digital model, which can be processed for presentation, structural analysis, manufacturing, or other downstream design pipelines. Traditionally, architects and designers relied on pen and paper during the ideation process. However, the growing availability of 3D sketching interfaces and Augmented, Virtual, and Mixed Reality (AR/VR/MR) technologies has led to a paradigm shift. These emerging environments allow designers to sketch in 3D, enhancing efficiency and maintaining better supervision over their creations. This shift has sparked interest among architects and experts, leading to explorations of architectural design within these environments [5].

Despite the advantages, manually translating a sketch into a digital model requires considerable time and is susceptible to misinterpretations, highlighting the need for an automated reconstruction pipeline. Recent studies have shown that 2D design sketches can be lifted into 3D digital models, and several 3Ds, AR, VR, and MR interfaces come with a coupled reconstruction pipeline allowing sketch-based modelling. However, most of these systems target industrial design, which operates under different assumptions from architectural design, thus questioning their applicability. Many existing 3D sketch-based modelling methods impose interface-specific constraints or progressively neaten strokes on the fly to facilitate modelling. These constraints can inhibit the designer's freedom and disrupt the ideation process, leading to a loss of authorship and control over their creations. This highlights the need for an automated geometry reconstruction method tailored specifically for architectural design, functioning akin to a "magical button" that captures the design intention and translates the completed sketch into the desired geometry in an offline manner [23].

4.3.1 The 4D Drawing Interface. Strokes2Surface is built upon a 4D sketching interface for architectural design, utilizing a tablet (iPad) and a stylus (Apple Pencil). The interface enables the creation of 4D sketches by employing 3D canvases, where 2D strokes drawn on the tablet are projected onto the canvases, forming 3D strokes. Temporal data of all strokes are continuously captured, providing the fourth dimension (timestamp) to the sketch. The interface includes a ground plane and offers various geometric primitives as preset canvases, such as planes, cubes, spheres, and cylinders. The designer can transform these canvases and control the camera viewpoint. Once the camera and canvas are in the desired position, the designer can lock both and start drawing strokes on the canvas. The 2D strokes are ray-cast from the camera viewpoint to the canvas, creating 3D strokes rendered in different forms based on the chosen brush type. Designers can use multiple canvases, enabling the design of complex architectural objects. A 3D grid aids in maintaining accurate scale measurements, and additional metadata is recorded to facilitate data-driven sketch analysis. Properties recorded include brush colour, width, camera position, rotation, canvas ID, and transformation matrix, as well as normal, tilt, twist, and pressure for each stroke polyline vertex [23].

4.3.2 ML-Models for Geometry Reconstruction. Strokes2Surface comprises three Machine Learning (ML) models that process the 3D strokes' polyline vertices and extracted features to reconstruct the intended geometry in an offline process initiated when the designer completes the concept design sketch. The first model, a meta estimator, classifies the Shape versus Scribble strokes. Subsequently, two clustering models parse strokes of each type into separate groups, representing either oversketched strokes forming a single boundary or edge, or a single face of the geometry. Inspired by sketch beautification methods, Shape clusters are consolidated into aggregate curves using cubic B-spline approximation. A well-connected curve network is then formed by recovering the intended topology of the curves as a minimization problem. Scribble clusters guide the pipeline to infer which curve network cycles must bound patches and which must not, facilitating the reconstruction of the user-intended geometry [2].

4.3.3 Evaluation and Usability. The evaluation of the Strokes2Surface pipeline is threefold. First, architectural sketching practices and the usability of the pipeline in architectural design are confirmed via a user study. Second, the choice of features is validated through statistical analysis and ablation tests on the dataset. Finally, the outputs produced by different steps of the pipeline are compared against point cloud, stroke cloud, and curve network surfacing methods. Strokes2Surface demonstrates a significant advancement in bridging the gap between freehand sketching and digital modelling in architectural design, offering a seamless and intuitive tool for designers to translate their conceptual sketches into precise digital models.

4.4 SecondSkin: Sketch-Based Modelling for Layered 3D Structures

SecondSkin is an innovative sketch-based modelling system designed for creating structures composed of layered, shape-interdependent 3D volumes. The project introduces a novel approach built on three key insights derived from an analysis of representative artist sketches. Firstly, it was observed that closed loops of strokes typically define surface patches that bound volumes, working in conjunction with underlying surfaces. Secondly, a significant majority of these strokes correspond to a small set of curve-types that describe the 3D geometric relationship between the stroke and underlying layer geometry. Thirdly, a few simple geometric features enable consistent classification of 2D strokes into the proposed set of 3D curve-types [11].

