Bridging The Gap Between Imagination And Reality: VR Innovations in Design

Harshil Pandya - Bachelor of Creative Technologies,

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School of Future Environments **Supervisor: Clinton Watkins**

Abstract

Purpose:

This research investigates the evolving role of Virtual Reality (VR) and Augmented Reality (AR) in professional 3D design workflows, examining their current effectiveness, limitations, and potential for future development. As immersive technologies become more integrated into disciplines like industrial design, architecture, and product development, it becomes increasingly important to assess whether these tools meet the precision, control, and standardization required in professional environments. This study will center on two widely adopted VR applications: Gravity Sketch, valued for its CAD-compatible modeling features, and Open Brush, known for its expressive sketching capabilities. By analyzing their toolsets, user experiences, and design workflows, this research highlights how different approaches to immersive interaction either support or restrict both creative exploration and technical accuracy. The findings underscore a growing need for hybrid solutions that combine the freedom of intuitive interaction with the rigor of professional-grade precision.

Literature Review:

A significant gap exists in the current discourse surrounding VR design tools, particularly regarding their precision and applicability within real-world professional design workflows. Much of the existing literature emphasizes the immersive and engaging qualities of these tools, yet it offers limited analysis of their performance in tasks that require detailed modeling, fine adjustments, or seamless integration with CAD software. Critical features such as accurate snapping systems, precise measurement tools, and robust export compatibility are often overlooked. There is a noticeable lack of Applied testing in technically demanding use cases, making it difficult to assess the reliability and effectiveness of these tools beyond exploratory or artistic applications.

Design/methodology/approach:

This study employs a case study methodology supported by desktop-based tool analysis, expert reviews and use-case scenarios such as industry blogs and YouTube reviews, extensive secondary research drawn from academic publications, developer documentation, Unlike traditional user centered testing, this approach allows me to triangulate multiple forms of documented evidence to evaluate usability, tool precision, technical scalability, and software interoperability. Key evaluation metrics include ease of use, hand tracking fidelity, export format compatibility (e.g., FBX, OBJ, STEP), and integration with traditional desktop software like Blender, Rhino, and Maya.

Case Study:

To implement the proposed methodology, this study examined two distinct VR design tools: Gravity Sketch and Open Brush. Gravity Sketch is oriented toward technical modeling, offering features such as parametric surfaces and snapping tools that support structured design workflows. In contrast, Open Brush emphasizes freeform, brush-based creativity, prioritizing expressive interaction over precision. Evaluation of Gravity Sketch revealed its effectiveness in early-stage conceptual modeling; however, it lacked the fine-grained accuracy required for detailed design tasks. Open Brush demonstrated strengths in user experience and creative freedom, but its limitations in measurement accuracy, structured modeling capabilities, and export flexibility were evident. The comparative analysis revealed a fundamental divergence in design philosophy. Gravity Sketch is engineered for technical refinement, whereas Open Brush fosters an open-ended, expressive approach to immersive creation.

Research limitations/implications:

One limitation of this study is the absence of direct user testing, which restricts the ability to fully assess how these tools perform under varied real-world conditions. To address this, the research draws on a diverse range of credible sources, including insights from experienced designers, academic literature, and official developer documentation.

The findings indicate a clear need for further hands-on research, particularly in evaluating how immersive design tools function across different professional scenarios, a topic that remains underrepresented compared to other areas within VR research.

An additional limitation emerged during the development of the prototype. The process was hindered by the high computational demands of the software and the limited availability of comprehensive documentation and training resources. These challenges highlight the steep learning curve associated with next-generation immersive tools and underscore the importance of improving accessibility and support for professionals adopting these technologies.

Originality/value:

This research provides a practical examination of the flagship current VR/AR design tools, offering insights into their operational strengths and critical shortcomings in professional contexts. By identifying existing functional gaps and proposing technically grounded enhancements such as photogrammetry integration, this study contributes to a forward-looking roadmap for tool developers and industry stakeholders. It highlights the urgent need for VR systems that not only foster creative exploration but also deliver the precision and control demanded by modern design disciplines.

Keywords:

Virtual Reality, Gravity Sketch, Open Brush, 3D Modeling, Design Technology, CAD Integration, Immersive Workflows, Precision Tools, Photogrammetry, AI Stabilization

Paper Type:

Exegesis with a Practice-Based Research Component

Table of Contents:

Glossary:

3DoF: Three Degrees of Freedom; allows tracking of rotational movement only (pitch, yaw, and roll).

6DoF: Six Degrees of Freedom; allows full tracking of both rotational and positional movements.

AR Foundation: A Unity framework for building Augmented Reality applications across ARKit and ARCore platforms.

Augmented Reality: A technology that overlays digital information onto the physical world through a device like a smartphone or AR headset.

CAD: Computer-Aided Design; software used for precision drawing and technical illustration, widely used in engineering and architecture.

Eye Tracking: A method that detects and responds to where a user is looking, used to improve interface control and user interaction.

FBX: Filmbox; a file format used to transfer 3D assets between software platforms such as Unity and Maya.

Hand Tracking: The use of sensors or cameras to capture the movement and gestures of a user's hands in real-time.

Haptics: Technology that simulates touch through vibrations or force feedback, enhancing realism in VR experiences.

Mesh: A collection of vertices, edges, and faces that define the shape of a 3D object.

Mixed Reality: A hybrid environment that merges the real and virtual worlds where physical and digital objects coexist and interact in real time.

OBJ: A standard 3D geometry definition file format, used to store 3D models as collections of vertices, edges, and faces.

Passthrough: A feature in VR headsets that uses external cameras to display the real world inside the headset.

Photogrammetry: A technique that creates 3D models by analyzing and combining multiple 2D photographs of a real-world object. Meshroom: Software that processes photographs to produce 3D photogrammetric models.

Unity: A cross-platform game engine used to develop video games and simulations for computers, consoles, and VR/AR devices.

Virtual Reality: A computer-generated simulation of a 3D environment that can be interacted with using specialized equipment like a VR headset.

XR: Extended Reality; an umbrella term that includes VR, AR, and MR technologies.

XR Interaction Toolkit: A Unity toolkit that provides prebuilt components for building VR and AR interactions.

List of Figures (if any)

Attestation of Authorship

I hereby declare that this submission is my work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed: **Harshil Jigar Pandya Student** 20112688 Date: 14th August 2025

What functionalities and integrations are required in current VR/AR design tools to support professional-grade precision and efficient 3D modeling workflows?

1) Introduction

1.1 Background and Context

Immersive virtual reality environments enable designers to create and manipulate three-dimensional forms within spatially embodied contexts. What was once technologically speculative has become increasingly accessible through consumer-grade head-mounted displays and purpose-built design software. Contemporary platforms such as Gravity Sketch, Open Brush, and ShapesXR provide immersive modelling environments in which designers can sketch, sculpt, and evaluate spatial concepts at full scale.

These systems offer affordances not readily available in traditional desktop-based tools, including embodied navigation, spatial immersion, and real-time perspective shifting. Designers are able to sketch in three-dimensional space, move around and within models, and evaluate spatial relationships from multiple vantage points. Such capabilities can enhance intuitive understanding of proportion, scale, and spatial configuration.

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This contrast foregrounds a central tension: immersive systems priorities expressive freedom and spatial engagement, yet professional design contexts demand technical exactitude, measurement fidelity, and interoperability with established production pipelines. The persistence of this gap motivates the present research. This exegesis investigates how immersive VR environments might better support early-stage conceptual exploration while addressing the structural limitations that currently constrain their application in precision-driven design domains.