The *SecondSkin* algorithm processes strokes as they are drawn, identifies their curve-type, and interprets them as 3D curves on and around the underlying 3D geometry, using other connected 3D curves for context. Curve loops are automatically surfaced and transformed into volumes bound to the underlying layer, creating additional curves and surfaces as necessary. Stroke classification by 15 viewers on a suite of ground truth sketches validates the curve-types and the classification algorithm. The system is evaluated through a compelling gallery of layered 3D models, which would be tedious to produce using current sketch modellers.

SecondSkin is, to the best of our knowledge, the first sketch-based system focused on the creation of layered 3D solid models. Our technical contribution includes a principled approach to the interactive inference of layered structures sketched over existing geometry. We spoke to artists, analysed sketches, hypothesized, and perceptually validated curve-types that describe the majority of strokes sufficient to create compelling 3D models. Specifically, we formulated a set of curve-types commonly used to depict layered structures and developed an algorithm that infers 3D curves from sketched 2D strokes and their curve-type. Our implementation introduces a novel drawing workflow that facilitates the creation of curves, surfaces, and volumes.

The *SecondSkin* system is interactive and designed for use with a graphics tablet. It supports single-view sketching, but also allows free camera manipulation. Implemented on a PC with an Intel i7 CPU, 8 GB of RAM, and an ATI Radeon HD 5700, the system operates in real-time, with minimal pauses during interactive construction of mesh surfaces and volumes. The system utilizes a kd-tree for 3D distance calculations to determine height values between newly sketched strokes and the base layer. Distance offset surfaces are approximated on the GPU using a vertex shader to inflate the mesh, a method found reasonable since these surfaces are only used for stroke projection from the current view [11].

4.4.1 Layered Curve, Surface, and Volume Workflow. The *SecondSkin* workflow includes typical sketch-based modelling functions such as erase gestures, stroke smoothing, and global symmetry. Users sketch strokes to construct curves, surfaces, and volumes in the scene, similar to drawing with pen and paper. The system segments closed loops at inflections and points of high curvature to form surfaces and volumes. When a segment in the curve is detected, a 2D preview of the completed closed loop is shown to the user. At any time, there is an active base layer forming the geometry relative to which new strokes are inferred in 3D and placed in the active drawing layer. All layers below the active drawing layer form the underlying 3D geometry, while layers above it, if present, are passive and serve as visual references. Although *SecondSkin* has limited layer editing and management functionality, a layer editor similar to that found in image editing software like Adobe Photoshop is envisaged and implementable.

The system uses three geometric primitives: curves, surfaces, and volumes. These primitives are defined using a solid modelling structure, where surfaces are bound by closed sets of curves, and volumes are bound by closed sets of surfaces. The system maintains connections between primitives using a graph structure. When closed loops are detected in the curve graph, a surface is constructed. Users can also form closed loops by sketching smooth strokes connecting 3D curves in the scene.

In summary, *SecondSkin* provides a sophisticated tool for artists and designers to create complex, layered 3D models interactively. The system's ability to interpret and process sketches into 3D structures in real-time, while maintaining a user-friendly interface, represents a significant advancement in sketch-based modelling technology.

4.5 Comparative Analysis of 3D Visualization Projects in Education and Design

4.5.1 Introduction. The rapid advancement of 3D visualization technologies has profoundly impacted various fields, including education and architectural design. This section presents a comparative analysis of three innovative projects: *VISTA3D*, *3D Educational Tools*, and *SecondSkin*. Each project exemplifies the unique applications of 3D modelling and visualization technologies, highlighting both their similarities and differences in approach, implementation, and outcomes.

4.5.2 VISTA3D: Enhancing Visual Learning. *VISTA3D* is a project aimed at improving visual learning through interactive 3D models. The project focuses on creating detailed and interactive 3D visualizations to aid in the comprehension of complex subjects, particularly in the fields of science and engineering. By allowing students to manipulate and explore 3D models, *VISTA3D* enhances engagement and facilitates a deeper understanding of abstract concepts. The project leverages advanced 3D modelling software and virtual reality (VR) environments to create immersive learning experiences [7].

4.5.3 3D Educational Tools: Broadening Learning Horizons. Various 3D educational tools have significantly impacted the field of education. For instance, *Google Expeditions* enables students to embark on virtual reality field trips, transforming abstract concepts into tangible experiences. This tool is particularly effective in geography and history classes, where students can virtually visit ancient ruins or explore distant ecosystems. Similarly, *zSpace* combines augmented reality (AR) and VR to create immersive learning experiences across subjects like biology and physics. *Unity3D* is widely used in medical training, enabling the creation of realistic simulations for studying human anatomy and practising surgical procedures. These examples demonstrate how 3D visualization tools can enrich educational content, making learning more interactive and effective.

4.5.4 SecondSkin: Sketch-Based Modelling for Layered 3D Structures. *SecondSkin* is a sketch-based modelling system focused on the creation of structures composed of layered, shape-interdependent 3D volumes. This project is built on insights from an analysis of artist sketches, identifying common curve-types and geometric features that allow consistent classification of 2D strokes into 3D curves. The *SecondSkin* algorithm processes strokes as they are drawn, interprets them as 3D curves on underlying geometry, and automatically generates volumes bound to the underlying layers. This system is particularly beneficial for artists and designers, facilitating the creation of complex 3D models through an intuitive sketch-based interface [11].

4.5.5 Comparative Analysis. A comparative analysis of the aforementioned projects reveals key similarities and differences:

4.5.6 Similarities.

- **Common Goals:** All three projects aim to enhance engagement and comprehension through the use of 3D visualization technologies.
- **Interactive Models:** Each project employs interactive 3D models to facilitate experiential learning and design, allowing users to manipulate and explore content in an immersive manner.
- **Positive Impacts:** These projects demonstrate positive impacts on motivation, retention of information, and the ability to understand complex concepts.

4.5.7 Differences.

- **Technological Platforms:** The projects utilize varied technological platforms and tools, such as VR, AR, and advanced 3D modelling software.
- **Target Demographics:** The target demographics differ, with *VISTA3D* and *3D Educational Tools* primarily focusing on educational settings ranging from K-12 to higher education, while *SecondSkin* targets professional artists and designers.
- **Subject Areas:** The educational content and subject areas covered by each project vary significantly. *VISTA3D* and *3D Educational Tools* cover a broad range of subjects, including science, geography, history, biology, and physics. In contrast, *SecondSkin* focuses on architectural and artistic design.

4.5.8 Conclusion. This analysis highlights emerging trends in the use of 3D visualization technologies, such as the increasing integration of VR and AR in educational and design contexts. It also identifies gaps in current research, such as the need for more long-term studies on the effectiveness of these tools. The comparative insights underscore the transformative potential of 3D visualization in enhancing learning and creative processes across diverse fields.

5 RESULTS

5.1 RQ1: Impact on User Engagement and Comprehension

The integration of interactive 3D visualization in web-based educational and design tools has shown significant positive impacts on user engagement and comprehension of complex subjects compared to traditional 2D methods. According to Samy A. Azer [7], while further research is needed to determine the full effects of employing 3D anatomy models in the classroom, existing studies suggest short-term performance increases. Additionally, "*Studying natural history far from the museum: the impact of 3D models on teaching, learning, and motivation*" [16] highlights the immersive engagement experience provided by 3D models, aiding educators in explaining scientific notions effectively. For instance, in the teaching of biology, 3D models aid in the comprehension of molecular and anatomical structures, thereby enhancing learning outcomes.

5.2 RQ2: Technical and Usability Challenges

Implementing WebGL/WebGPU for real-time 3D rendering in educational and design applications presents several technical and usability challenges. These include browser compatibility, performance optimization for complex 3D models, and the learning curve for developers unfamiliar with 3D graphics programming. Strategies such as polyfills, progressive enhancement, and engaging with the open-source community can help overcome these challenges and ensure a seamless user experience. As mentioned by Park [21] and Murali [18], leveraging polyfills to fill in the gaps in browser support, optimizing performance, and following best practices in UX/UI design are essential steps in addressing these challenges.

5.3 RQ3: Contribution of Open-Source Development

Open-source development models can contribute significantly to the sustainability and innovation of web-based 3D visualization tools. By fostering collaboration and transparency, open-source projects like VISTA3D, 3D Educational Tools, and SecondSkin can benefit from community feedback and contributions, leading to continuous improvement and innovation. As outlined by Andersen and Gottschalk [3], the open-source model fosters innovation through collaborative development, enhances security through transparency, and provides cost savings for both individuals and organizations.

5.4 RQ4: Designing for Accessibility

User interfaces must be designed to ensure broad accessibility and usability for diverse user demographics, including students, educators, and professional designers. This involves considerations such as screen reader compatibility, keyboard navigation, color contrast, and font size. Providing alternative text for images and multimedia content, along with customizable settings, can enhance accessibility. Following accessibility guidelines and engaging with users from diverse backgrounds can ensure that the user interface meets the needs of all users.

5.5 RQ5: Scalability Challenges and Strategies

Integrating interactive 3D visualizations into educational platforms poses scalability challenges related to infrastructure, data management, and user support. Cloud-based solutions, data caching, and optimization techniques can address infrastructure and data management challenges, while user training and support resources can assist educators and students in navigating the platform effectively. Scaling strategies such as load balancing, horizontal scaling, and vertical scaling can ensure that the platform remains accessible and responsive even as user traffic increases.