1.2 Why VR Design Matters Now?

Over the past decade, engagement with immersive technologies in design practice has fluctuated. While early enthusiasm positioned virtual reality as a transformative design medium, broader industry adoption has progressed unevenly. Recent advances in headset affordability, display resolution, tracking fidelity, and software interoperability have renewed interest among designers, engineers, and architects exploring immersive workflows.

Immersive environments offer affordances not readily available in desktop-based systems, including embodied spatial evaluation, full-scale walkthroughs, and real-time remote collaboration. These capabilities are increasingly being incorporated into early-stage design and prototyping contexts. Large automotive manufacturers such as Ford and BMW have reported the integration of VR within concept development and visualization processes. As noted by Morval (2025), BMW has incorporated VR across aspects of design and showroom experience, suggesting a shift toward immersive evaluation environments. Similarly, architecture and industrial design practices have adopted VR-based walkthroughs and AR overlays to support client communication and spatial visualization during preliminary development stages.

Beyond VR, augmented reality systems are also expanding the spatial computing landscape. Companies such as Meta are investing in AR hardware and interaction models that support spatial anchoring, gesture-based control, and real-time environmental overlays. These developments indicate a movement toward hybrid workflows in which immersive and physical environments intersect.

Despite these advancements, immersive technologies have not yet achieved widespread integration into high-precision professional design pipelines. Adoption remains concentrated in exploratory and presentation phases rather than detailed production modelling. Limitations related to input stability, measurement fidelity, interoperability with established CAD systems, and workflow continuity continue to constrain broader implementation. As a result, while industry interest persists, immersive systems currently function more as complementary tools than as direct replacements for established professional platforms.

1.3 Current VR Design Tools

Figure 1: Gravity Sketch Logo/Figure 2: Open Brush Logo/Figure 3: ShapesXR logo/Figure 4: Adobe Medium logo

Virtual reality design platforms such as Gravity Sketch, Open Brush, ShapesXR, and Adobe Substance 3D Modeler demonstrate the growing diversity of immersive creative tools. Each platform reflects a distinct design philosophy. Gravity Sketch positions itself at the intersection of spatial creativity and structured modelling, incorporating snapping systems, surface controls, and CAD-compatible export formats that aim to bridge exploratory sketching with downstream production workflows. In contrast, Open Brush, derived from Google's Tilt Brush, prioritises gestural expressiveness and fluid mark-making, enabling rapid spatial ideation without emphasising geometric constraint or dimensional control. ShapesXR focuses on spatial prototyping and collaborative UI and UX development, supporting immersive storytelling and workflow simulation. Adobe Substance 3D Modeler adopts a sculptural paradigm, offering clay-like manipulation techniques that appeal to artists accustomed to digital sculpting environments such as ZBrush.

While these platforms represent significant technological progress, their applicability within precision-driven professional contexts remains limited. A recurring challenge concerns input stability and dimensional accuracy. Although many tools incorporate grid systems, snapping functions, or visual guides, mid-air interaction inherently lacks the physical reference surface that stabilises traditional drawing or modelling input. Empirical research has identified the absence of a physical support surface as a major contributor to positional inaccuracy in VR sketching tasks, noting that improvements in visual guidance may enhance placement accuracy but can simultaneously reduce stroke fluidity and quality. Additional evaluations of consumer-grade tracking systems have reported measurable spatial deviations in finger-tracking interfaces during pointing and drawing operations, with positional errors sufficient to affect fine-grained geometric adjustment.

Beyond input variability, limitations are also evident in measurement tooling and interoperability. Several immersive design platforms provide only rudimentary numeric input systems, limited parametric constraint capabilities, or mesh-based export pipelines that do not preserve editable geometric histories. When transferred into established CAD environments, such outputs frequently require reconstruction or cleanup to meet production standards. For workflows demanding millimetre-level tolerance, surface continuity control, and parametric editability, these constraints restrict immersive tools to early-stage conceptual development rather than detailed technical refinement.

This divergence reveals a broader structural tension between the exploratory affordances of immersive environments and the operational requirements of professional design pipelines. While VR platforms excel in embodied spatial ideation and intuitive form generation, challenges relating to input precision, data interoperability, and workflow continuity continue to limit their integration into high-demand industrial contexts. Addressing this gap requires not only incremental feature enhancements but reconsideration of how immersive systems align with established production infrastructures.

1.4 The Precision Problem in VR Design

In precision-driven disciplines such as automotive design, architecture, and engineering, dimensional accuracy is a fundamental requirement rather than an optional attribute. Even minor deviations at the sub-millimeter scale can affect component fit, structural alignment, or manufacturing tolerances. In industrial production environments, modelling inaccuracies may propagate downstream, resulting in rework, inefficiencies, or performance compromise.

Within immersive VR design systems, achieving this level of fidelity remains challenging. Although immersive platforms provide flexibility and spatial engagement, their interaction paradigms differ significantly from desktop-based modelling environments. Mid-air input relies on handheld controllers or optical hand-tracking systems, both of which are subject to micro-movements, tracking noise, and sensor drift. These factors introduce variability that becomes increasingly consequential when precise geometric adjustments are required.

While some VR tools incorporate snapping systems, grid constraints, or stroke stabilisation features, these mechanisms often remain limited when compared to the parametric precision and constraint-based modelling frameworks found in established CAD applications. The absence of stable physical reference surfaces further contributes to reduced input consistency, particularly during extended modelling sessions.

As a result, immersive design tools currently demonstrate stronger performance in exploratory and conceptual phases than in detailed technical refinement. The discrepancy between embodied creative interaction and measurable geometric control underscores a central challenge in the evolution of VR-based professional design workflows.

1.5 Creative Freedom vs. Technical Precision

Immersive VR environments prioritise spatial embodiment and gestural interaction, enabling designers to sketch and construct forms directly within three-dimensional space. This supports rapid ideation and exploratory modelling beyond the constraints of traditional screen-based interfaces.

However, as design tasks shift from conceptual exploration to detailed refinement, the demand for controlled alignment, dimensional accuracy, and specification-based adjustments increases. In immersive systems, the variability of mid-air interaction and limited constraint-based modelling tools can restrict this level of precision.

This tension between expressive freedom and technical exactitude remains a central challenge in VR-based design workflows. While immersive platforms demonstrate clear strengths in early-stage ideation, their integration into precision-driven professional contexts continues to require further development.

1.6 Emerging Technologies and Promising

Recent developments in immersive technologies suggest incremental progress toward addressing limitations in precision and interaction stability. Advances in AI-assisted modelling systems enable automated stroke smoothing, predictive geometry correction, and real-time surface cleanup, reducing the impact of hand tremor and input variability during mid-air interaction. Such systems aim to enhance modelling consistency without compromising gestural expressiveness.

Improvements in hand-tracking fidelity have also contributed to more responsive and natural interaction paradigms. Contemporary tracking systems demonstrate increased spatial accuracy and reduced latency compared to earlier implementations, potentially supporting more controlled manipulation of three-dimensional forms.

Hardware advancements further complement these developments. Newer head-mounted displays offer higher resolution rendering, improved depth sensing, and reduced device weight, contributing to improved visual clarity and decreased user fatigue during extended sessions. Collectively, these software and hardware refinements indicate ongoing efforts to reconcile immersive interaction with the technical control required in professional design contexts.