5.6 Impact on learning using 3D models

According to Samy A. Azer [7], more research is still needed to determine the effects of employing 3D anatomy models in the classroom. Further high-quality research is required to evaluate the effects of 3D models on the advancement of knowledge, clinical skills, integration, and application, even if some studies have indicated short-term performance increases.

A different finding from "*Studying natural history far from the museum: the impact of 3D models on teaching, learning, and motivation*" [16] is that 3D models give students an immersive engagement experience. 3D models have been a significant aid to educators in explaining scientific notions in science classes. One of the key benefits of using these models is that they are simple for teachers and students to utilize and provide them the opportunity to see structures from various perspectives. For instance, in the teaching of biology, 3D models can aid in the comprehension of molecular and anatomical structures and demonstrate the efficacy of using three-dimensional models to teach genetics students about DNA structure.

In a different study, the identification of animal internal structures was done by comparing 2D and 3D models. In this study, pupils who drew using 3D models included more details than those who drew using only 2D models [22]. In this sense, innovative teaching resources like 3D models served as crucial visual aids for students' learning. The 1950 discovery of the alpha-helix protein structure by Linus Pauling serves as a clear illustration of how the use of visual aids in three-dimensional models may significantly influence the advancement of knowledge. In addition to making the discovery easier to understand, this representation inspired other researchers to work on building models that depict structures at various scales. Visual resources improve the brain's ability to remember and comprehend abstract ideas.

5.7 Relevant Technologies

WebGL

WebGL (Web Graphics Library) is a JavaScript API that allows for rendering interactive 3D and 2D graphics within any compatible web browser without the use of plug-ins. It is based on OpenGL ES, a software API that simplifies the creation of complex visuals on embedded systems. WebGL is integrated directly into the web standards, enabling graphics to run natively in the browser and allowing developers to create detailed graphical applications and games [17].

WebGPU

WebGPU is an emerging standard that provides a modern way to access GPU resources in web applications. It is designed to offer high performance and more balanced CPU/GPU usage compared to older technologies like WebGL. WebGPU operates at a lower level, allowing for more efficient control over graphics rendering and computational tasks. It's based on the Vulkan API and is being developed to work across multiple platforms and operating systems, aiming to unify the web graphics landscape with a consistent and powerful API [9].

Three.js

Three.js is a cross-platform JavaScript library and application programming interface (API) used to create and display animated 3D computer graphics in a web browser. It uses WebGL underneath and provides a simpler interface for creating rich 3D visuals and animations. Three.js allows developers to bring 3D content to the web with relatively easy integration and is widely used for web-based games, art, and interactive websites [1].

IFrame

An iframe, or inline frame, is an HTML element that allows an external webpage to be embedded within the current webpage. It acts as a window or a portal, through which content from another web source can be displayed directly on the original page. This is particularly useful for incorporating third-party content like videos, interactive maps, or widgets into a website. Iframes can be customized with attributes such as size, scrolling options, and border visibility to integrate seamlessly with the rest of the page content.

5.8 Implementing a Web3D Application

The essence of Web3D technology lies in its browser-based 3D graphics APIs, enabling GPU-powered rendering and physics for 3D graphics across various web browsers. With HTML5's advancement, 3D rendering has shifted from client-based to web-based platforms, employing APIs like Stage3D, WebGL, WebGPU, and WebXR. These APIs contribute to the widespread application of 3D visualization on the web.

Implementing WebGL/WebGPU in educational applications presents technical challenges such as browser compatibility and performance optimization for complex 3D models. Additionally, usability issues arise, including the need for intuitive user interfaces and accessibility for all users. To address these challenges, developers can leverage techniques like polyfills for broader compatibility, optimization methods for efficient rendering, and adherence to UX/UI design best practices. Engaging with the open-source community can also enhance usability through shared resources and feedback.

Polyfills are JavaScript scripts that implement features not supported by a browser, allowing developers to use modern APIs and functionalities across older browsers lacking these capabilities natively. They bridge gaps in browser support, ensuring a consistent experience for all users. For example, the Promise API, essential for asynchronous operations, can be polyfilled to enable its usage in older browsers. Similarly, the fetch API for network requests can be polyfilled in browsers supporting only older XMLHttpRequest.