1.7 Industry Adoption and Demand:

Even though there are more and more VR design tools popping up, the reality is that most industries are still pretty hesitant to bring them into their everyday workflows. Sure, there is a lot of excitement from concept artists, indie developers, experimental creators, and people already working in immersive media, but when it comes to full-scale production teams in architecture, engineering, product design, or manufacturing, VR adoption is still very limited. One of the biggest reasons is that VR does not easily slot into how these industries already work. Most professionals are used to very specific software, like Rhino, SolidWorks, or Revit, and those programs are deeply embedded in everything from team processes to client approvals. Introducing a new, immersive tool often means retraining staff, figuring out export compatibility, and investing in new hardware. it is not that companies do not find the idea interesting; It is that the value has not outweighed the disruption.

Another issue is the lack of standardization. There is no consistent file format, modeling convention, or UX pattern that crosses over smoothly from one VR tool to another or between VR tools and traditional CAD or BIM software. That makes collaboration messy. If a designer builds something in Gravity Sketch, there is no guarantee that it will behave the same way when imported into a CAD pipeline, which can lead to extra cleanup, version mismatches, or even loss of detail. Until VR tools mature to the point where they feel like a natural extension of existing workflows rather than a separate creative detour, they are going to be seen as optional, not essential.

In a way, it is not just a hardware or software problem; it is a mindset one. For VR to gain serious traction in the industry, there needs to be a shift in how companies think about design. It is not just about replacing 2D screens with 3D environments; it is about rethinking how teams collaborate, how ideas get 11 communicated, and how fast feedback can happen when the process becomes more spatial and hands-on. Until that shift happens, until VR proves it can improve speed, precision, or communication in a meaningful way, it's going to remain on the fringes of professional use

1.8 Thesis Aims and Overview

This thesis investigates how immersive virtual reality environments may support early-stage design workflows through the integration of photogrammetry within a practice-led research framework. Rather than positioning VR as a validated replacement for established professional design tools, the study critically examines the affordances and constraints of immersive environments as exploratory design spaces.

The research focuses on the tension between creative freedom and technical precision within contemporary VR design platforms. Although immersive systems offer intuitive spatial interaction and embodied modelling, they continue to present limitations in achieving the dimensional control and measurement of fidelity required for professional-level accuracy. Applications such as Gravity Sketch support structured modelling and CAD-compatible exports, yet constraints remain in fine-grained adjustment and input stabilization. Conversely, Open Brush prioritizes expressive interaction but lacks formal constraint systems such as robust snapping, measurement tools, and parametric control.

Building on this analysis, the study explores whether a VR-based photogrammetry pipeline can introduce grounded spatial reference into immersive workflows. Specifically, it investigates whether the capture, reconstruction, and integration of real-world objects can contribute meaningfully to conceptual development and scale calibration within VR design environments.

To address this aim, the thesis pursues the following objectives:

- To examine the evolution of VR design tools and input systems, including comparisons between immersive platforms and desktop-based modeling environments.
- To analyze the influence of input modalities, including six-degree-of-freedom controllers, gesture tracking, and haptic systems, precision, embodiment, and workflow control.
- To design and develop a prototype VR application, ClickVR, integrates image capture and photogrammetry processing within an immersive workflow.
- To evaluate the prototype through reflective case study analysis, identifying its affordances, limitations, and technical constraints.
- To situate the findings within broader discussions of immersive design practice, outlining areas requiring further empirical investigation and user-based evaluation.

Through this approach, the research identifies key challenges relating to input variability, cognitive load, and interoperability with established desktop-based production pipelines. Photogrammetry is examined as a potential grounding mechanism rather than a validated solution, and its implementation is demonstrated through a Unity-based proof-of-concept prototype. This study does not claim measurable improvements in modeling precision or workflow efficiency through empirical testing. Instead, it contributes to a critically evaluated exploratory system that highlights both the possibilities and current technical limitations of integrating photogrammetry into immersive VR design workflows. The findings establish a foundation for future research incorporating structured user evaluation and performance-based validation.

Chapter 2: Literature Review

2.1 Historical evolution of VR/AR tools in design (from early tools like Tilt Brush to Gravity Sketch's CAD integrations).

The development of immersive design tools has followed a trajectory shaped by early experimentation, artistic exploration, and gradual technical refinement. In the early 1990s, systems such as CAVE environments and head-mounted displays enabled users to visualize and interact with engineering and CAD models in stereoscopic three-dimensional space. Although constrained by hardware limitations, these systems established foundational principles of spatial immersion and embodied interaction within scientific and engineering contexts (Marks, Estevez, & Connor, 2014).

The emergence of consumer-grade VR platforms in the mid-2010s marked a significant shift in accessibility and creative application. Tools such as Tilt Brush and Oculus Medium introduced gesture-based 3D sketching and sculpting using six-degree-of-freedom controllers. These systems foregrounded expressive spatial creation and intuitive interaction; however, they offered limited support for precision modelling, constraint-based geometry, or structured measurement frameworks required in professional design workflows.

Subsequent platforms, including Gravity Sketch, reflected attempts to integrate immersive interaction with more structured modelling capabilities. Features such as snapping tools, symmetry functions, orthographic views, and CAD-compatible export formats signalled a move toward greater interoperability with established desktop-based software ecosystems. Academic research has similarly explored methods for increasing geometric control within immersive environments. Santoni et al. (2016) examined how brush mechanics influence stroke accuracy and user fatigue, highlighting interface design as a critical factor in precision. More recently, Okuya et al. (2023) investigated the integration of parametric modelling principles within VR, incorporating constraint-based logic to support real-time geometric manipulation.

This progression demonstrates a shift from primarily expressive, exploratory systems toward increasingly structured immersive design environments. However, despite these advancements, the reconciliation of embodied gestural interaction with production-level dimensional fidelity remains incomplete. The historical evolution of these tools therefore illustrates both technological progress and persistent structural challenges, providing context for the present investigation into precision, workflow integration, and photogrammetry-supported grounding mechanisms.

2.2 What are some Design Applications that currently exist?

Gravity Sketch has emerged as one of the most widely adopted VR-based 3D design platforms, particularly within the product, automotive, and footwear industries. Since its release in 2014, it has redefined spatial creativity by enabling users to sketch directly in three dimensions using hand gestures, offering an experience akin to sculpting ideas in mid-air. One of its key strengths lies in reducing the cognitive gap between ideation and form. Unlike traditional CAD tools that require precise planning, Gravity Sketch allows designers to intuitively build around their instincts. This capability has translated into practical industry use. For example, Ford's design teams have utilized Gravity Sketch to prototype full vehicle interiors. In one documented case, designers conducted immersive walkthroughs of cabin spaces, made real-time adjustments based on spatial perception, and exported models directly to CAD for engineering refinement.

Similarly, footwear brands such as Adidas and Under Armor have leveraged Gravity Sketch's symmetry tools and subdivision surfaces to develop entire shoe collections in immersive 3D environments. These workflows have accelerated concept review cycles, with one Adidas designer noting a reduction in review time by 50%.

In architecture, smaller firms have begun integrating Gravity Sketch with platforms like Rhino and Revit. Beyond modeling, its use in client presentations has proven transformative. Instead of static floor plans, clients are invited to experience spatial layouts through VR headsets, resulting in significantly improved comprehension and engagement. Open Brush, by contrast, continues to be favored for its expressive freedom. A 2024 user study by Puhakka highlighted its strengths in ideation, noting its minimal learning curve and capacity to foster rapid, experimental creativity. While it lacks CAD-level precision, Open Brush excels in early-stage concept development, particularly among visual artists and worldbuilders. Anecdotal feedback from professional users supports this; one Reddit contributor described it as the only tool that consistently helps overcome creative block.

Recent platform updates have further expanded the utility of these tools. In 2024, Gravity Sketch introduced a web-based collaborative viewer, allowing stakeholders to explore 3D models without installing software or using headsets, an important step toward accessibility in client-facing workflows.

Meanwhile, ShapesXR launched a Figma plugin in 2025, bridging 2D interface design with spatial prototyping. Designers can now import wireframes from Figma into ShapesXR and build immersive UX flows directly in VR. Community feedback also provides valuable insight into evolving workflows. On the Gravity Sketch subreddit, a footwear designer described their process: starting with Gravity Sketch for proportion and silhouette, exporting to Blender for materials, and finishing in Substance Painter. They emphasized the tactile nature of VR modeling, stating, "VR lets me feel the silhouette before committing to 13 details." Despite their strengths, these platforms are not without limitations. Gravity Sketch has a learning curve, with advanced features like NURBS curves and mesh snapping requiring 10–15 hours of practice to master. Open Brush, while intuitive, lacks essential CAD functionalities such as snapping, numeric input, and unit scaling.

Together, these tools illustrate a clear divide in the VR design landscape: Gravity Sketch aims to merge spatial creativity with technical precision, while Open Brush prioritizes uninhibited expression. The ideal solution lies in a hybrid platform, one that supports freeform ideation while offering structured refinement within the same immersive environment. Emerging tools like ShapesXR and Adobe Medium are beginning to explore this middle ground, but a fully integrated solution remains elusive

2.2.1 Bonus: Other VR Tools – ShapesXR & Adobe Medium

While Gravity Sketch and Open Brush are prominent in the VR design landscape, other tools, such as ShapesXR and Adobe Medium, offer unique features but also come with certain limitations. ShapesXR is designed primarily for collaborative spatial design and prototyping. It enables teams to brainstorm and create immersive storyboards directly in VR, making it particularly useful for early-stage ideation and user flow mapping. Its intuitive interface allows users to sketch out concepts in 3D space quickly.

However, ShapesXR is more suited for low- to mid-fidelity prototyping and lacks the advanced modeling tools required for detailed design work. As noted by Farahmand (2023), while it excels in fostering collaborative ideation, it does not support the high-fidelity modeling needed for production-ready outputs.

Adobe Medium, formerly known as Oculus Medium, offers a sculpting-focused approach. It provides artists with a virtual clay environment, allowing for organic modeling using intuitive hand gestures. Users can create complex, free-form shapes, making it ideal for character design and artistic exploration

However, Adobe Medium is primarily tailored for artistic expression and lacks the precision tools necessary for technical modeling tasks. According to a user review on Capterra (2022), while it is excellent for early-stage creativity, it does not integrate seamlessly into workflows that require exact measurements or CAD compatibility. In summary, while ShapesXR and Adobe Medium offer valuable features for specific aspects of the design process, collaborative ideation, and organic sculpting, respectively, they fall short when it comes to precision and technical modeling. This highlights the ongoing challenge in VR design tools: balancing intuitive, creative interfaces with the technical capabilities required for professional-grade design work.

2.3 Comparing Desktop and Immersive 3D Tools: Rhino, Blender, Revit vs. Gravity Sketch, ShapesXR, Open Brush

Comparing traditional desktop tools such as Rhino, Blender, and Revit with immersive platforms like Gravity Sketch, ShapesXR, and Open Brush reveals distinct strengths and limitations that shape professional design workflows. Desktop tools are renowned for their precision. Rhino and Revit offer parametric modeling, detailed measurement tools, and tight tolerance control essential for engineering and architectural design. Input via mouse, keyboard, or stylus, combined with numerical snapping and constraints, enables fine adjustments down to the millimeter.

Blender, while more flexible and artistically oriented, still provides refined mesh editing, modifier stacks, and scripting capabilities that ensure reproducibility and control. Immersive tools, in contrast, rely on midair gestures that offer intuitive interaction but introduce hand jitter and limited snap accuracy. Even Gravity Sketch, with its snapping and export features, struggles to match the micro-level precision of desktop systems.

Both Open Brush and ShapesXR prioritize spatial creativity over technical granularity. That said, immersive environments offer powerful spatial understanding. Horvat et al. (2019) found that reviewing CAD models in VR significantly improved users' perception of fit and dimensional accuracy compared to desktop interfaces, especially for complex models. The immersive context provides richer sensory information and reduces cognitive load, helping designers intuitively evaluate spatial relationships. This contrasts with desktop CAD, which often requires users to mentally piece together multiple orthographic and perspective views.

On the integration front, mature export pipelines give desktop tools an edge. Rhino and Blender seamlessly output OBJ, STEP, IGES, and native CAD formats, facilitating downstream use in simulation, rendering, or fabrication workflows. Immersive platforms have made strides. Gravity Sketch exports FBX, OBJ, and IGES, and ShapesXR supports collaborative storytelling and spatial prototyping.

However, immersive-to-desktop workflows often require mesh cleanup or re-tessellation to ensure compatibility, and they rarely preserve parametric histories or editable geometry. Creative flow and speed further differentiate the platforms. Desktop tools demand rigor menus, tool panels, and structured workflows that can slow down the creative spark. VR tools, by contrast, support rapid ideation. A designer can gesture in free space, twist around concepts, and collaborate in real time with minimal friction. Yet, when accuracy and refinement are needed, whether technical details or project sign-off, desktop precision tools remain indispensable.

The emerging consensus from research and industry practice supports hybrid workflows. Designers can begin VR or AR for freeform concept generation and spatial evaluation before refining designs in tools like Revit or Rhino. Academic work by Okuya et al. (2023) demonstrates how integrating parametric controls in VR could push such hybrid models further, allowing users to sketch in immersive space while tying that work to constraint-driven backends. These hybrid systems aim to bridge the gap between creativity and control, a tension central to this thesis, which explores how a photogrammetry-enhanced Unity prototype can offer spatial intuition grounded in precision.

2.4 Input Limitations and Degrees of Freedom

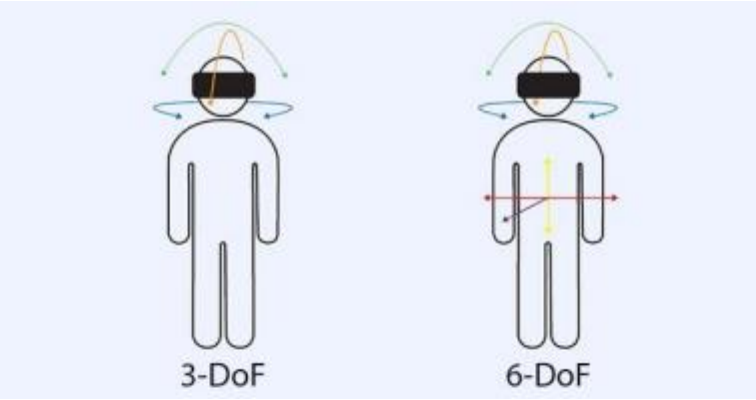


Figure 5: A visual comparison between 3DoF and 6DoF tracking in VR headsets, highlighting differences in movement and interaction capabilities. Source: Virtual Speech (n.d.)

As immersive technologies are increasingly explored within professional design contexts, persistent tension emerges between input precision and usability. Systems designed to maximize spatial control often introduce interaction complexity, particularly for novice users.