5.9 Action Plan

Expanding VISTA3D using WebGL/WebGPU involves several steps:

(1) **Familiarize with Technologies**: Learn JavaScript for scripting and HTML/CSS for UI. Acquire knowledge of WebGL for current browser graphics capabilities or WebGPU for next-gen graphics.
(2) **Study Penzil's Architecture**: Understand Penzil's implementation and its utilization of three.js for 3D visualization.
(3) **Integrate 3D Labeling**: Develop features for adding, editing, and displaying labels on 3D models within the VISTA3D environment.
(4) **Implement Import and Export Functions**: Enable users to import existing 3D models and export their creations and labels.
(5) **Enhance User Interface**: Design intuitive UI/UX for interacting with 3D models and labels.
(6) **Testing and Optimization**: Ensure compatibility across devices and browsers, focusing on performance optimization.
(7) **Documentation and Open Source Community Engagement**: Write comprehensive documentation and engage with the open-source community for feedback and contributions.

Resources:

- WebGL Fundamentals: Provides basics of WebGL.
- Introduction to WebGPU: Offers an understanding of WebGPU's capabilities.
- Three.js Documentation: Provides insights into using three.js effectively.

These steps and resources will guide the enhancement of VISTA3D, leveraging Penzil's architecture to create a more interactive and useful tool for embedding 3D models and sketches in documents.

5.10 Open-source 3D Visualization Tools

Penzil is a web application designed for 3D sketching, utilizing three.js and Vue for its development. It aims to be a simplified web version of Blender's Grease pencil, optimized for use with a tablet and pen. Penzil allows users to draw or erase on a 3D canvas, adjust its position, and manipulate the camera view. While Penzil is currently a local application, it supports exporting in a format compatible with Blender's grease pencil. The project is available as-is, offering potential for further development and integration with other tools.

As an open-source 3D sketching tool, Penzil can significantly enhance educational and knowledge transfer processes. Its interactive 3D models provide a dynamic learning experience, aiding in the comprehension of complex spatial concepts or structures. Additionally, Penzil's potential for labeling and annotating 3D objects can facilitate detailed explorations in scientific models, architectural designs, or historical reconstructions, making it valuable for educators and students alike.

Expanding Penzil with object labeling capabilities using WebGL/WebGPU involves integrating interactive 3D labeling tools. This includes developing functionalities for attaching text labels to specific points or objects within the 3D environment, creating a user interface for entering labels, and rendering techniques for displaying text within the 3D scene. Leveraging WebGL/WebGPU ensures smooth rendering and interaction with these labels, enhancing the educational utility of Penzil by allowing detailed annotations and descriptions of 3D models.

5.11 Open-source Benefits

The benefits of open-source software include fostering innovation through collaborative development, enhancing security through transparency, and providing cost savings for both individuals and organizations. By encouraging community participation and sharing resources, open-source projects like VISTA3D, 3D Educational Tools, and SecondSkin can benefit from diverse perspectives and contributions, leading to continuous improvement and innovation. Additionally, the open-source model promotes flexibility and customization, allowing users to adapt software to meet their specific needs and preferences. Furthermore, open-source development models contribute to the sustainability and innovation of web-based 3D visualization tools in several ways:

(1) **Collaborative Development**: Open-source projects encourage collaboration among developers worldwide, leading to rapid iteration and improvement. By allowing contributions from a diverse community of developers, these projects benefit from a wide range of expertise and perspectives.

(2) **Transparency and Trust**: The open nature of source code fosters transparency, allowing users to inspect the code for security vulnerabilities and ensure the integrity of the software. This transparency builds trust among users and promotes confidence in the reliability of open-source tools.
(3) **Cost Savings**: Open-source software is typically available for free, reducing the financial barriers to access for individuals and organizations. This affordability makes web-based 3D visualization tools more accessible to a broader audience, including educational institutions, small businesses, and independent creators.
(4) **Customization and Adaptability**: Open-source projects provide flexibility for users to customize and adapt the software to meet their specific needs. Whether modifying existing features or adding new functionality, users have the freedom to tailor the software to suit their requirements, fostering innovation and creativity.
(5) **Community Support and Documentation**: Open-source projects often have active communities of users and developers who provide support, documentation, and resources. This community-driven approach ensures that users have access to the information and assistance they need to effectively use and contribute to the software.

In summary, open-source development models play a crucial role in the sustainability and innovation of web-based 3D visualization tools like VISTA3D, 3D Educational Tools, and SecondSkin. By fostering collaboration, transparency, affordability, customization, and community support, open-source projects enable the continuous improvement and evolution of these tools, ultimately benefiting users and developers alike.

6 DISCUSSION

The discussion of 3D visualization technologies in educational settings synthesizes insights from a literature review encompassing diverse dimensions of research, technological advancements, and potential applications.

6.1 Publication Trends

An analysis of publication trends reveals a notable surge in research output concerning interactive 3D visualization. This trend underscores a growing interest within both academic and industrial spheres to leverage immersive tools for educational enhancement. Studies span a wide array of disciplines, signalling a shift from traditional fields like engineering to embrace arts, sciences, and medical education. Geographically, contributions emanate predominantly from North America and Europe, with emerging participation from Asia, reflecting a global acknowledgment of the significance of advanced visualization technologies in education.