Although motion controllers and optical hand-tracking systems have significantly advanced spatial interaction capabilities, they continue to differ from the fine-grained stability associated with traditional desktop input devices such as a mouse or stylus. Arora et al. (2017) demonstrated that controller-based VR drawing tools can achieve higher positional accuracy than bare-hand input in precision-oriented tasks. However, these systems may also increase cognitive and procedural demands, particularly when performing operations such as vertex adjustment or curvature refinement.

Degrees of freedom further influence this dynamic. Six-degree-of-freedom systems enable full positional and rotational tracking, supporting embodied spatial manipulation and surface modelling. However, the increased control space may require greater coordination and adaptation. In contrast, three-degree-of-freedom devices provide simplified rotational input, which may reduce interaction complexity but restrict positional accuracy and detailed geometric adjustment.

Collectively, these findings suggest that immersive input systems currently operate within a trade-off space between accessibility and precision. While advanced control mechanisms support expert-level modelling tasks, they may introduce barriers to usability. Conversely, simplified interaction models may enhance intuitive engagement while limiting technical refinement. This balance remains a central consideration in the development of immersive design tools and informs ongoing research into stabilization techniques, constraint systems, and adaptive interfaces.

2.5 Gesture Tracking and Stabilization Methods

Gesture tracking is the backbone of immersive design, the bridge between user intention and system response. But this bridge is not always stable. Tracking systems vary in accuracy and can introduce jitter or latency, while gesture recognition must balance natural movement with consistency. According to Sabella et al. (2024), modern gesture recognition methods from camera-based tracking to wearables differ significantly in their detection of static gestures (like pointing) versus dynamic gestures (such as drawing). Their review emphasizes that stabilization algorithms, such as Kalman filters and dynamic smoothing, are essential for reducing tracking noise. Without these filters, even slight hand jitters can result in erratic strokes, making precision-based tasks difficult or impossible.

Hardware accuracy also plays a critical role. 6DoF systems offer full positional and rotational tracking, ideal for surface sculpting and spatial manipulation. However, this added control can overwhelm beginners. In contrast, 3DoF devices are more user-friendly but limited to rotational input, making millimeter-level precision unattainable. In a controlled comparison, Schneider et al. (2021) assessed finger tracking on commodity HMDs (Oculus Quest, Vive Pro, Leap Motion) and found median positional errors of 1–2 cm even under controlled conditions. These discrepancies significantly impact alignment of fine 3D details, underscoring the importance of stabilization strategies like prediction filters and spatial anchoring.

Deep learning approaches further enhance gesture recognition. Kumar et al. (2025) demonstrated that convolutional neural networks (CNNs), when applied to Leap Motion data, can improve dynamic gesture detection by reducing false positives and improving frame-to-frame consistency. This intelligent filtering allows immersive tools to better interpret user intent, rather than merely reacting to raw movement.

Together, these trends show that while gesture tracking hardware is improving, the real gains come from stabilization software that cleans data in real time. Techniques like temporal smoothing, prediction filtering, and intelligent gesture reconstruction are the unseen gears that turn fluid motion into usable, precise input. For VR design tools, these systems are not luxuries; they are necessities, ensuring that midair creativity does not fragment into jittery frustration.

2.6 Haptic Feedback as a Precision Multiplier

Recent research increasingly positions haptic feedback as a mechanism for enhancing precision and control within immersive environments. Unlike visual or auditory cues alone, tactile feedback engages the somatosensory system, allowing users to physically perceive resistance, contact, and alignment during interaction. This multisensory reinforcement is particularly relevant for tasks requiring fine motor control, such as sculpting virtual forms, aligning components, or manipulating geometry within constrained spatial parameters.

Ultraleap’s mid-air haptic systems, which utilise focused ultrasound to generate tactile sensations in open space, represent one emerging approach to this challenge. Through phased arrays of ultrasonic transducers and modulation techniques, these systems project localized tactile feedback directly onto the user’s hands without requiring wearable hardware. Such technologies aim to simulate surface resistance, edge boundaries, or confirmation cues that would otherwise be absent in mid-air interaction.

Empirical studies support the precision-enhancing potential of haptic systems. Culbertson, Unwin, and Kuchenbecker (2018) demonstrated that the integration of tactile feedback reduces cognitive load and improves alignment accuracy by engaging the body’s proprioceptive mechanisms. Similarly, Pacchierotti et al. (2017) argue that haptic cues enhance both task performance and user embodiment in mixed reality contexts, strengthening the perceptual link between virtual and physical objects.

More recently, Tanioka et al. (2025) examined the effects of haptic feedback in a precision peg insertion task under varying visual and communication latency conditions. Their findings indicate that participants receiving haptic feedback demonstrated improved control and reduced mental workload compared to those relying solely on visual input. Importantly, performance improvements were particularly evident when visual information was degraded, suggesting that tactile cues compensate for perceptual uncertainty. Although conducted in a teleoperation context rather than a creative VR design setting, the study provides measurable evidence that haptic feedback can enhance spatial accuracy in precision-driven tasks.

Collectively, these findings reinforce the argument that haptic feedback functions as a potential precision multiplier within immersive systems. By introducing tactile confirmation and resistance simulation, haptics may mitigate the instability associated with mid-air gestural input. However, despite promising results, such technologies remain only partially integrated into mainstream VR design platforms. Their limited interoperability with established modelling environments highlights an ongoing gap between experimental hardware capabilities and production-level immersive workflows.

2.7 The Role of Haptics in VR Design

Haptic feedback adds a crucial layer of “touch” to virtual environments, creating a bridge between intuitive gesture and design accuracy. In tasks that demand precision, such as aligning edges or sculpting surfaces, vibration or force cues can reinforce visual signals, making manipulation feel more grounded and dependable. Richard et al. (2021) explored this in a VR drawing task, comparing no haptics, vibrotactile feedback, and full force feedback. Their study found that force feedback significantly improved users’ sense of embodying the feeling of truly being in the virtual environment and reduced both mental workload and error rates compared to visual-only or vibration-based cues.

These findings reinforce the idea that tactile realism matters not just for immersion, but for precise task performance. Similarly, Kourtesis et al. (2022) used a Fitts’ Law task to investigate how different haptic feedback types, electro tactile, vibrotactile, and visual-only, affect accuracy and perception. They discovered that electro tactile feedback led to the highest placement accuracy, while vibrotactile feedback resulted in slower responses. This suggests that richer haptic information can directly enhance both physical performance and task awareness.

Together, these studies highlight a clear message: when haptic feedback aligns with a user’s intent, especially via force or precise tactile cues, it not only boosts immersion but also directly supports accuracy and cognitive focus. In design workflows where users move beyond rapid sketching into fine manipulation, integrating haptics may be key to overcoming the guesswork and jitter that often accompany mid-air gestures.

2.8 Cognitive Load and Interface Complexity

As VR design tools become increasingly feature-rich, one of the emerging challenges is managing cognitive load, the mental effort required to operate the interface while performing creative tasks. In immersive environments, users are often required to remember gesture sequences, navigate complex radial menus, or interpret abstract visual cues. This multitasking can strain working memory and interrupt the flow of ideation, particularly during early-stage sketching or prototyping. Collins et al. (2019) highlight that VR environments inherently demand higher levels of cognitive processing due to their multisensory input and spatial interaction requirements.

In their study, they measured cognitive load using eye tracking and physiological sensors, finding that overly complex UI systems led to reduced insight and lower task efficiency even among experienced VR users. These findings suggest that VR interface design should prioritize clarity and support progressive disclosure, revealing tools only when needed to avoid overwhelming users. Building on this, Nasri et al. (2024) explored how interface complexity affects user performance in VR training simulations. Their results showed that participants using simplified, guided interfaces had higher task completion rates and reported lower mental workload compared to those using standard UI layouts. The study also emphasizes that interface design must account not only for functionality but also for cognitive ergonomics, especially in tasks that require sustained attention and precision.

Together, these insights reinforce the idea that well-designed VR interfaces should reduce cognitive friction, allowing users to focus more on creativity and less on remembering how to operate the tool. Balancing expressive power with ease of use remains a central design challenge in the evolution of VR creative system.

2.8.1 Cognitive Load in Immersive UI Design

Working in VR involves more than just visual immersion; it demands significant cognitive effort. Cognitive load, defined as the mental energy required to process and manage information, becomes a major barrier when interfaces are overly complex or unintuitive. While VR environments can be visually rich and engaging, poorly designed user interfaces can force users to juggle multiple tasks, disrupting focus and slowing creative momentum. Collins et al. (2019) investigated cognitive load in VR by analyzing physiological signals such as electrodermal activity and heart rate, alongside emotional responses during learning tasks.

Their findings revealed that even basic virtual environments can overwhelm working memory, particularly when users encounter unclear objectives or insufficient interface feedback. Similarly, Nasri et al. (2024) employed eye-tracking and NASA TLX metrics to assess mental workload during complex assembly tasks in VR. They found that when interface elements required more than a glance to interpret, users experienced a sharp rise in cognitive demand, leading to performance drops and mental fatigue.

These studies underscore a critical insight for VR design: functionality must be immediately accessible to be effective. Rich feature sets do not justify complexity if they hinder usability. Designers must prioritize intuitive interaction through clear affordances, spatially anchored tools, intelligent previews, and adaptive menus that appear contextually. Without these considerations, cognitive friction can disrupt the ideation flow, undermining the very advantages that immersive 3D environments are meant to offer.

2.9 Identifying Research Gaps.

Immersive VR environments are frequently recognised for supporting creative exploration, rapid ideation, and spatial engagement during early-stage design. However, a persistent gap remains in their capacity to support the technical precision required within engineering and production-oriented workflows. While many contemporary VR platforms prioritise intuitive interaction and gestural modelling, they often provide limited support for high-fidelity geometric control and parametric constraint systems.

Kukreja et al. (2024) highlight this disparity in their comparative evaluation of VR-based CAD modelling platforms. Their findings indicate that many commercially available tools are optimised for aesthetic-driven applications such as animation, fashion design, or conceptual product development, but lack structured support for complex geometries including Non-Uniform Rational B-Splines and constraint-based modelling frameworks essential for precision engineering tasks. As a consequence, operations such as surface filleting, curvature continuity adjustment, and tolerance-based refinement remain challenging within current immersive environments.

Interoperability further compounds this limitation. Many VR platforms provide limited compatibility with industry-standard parametric exchange formats such as STEP and IGES, which are central to integration with established CAD systems including SolidWorks, Rhinoceros 3D, and Autodesk Inventor. In practice, this may require model reconstruction within desktop environments or reliance on mesh-based exports that do not preserve parametric metadata or constraint logic, thereby introducing workflow discontinuities.

Emerging research has begun to address these concerns. Okuya et al. (2023) propose a VR-based CAD framework incorporating parametric editing directly within immersive environments through gesture-driven constraint manipulation. Although currently experimental, such approaches indicate potential pathways toward integrating immersive interaction with structured modelling logic.

Across the literature, a recurring limitation remains the absence or limited accessibility of micro-level accuracy tools within immersive platforms, including numerical input fields, robust snapping systems, and precision measurement controls. These features are foundational within traditional CAD workflows and are particularly critical in mechanical and architectural contexts where tolerance, alignment, and scale must be explicitly defined.

Collectively, these findings reveal a structural gap between the exploratory strengths of immersive design tools and the precision-driven requirements of professional production pipelines. This gap frames the central inquiry of the present research, which investigates whether photogrammetry-based grounding mechanisms may contribute to improved dimensional reference and workflow integration within immersive environments.

2.9.1 Unresolved Challenges and Research Gaps

Despite continued advancements in immersive technologies, several unresolved challenges constrain the integration of VR into precision-driven professional workflows. One recurring limitation concerns the restricted incorporation of haptic feedback within mainstream immersive design platforms. While systems such as Ultraleap’s STRATOS Explore SDK demonstrate the potential of mid-air tactile feedback to enhance spatial confirmation and gesture-based interaction, such technologies remain largely disconnected from widely adopted design applications including Gravity Sketch, Open Brush, and ShapesXR. This separation limits the practical evaluation of tactile augmentation within established design workflows.

Interoperability presents a further structural constraint. Kukreja et al. (2024) report that a substantial proportion of VR-generated models require manual correction when transferred into conventional CAD environments due to mesh inconsistencies, topological errors, and the absence of parametric metadata. Reported delays associated with cleanup and reconstruction highlight the friction that can arise when immersive outputs intersect with established production pipelines. These findings suggest that geometric fidelity alone is insufficient without compatible data structures and constraint preservation.

Input stability and user fatigue also remain relevant concerns. Although six-degree-of-freedom controllers enable embodied spatial manipulation, they provide limited tactile granularity compared to traditional desktop input devices. Prolonged interaction may introduce variability related to hand fatigue, calibration drift, or tracking inconsistencies. Emerging alternatives, including pressure-sensitive haptic gloves such as the SenseGlove Nov, aim to enhance fine-grained interaction through force feedback and resistance simulation. However, these systems introduce additional considerations, including calibration variability and integration complexity within controller-dominant software ecosystems.

Taken together, these unresolved issues indicate that immersive design tools operate within a broader technological ecosystem that remains under development. While VR environments demonstrate clear exploratory strengths, sustained integration into precision-oriented workflows depends not only on interface refinement but also on advancements in hardware interoperability, parametric data integrity, and stabilised input systems. These structural gaps frame the necessity for further research into grounding mechanisms and workflow integration strategies.

2.9.2 Directions for Addressing Identified Gaps

Addressing the limitations identified in the preceding sections requires developments across hardware integration, modelling logic, and interface design.

One area of ongoing research concerns the standardization of integration frameworks for haptic devices within immersive modelling environments. Although systems such as Ultraleap's STRATOS and SenseGlove Nova demonstrate the feasibility of mid-air tactile feedback and force-based interaction, their limited compatibility with widely adopted modelling platforms restricts practical implementation. Broader standardization efforts, analogous to the cross-device abstraction model adopted by OpenXR, may provide a pathway toward more consistent hardware integration. Such frameworks could enable immersive environments to incorporate tactile confirmation and resistance of simulation without fragmenting software ecosystems.

A second area involves the incorporation of parametric modelling structures within immersive environments. Many current VR tools rely predominantly on freeform mesh-based sculpting, which supports expressive modelling but lacks constraint-based editing and dimensionally editable geometry. As noted by Kukreja et al. (2024), mesh-dominant workflows frequently require post-processing within desktop CAD environments to restore parametric control and ensure engineering compatibility. Research exploring immersive constraint systems and parametric editing frameworks suggests potential pathways for reducing this discontinuity, although such systems remain in early stages of development.