6.2 Research Focus

Research in 3D visualization technologies gravitates towards several focal points:

- Technological Advancements: Studies concentrate on refining WebGL and WebGPU capabilities, with an emphasis on enhancing rendering efficiency and real-time interaction within web browsers.
- Educational Impact: A considerable portion of the literature examines the efficacy of 3D visualization tools in improving learning outcomes. Findings consistently demonstrate heightened comprehension of complex spatial concepts and increased engagement, particularly in subjects demanding abstract thinking.
- Usability and Accessibility: Research endeavours delve into UX design to make 3D tools more user-friendly and accessible across diverse user demographics, encompassing varying levels of technological proficiency and abilities.

6.3 Potential for Industrial Adoption

The potential for industrial adoption of technologies such as VISTA3D appears promising, evidenced by interest from sectors beyond education, including architecture, healthcare, and digital content creation. Industries recognize the value of 3D visualization not only for training and education but also for planning, designing, and marketing purposes. The open-source nature of many of these tools facilitates customization and integration into diverse industrial applications, potentially lowering entry barriers and costs. Furthermore, the literature suggests a symbiotic relationship between educational technology and industrial demands, wherein tools initially developed for educational purposes find utility in commercial settings. This convergence underscores the dual benefits of investing in such technologies—enhancing educational outcomes and furnishing industries with robust visualization and interaction tools. In essence, the discussion underscores the dynamic and evolving landscape of 3D visualization technologies. As these tools evolve and proliferate across educational and industrial domains, they offer substantial benefits, augmenting both learning experiences and professional interactions with complex data and designs across diverse sectors.

6.4 Summary

This section synthesizes the findings from the exploration of 3D visualization tools in educational and design contexts, addressing the research questions posed at the outset of the study. The insights gathered extend beyond any single tool, offering a broader perspective on the application and effectiveness of interactive 3D visualizations.

- **Impact on User Engagement and Comprehension (RQ1)**: The integration of interactive 3D visualization in educational and design tools markedly improves user engagement and comprehension of complex subjects. 3D models provide an immersive experience that enhances spatial understanding and retention, compared to traditional 2D methods. These findings suggest that educational tools incorporating 3D elements can significantly enhance learning outcomes.
- **Technical and Usability Challenges (RQ2)**: Implementing WebGL/WebGPU for real-time 3D rendering involves technical challenges such as browser compatibility and performance optimization. Addressing these challenges requires strategies like using polyfills, progressive enhancement, and leveraging community contributions for continuous tool improvement and to ensure a seamless user experience.
- **Contribution of Open-Source Development (RQ3)**: Open-source development models play a crucial role in sustaining and innovating web-based 3D visualization tools. These models encourage widespread collaboration, reduce costs, and enhance tool adaptability and quality through community feedback and contributions. This collaborative approach helps in keeping the tools up-to-date and relevant.
- **Designing for Accessibility (RQ4)**: User interfaces must be designed to ensure broad accessibility and usability for diverse user demographics, including students, educators, and professional designers. Key considerations include screen reader compatibility, keyboard navigation, color contrast, and font size. Engaging users from various backgrounds in the design process can ensure that interfaces meet diverse needs.
- **Scalability Challenges and Strategies (RQ5)**: Integrating interactive 3D visualizations into educational platforms presents scalability challenges related to infrastructure, data management, and user support. Effective strategies to address these challenges include using cloud-based solutions, data caching, optimization techniques, and providing comprehensive user training and support resources.
- **Relevant Technologies**: Technologies such as WebGL, WebGPU, Three.js, and iframes are integral to the implementation of interactive 3D visualizations in web-based applications. A solid understanding of these technologies is essential for developing effective and efficient educational and design tools.
- **Action Plan**: Expanding capabilities in 3D visualization tools involves familiarizing with relevant technologies, understanding existing tool architectures, integrating advanced features like 3D labeling, enhancing user interfaces, optimizing performance, thorough testing, and community engagement. Resources such as documentation and community forums are vital for supporting these efforts.
- **Open-source 3D Visualization Tools**: Open-source tools such as Penzil provide valuable contributions to educational and design fields by offering interactive 3D models that aid in comprehension of complex concepts. These tools can be enhanced with features like interactive labeling and annotation, leveraging technologies like WebGL/WebGPU for improved performance and usability.
- **Open-source Benefits**: Open-source development models contribute significantly to the sustainability and innovation of web-based 3D visualization tools. They foster collaboration, transparency, affordability, customization, and community support. These benefits ensure continuous improvement and adaptability, making these tools more effective and accessible to a broad audience.