Interface design represents a further domain requiring refinement. Existing immersive platforms often prioritise either simplified interaction for accessibility or advanced toolsets for expert users, with limited adaptive scaling between these modes. Studies examining cognitive load in immersive environments (Collins et al., 2019; Nasri et al., 2024) indicate that interface complexity significantly influences performance and user fatigue. Adaptive interface models that adjust tool visibility, constraint access, or stabilization features according to task context may offer a means of balancing usability and precision without overwhelming users.

Collectively, these research directions suggest that resolving the identified gaps will depend not solely on incremental feature additions, but on coordinated developments across hardware compatibility, modelling logic, and interaction design. These considerations provide the conceptual foundation for the present investigation into grounding mechanisms and workflow integration within immersive design systems.

Chapter 3) Incorporating Frameworks: Usability Heuristics and Design Affordances in VR

3.1 Theoretical Framework for Evaluating Immersive Interaction

Enhancing user experience in immersive VR design environments requires more than the identification of isolated usability concerns. Without structured evaluative frameworks, assessments risk becoming descriptive rather than analytically grounded. This chapter adopts two complementary theoretical lenses: Nielsen's usability heuristics and affordance theory.

Nielsen's heuristics provide a system-oriented framework emphasising visibility of system status, error prevention, consistency, and interface coherence (Nielsen Norman Group, 2020). These principles offer criteria for evaluating interaction clarity, feedback mechanisms, and workflow stability within immersive platforms. In contrast, affordance theory, originating in Gibson's ecological psychology (1979) and extended by Norman (1988), focuses on the perceived action possibilities available to users. Within VR environments, this perspective is particularly relevant to gesture-based interaction, spatial manipulation, and embodied navigation.

Although both frameworks were originally developed within non-immersive contexts, their analytical value remains significant. Immersive systems introduce interaction modalities such as six-degree-of-freedom input, mid-air gesture control, and spatial embodiment that extend beyond conventional two-dimensional interface models. Rather than assuming direct transferability, this chapter critically examines the adaptability of these frameworks to immersive design contexts, particularly in relation to cognitive load, perceptual clarity, and interaction stability.

Used together, usability heuristics and affordance theory provide a structured basis for analysing immersive VR design tools in subsequent chapters. Heuristics inform the evaluation of system feedback, constraint visibility, and error management, while affordance theory supports analysis of gesture legibility, spatial alignment cues, and embodied precision. This dual-framework approach functions not as a prescriptive design template, but as an interpretive scaffold through which interaction strengths and limitations can be systematically examined in relation to the broader tension between creative freedom and technical exactitude.

3.2 Usability Heuristics in VR Design

Jakob Nielsen's ten usability heuristics, first articulated in the 1990s, remain foundational to interface evaluation across digital systems. These heuristics covering principles such as system status visibility, match between system and real-world expectations, and user control were developed in the context of desktop-based, graphical user interfaces (Nielsen Norman Group, 2020)

However, the transition to immersive environments necessitates a critical re-examination of their relevance. Virtual reality interfaces move beyond point-and-click paradigms, incorporating embodied spatial interaction, gesture input, and real-time motion tracking within three-dimensional space. This transformation fundamentally alters how users perceive, interpret, and engage with digital content.

While the core objective of usability, developing intuitive, efficient, and error-tolerant systems, remains constant, VR introduces new constraints and affordances. Designers must now account not only for what users see, but also for how they physically move, where they direct attention, and how they process multisensory feedback. These embodied interactions bring challenges related to motion-induced discomfort, proprioceptive feedback, cognitive load, and presence, all of which complicate the direct application of traditional heuristics.

This section critically examines how key usability heuristics are being reinterpreted for immersive contexts. It draws on examples from contemporary VR tools to highlight where heuristics are effectively translated into spatial environments and where they encounter limitations due to the embodied and multimodal nature of VR. Ultimately, achieving usability in virtual environments is not solely about visual or interface clarity. It requires the design of spatial experiences that are perceptually grounded, interactionally coherent, and responsive to the sensorimotor dynamics of the user.

3.2.1 Visibility of System Status

In conventional two-dimensional interfaces, system status is typically conveyed through straightforward graphical elements such as loading indicators, button highlights, or notification banners. These cues offer immediate and interpretable feedback, aligning with Nielsen's heuristic that users should always be kept informed about system operations through timely and appropriate responses (Nielsen Norman Group, 2020). In virtual reality, however, this principle requires significant reinterpretation. The immersive nature of VR introduces a multisensory context in which feedback must not only be visible, but also spatially and temporally integrated across visual, auditory, and haptic channels. For example, observing one's virtual hands move in synchrony with physical motion, hearing spatialized audio cues in response to interaction, or receiving subtle haptic feedback when selecting an object are all mechanisms through which system status can be conveyed. These feedback modalities must be both context-aware and temporally precise to preserve user presence and prevent disorientation. In immersive environments, system status is not simply a matter of visual notification but of embodied responsiveness that reassures users that their actions are being registered and interpreted in real time

3.2.2 Match Between System and the Real World

Virtual reality interfaces feel most natural when they behave in ways consistent with real-world physics. When objects fall after being dropped, or when resistance is encountered upon contact with a virtual surface, users can more accurately predict outcomes, reducing the cognitive effort required for navigation and interaction. This principle, aligned with ecological validity, supports perceptual stability and reduces disorientation (Jerald, 2016). When these expectations are violated, users may experience increased mental workload and reduced spatial coherence. While specific quantitative thresholds remain debated, empirical studies have shown that inconsistencies in environmental behavior or feedback mechanisms elevate cognitive load and can disrupt task flow (Slater & Wilbur, 1997; LaViola et al., 2017).

Research has also highlighted the importance of temporal precision in immersive environments. Even small latency delays can disrupt presence, with thresholds below two hundred milliseconds often required to preserve immersion (Stauffert, Niebling, & Latoschik, 2020). These findings underscore the heightened sensitivity of VR users to feedback timing and perceptual congruence. However, while responsiveness is essential, the assumption that increased sensory feedback invariably enhances usability warrants critical scrutiny. Overly rich or poorly calibrated feedback, particularly in haptic and auditory channels, can lead to cognitive overload, fatigue, or distraction, especially in tasks requiring sustained attention or fine motor control (Wickens, 2008).

This creates a critical design tension between feedback richness and perceptual restraint. In VR, visibility of system status should not be conflated with constant stimulation but rather approached as contextsensitive signaling that aligns with user goals and ergonomic thresholds. Future research must address not only the risks of under-feedback but also the potential cognitive costs of its excess, particularly how multimodal cues intersect with attention, memory, and user perception across varied task domains.

3.2.3 User Control and Freedom

User control and freedom remain foundational to interface usability, particularly in enabling individuals to recover from errors or unintended actions. In traditional two-dimensional environments, this is typically accomplished through familiar undo or redo mechanisms. Within immersive VR interfaces, however, such systems are often limited to linear reversal, lacking the flexibility required for exploration or spatially distributed workflows. Gravity Sketch, for example, provides a timeline-based sequential undo system, but it does not yet accommodate non-linear editing or spatial backtracking across multiple concurrent actions (Gravity Sketch, 2024). This limitation reflects a broader challenge in immersive design: the interface's inability to anticipate or guide user intention in real time. As Rasch et al. (2024) note, undo systems in VR remain underdeveloped in both interaction fidelity and contextual sensitivity, despite their critical role in collaborative and creative tasks.