In conclusion, the integration of advanced 3D visualization tools in educational and design contexts has transformative potential. Addressing the technical and usability challenges and embracing open-source development models can significantly enhance the effectiveness, sustainability, and innovation of these tools, benefiting users across various fields.

7 CONCLUSION

In conclusion, this study delves into the multifaceted realm of integrating interactive 3D visualization into web-based educational and design tools. Through the exploration of several research questions, we've unearthed critical insights into the impact, challenges, and potential solutions within this domain.

Firstly, the integration of interactive 3D visualization appears to significantly enhance user engagement and comprehension of complex subjects compared to traditional 2D methods, as evidenced by various studies and scholarly discourse. This immersive approach fosters a deeper understanding of spatial concepts and structures, thereby enriching the learning experience for students and educators alike. Secondly, while the adoption of WebGL/WebGPU for real-time 3D rendering in educational and design applications presents promising opportunities, it also poses technical and usability challenges. These hurdles encompass browser compatibility, performance optimization, and accessibility considerations. However, through the diligent application of polyfills, optimization techniques, and community engagement, these challenges can be effectively mitigated. Thirdly, the integration of open-source development models emerges as a pivotal factor in fostering sustainability and innovation within web-based 3D visualization tools. By embracing collaboration, transparency, and community-driven contributions, these models catalyse progress and propel the evolution of such tools towards greater accessibility and functionality. Fourthly, user interface design plays a crucial role in ensuring broad accessibility and usability across diverse user demographics. By adhering to inclusive design principles and prioritizing user feedback, interfaces can be tailored to accommodate the needs and preferences of students, educators, and professional designers alike.

Lastly, scalability challenges may arise when integrating interactive 3D visualizations into educational platforms. These challenges encompass issues related to data management, system performance, and user scalability. However, by implementing strategies such as modular design, cloud-based solutions, and adaptive rendering techniques, these challenges can be effectively addressed, ensuring seamless scalability and robust performance. In essence, this study underscores the transformative potential of integrating interactive 3D visualization into web-based educational and design tools. By navigating the intricacies of technology, user experience, and community engagement, we can unlock new avenues for learning, creativity, and innovation in this dynamic landscape.

REFERENCES

[1] 2023. Utilization of Three.JS and Unity to Make A Webgl API to Perform 3D Immersiveness In Web. *American Journal of Electronics Communication* 3, 4 (2023).

[2] Marta Alvir, Luka Grbčić, Ante Sikirica, and Lado Kranjčević. 2023. Reconstruction and analysis of negatively buoyant jets with interpretable machine learning. *Marine pollution bulletin* 190 (2023), 114881.

[3] Morten Andersen-Gott, Gheorghita Ghinea, and Bendik Bygstad. 2012. Why do commercial companies contribute to open source software? *International Journal of Information Management* 32, 2 (2012), 106–117. https://doi.org/10.1016/j.ijinfomgt.2011.10.003

[4] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. 2018. Symbiosissketch: Combining 2d & 3d sketching for designing detailed 3d objects in situ. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–15.

[5] Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George W Fitzmaurice. 2017. Experimental Evaluation of Sketching on Surfaces in VR.. In *CHI*, Vol. 17. 5643–5654.

[6] Rahul Arora and Karan Singh. 2021. Mid-air drawing of curves on 3d surfaces in virtual reality. *ACM Transactions on Graphics (TOG)* 40, 3 (2021), 1–17.

[7] Samy A. Azer and Sarah Azer. 2016. 3D Anatomy Models and Impact on Learning: A Review of the Quality of the Literature. *Health Professions Education* 2, 2 (2016), 80–98. https://doi.org/10.1016/j.hpe.2016.05.002

[8] Pouria Babahajiani, Lixin Fan, Joni-Kristian Kämäräinen, and Moncef Gabbouj. 2017. Urban 3D segmentation and modelling from street view images and LiDAR point clouds. *Machine Vision and Applications* 28, 7 (2017), 679–694.

[9] Satyadhyan Chickerur, Sankalp Balannavar, Pranali Hongekar, Aditi Prerna, and Soumya Jituri. 2024. WebGL vs. WebGPU: A Performance Analysis for Web 3.0. *Procedia Computer Science* 233 (2024), 919–928. https://doi.org/10.1016/j.procs.2024.03.281 5th International Conference on Innovative Data Communication Technologies and Application (ICIDCA 2024).

[10] Matt Cook, Zack Lischer-Katz, Nathan Hall, Juliet Hardesty, Jennifer Johnson, Robert McDonald, and Tara Carlisle. 2019. Challenges and strategies for educational virtual reality: Results of an expert-led forum on 3D/VR technologies across academic institutions. *Information Technology and Libraries* 38, 4 (2019), 25–48.

[11] Chris De Paoli and Karan Singh. 2015. SecondSkin: sketch-based construction of layered 3D models. *ACM Transactions on Graphics (TOG)* 34, 4 (2015), 1–10.

[12] Iñigo Fernández Del Amo, John Ahmet Erkoyuncu, Rajkumar Roy, Riccardo Palmarini, and Demetrius Onoufriou. 2018. A systematic review of Augmented Reality content-related techniques for knowledge transfer in maintenance applications. *Computers in Industry* 103 (2018), 47–71.

[13] Iñigo Fernández del Amo, John Ahmet Erkoyuncu, Rajkumar Roy, Riccardo Palmarini, and Demetrius Onoufriou. 2018. A systematic review of Augmented Reality content-related techniques for knowledge transfer in maintenance applications. *Computers in Industry* 103 (2018), 47–71. https://doi.org/10.1016/j.compind.2018.08.007

[14] Viet-Tham Huynh, Tam V Nguyen, and Minh-Triet Tran. 2023. Sketch2Reality: Immersive 3D Indoor Scene Synthesis via Sketches. In *Proceedings of the 12th International Symposium on Information and Communication Technology*. 863–869.

[15] Jamil Joundi, Yannick Christiaens, Jelle Saldien, Peter Conradie, and Lien De Marez. 2020. An explorative study towards using VR sketching as a tool for ideation and prototyping in product design. In *Proceedings of the Design Society: DESIGN Conference*, Vol. 1. Cambridge University Press, 225–234.

[16] Claudio Juan Bidau Kathleen Mahra da Silva Alcântara Castro, Talita Ferreira Amado and Pablo Ariel Martinez. 2022. Studying natural history far from the museum: the impact of 3D models on teaching, learning, and motivation. *Journal of Biological Education* 56, 5 (2022), 598–608. https://doi.org/10.1080/00219266.2021.1877774 arXiv:https://doi.org/10.1080/00219266.2021.1877774

[17] Catherine Leung and Andor Salga. 2010. Enabling WebGL. In *Proceedings of the 19th International Conference on World Wide Web (WWW '10)*. Association for Computing Machinery, New York, NY, USA, 1369–1370. https://doi.org/10.1145/1772690.1772933

[18] Shrihari Murali. 2024. JavaScript polyfills: Enhancing browser compatibility. https://medium.com/@shriharim006/javascript-polyfills-enhancing-browser-compatibility-c2e0b1344b51#:~:text=A%20polyfill%20is%20a%20piece,platform%20APIs%20in%20outdated%20environments.

[19] Alfred Oti and Nathan Crilly. 2021. Immersive 3D sketching tools: Implications for visual thinking and communication. *Computers Graphics* 94 (2021), 111–123. https://doi.org/10.1016/j.cag.2020.10.007

[20] Shu-Guang Ouyang, Gang Wang, Jun-Yan Yao, Guang-Heng-Wei Zhu, Zhao-Yue Liu, and Chi Feng. 2018. A Unity3D-based interactive three-dimensional virtual practice platform for chemical engineering. *Computer Applications in Engineering Education* 26, 1 (2018), 91–100.

[21] Shin-Hee Park. 2022. A Study on UX/UI Design Methodology as a Branding Strategy Using Digital Media: Focusing on UX/UI Education Cases. *Journal of Digital Contents Society* 23, 9 (Sept. 2022), 1661–1671. https://doi.org/10.9728/dcs.2022.23.9.1661

[22] Pavol Prokop, M.atej Prokop, Sue Tunnicliffe, and Carla Diran. 2010. Children's ideas of animals' internal structures. *Journal of Biological Education* Spring 2007 (12 2010), 62–67. https://doi.org/10.1080/00219266.2007.9656064

[23] S Rasoulzadeh, Michael Wimmer, and Iva Kovacic. 2023. Strokes2Surface: Recovering Curve Networks From 4D Architectural Design Sketches. *arXiv preprint arXiv:2306.07220* (2023).

[24] Yevhenii B Shapovalov, Zhanna I Bilyk, Artem I Atamas, Viktor B Shapovalov, and Aleksandr D Uchitel. 2018. The potential of using Google Expeditions and Google Lens tools under STEM-education in Ukraine. *arXiv preprint arXiv:1808.06465* (2018).

[25] Kathleen M Wolz. 2019. Building Faculty Competence and Self-Efficacy for Using Z Space Virtual Reality (VR) Software in the Classroom. (2019).

[26] Emilie Yu, Rahul Arora, Tibor Stanko, J Andreas Bærentzen, Karan Singh, and Adrien Bousseau. 2021. Cassie: Curve and surface sketching in immersive environments. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–14.