The frequent reliance on error correction also points to deeper design issues. If users consistently resort to undo functionality, it raises questions about the system's ability to communicate action consequences or scaffold appropriate input. Rather than framing undo as a necessary safeguard, designers should consider why such mechanisms are invoked so frequently. Are interactions overly ambiguous? Does the system fail to provide predictive or confirmatory feedback?

A more initiative-taking approach involves reducing the likelihood of errors through anticipatory design. Contextual affordances such as gesture previews, spatial constraints, and real-time visual guidance can help users predict outcomes before committing to actions. Predictive modeling and dynamic snapping systems can further align user input with design intent, decreasing the frequency of missteps.

Ultimately, supporting user freedom in VR is not limited to enabling reversibility. It involves minimizing cognitive friction by fostering environments that reduce the potential for error and support fluid exploration. By moving from reactive correction to intelligent prevention, immersive systems can better sustain creative momentum without requiring constant interface negotiation.

3.2.4 Adapting Heuristics for VR: Examples in Action

As immersive technologies continue to evolve, classical usability heuristics such as those introduced by Jakob Nielsen are being reinterpreted to meet the demands of virtual reality interaction. These adaptations aim to retain foundational principles of usability such as error minimization, intuitive operation, and cognitive offloading while accounting for the spatial, embodied, and multisensory nature of VR systems. Several industry-facing examples illustrate how these heuristics are being adapted to support spatial workflows and embodied interaction. Table 1 presents two illustrative cases where traditional heuristics have been translated into VR design contexts.

Heuristic	How it is Reimagined in VR	Real World Example
Error Prevention	Provide physical or sensory cues to reduce mistakes	Haptic-assisted object snapping in Autodesk VRED using collision damping
Recognition Over Recall	Use context-sensitive, spatially anchored UI elements	Oculus Dash's radial "pin-and-stretch" interface is positioned near the user's hand space

Source: Adapted from Nielsen Norman Group (2022) VR Usability Report.

These examples demonstrate that traditional usability guidelines can be meaningfully adapted to immersive contexts. However, as the Nielsen Norman Group (2022) observes, such adaptations often encounter new challenges unique to VR. First, spatially anchored tools may be easily forgotten or misplaced by users, especially in complex environments where UI components float in 3D space. Second, the physicality of interaction, such as sustained arm-raising or mid-air gestures, can lead to user fatigue over time, making interactions less sustainable during extended sessions. Third, the predominance of visual feedback in VR environments may result in underutilization or misinterpretation of haptic and auditory cues, weakening multisensory integration.

Taken together, these observations suggest that while heuristic frameworks remain valuable, their application in VR must be contextually and ergonomically sensitive. The embodied nature of VR interaction demands a rebalancing of usability priorities where cognitive, physical, and perceptual factors intersect. Future design strategies should prioritize not only interface efficiency but also long-term comfort, sensory clarity, and the spatial legibility of feedback mechanisms.

3.3 Affordance Theory in Immersive Environment

Affordance theory provides a critical framework for analysing how users perceive and enact interactions within immersive systems. In virtual reality environments, where conventional interface metaphors are often absent, interaction cues must be intentionally structured to ensure perceptual clarity and action legibility. Gibson's (1979) concept of ecological affordances and Norman's (1988) emphasis on perceived affordances remain particularly relevant in spatial computing contexts, where users rely on visual, spatial, and haptic signals to infer possible actions.

Jo and Park (2023) categorise affordances in immersive environments into four dimensions: cognitive, physical, functional, and sensory. Cognitive affordances support user comprehension of object behaviour and system logic. For example, gesture-based cursor changes or contextual highlighting can signal interactivity. Agirachman et al. (2022) demonstrated that alignment between visual affordances and real-world expectations significantly reduces response time, suggesting that perceptual clarity directly influences interaction efficiency.

Physical affordances relate to the extent to which interfaces align with natural bodily movement. Six-degree-of-freedom input systems enable full positional and rotational tracking, supporting embodied spatial manipulation more effectively than three-degree-of-freedom systems limited to orientation. Research indicates that embodied interaction enhances spatial comprehension and task performance in immersive environments (Jerald, 2016; LaViola et al., 2017). However, increased control dimensionality may also introduce coordination complexity, reinforcing the usability–precision trade-off discussed in previous sections.

Functional affordances concern the transparency of action–outcome mappings. Tools that clearly communicate adjustable parameters, constraint systems, or scaling behaviours reduce ambiguity and cognitive load. In contrast, immersive platforms that lack explicit manipulation controls or constraint visibility may limit precision refinement. For instance, while Open Brush supports expressive gestural modelling, its limited constraint and scaling systems restrict structured design control in professional contexts.

Sensory affordances involve multisensory reinforcement of interaction feedback. Mid-air haptic systems, such as those reported by Ultraleap (2023), demonstrate that tactile augmentation can reduce overreliance on visual processing, potentially improving interaction stability and spatial alignment. Multisensory feedback may therefore contribute to enhanced precision by distributing perceptual load across modalities.

An architectural VR evaluation system described by Agirachman, Kwon, and Kiyokawa (2022) illustrates layered affordance integration. By combining visual cues, force feedback, and material-specific audio signals, the system improved spatial legibility and reduced interaction ambiguity. Such findings indicate that affordance design in immersive environments influences not only usability, but also the stability and reliability of spatial interaction.

Taken together, affordance theory provides a structured lens for examining how perceptual cues, embodied input, and multisensory feedback shape interaction clarity in VR design tools. Importantly, the absence or misalignment of these affordances may contribute directly to the precision limitations identified in earlier chapters. This framework therefore supports a more granular analysis of how immersive systems succeed or fall short in reconciling expressive freedom with technical exactitude.

3.4 Applying Frameworks to My Photogrammetry-Based VR Prototype

Building on the preceding theoretical discussions, this section applies Nielsen's usability heuristics and affordance theory to the evaluation of a photogrammetry-enhanced VR prototype developed as part of this research. The prototype enables users to import three-dimensional scans of real-world objects and interact with them directly within an immersive environment. Unlike traditional VR modeling tools that begin with a blank canvas, this system grounds digital creation in familiar, tangible forms. The objective is to assess how the combination of spatial context, scale manipulation, and six degrees of freedom (6DoF) tracking can support more intuitive and precise workflows for design practitioners.

To evaluate system usability, Nielsen's heuristics offer a structured framework. One key area is visibility of system status: does the interface provide immediate, interpretable feedback when users manipulate objects? For instance, clear visual or auditory cues during translation, rotation, or scaling operations can help maintain user confidence and spatial awareness (Nielsen Norman Group, 2020). Similarly, error prevention mechanisms such as snapping tools or axis constraints are examined to determine whether they reduce the risk of misalignment or disproportionate scaling. User control and freedom are also central: does the system support reversible actions, and can users explore without being locked into linear workflows? Undo and redo features, as well as gesture-based navigation, are particularly relevant in this context (Rasch et al., 2024).

Affordance theory provides a complementary lens for analyzing interaction clarity. Cognitive affordances are assessed by observing whether objects visually or behaviorally communicate their potential action, for example, whether a scanned chair suggests that it can be moved or sat on. Physical affordances relate to Whether the system allows users to interact in ways consistent with real-world motion, such as reaching, grabbing, or rotating objects using natural gestures (Jerald, 2016; LaViola et al., 2017). Functional affordances are considered by examining whether object manipulation tools convey their capabilities, such as grip-based scaling or contextual UI prompts. Sensory affordances are evaluated by the extent to which feedback is distributed across modalities, e.g., visual deformation, audio cues, or controller haptics, which reinforce the believability of the interaction (Ultraleap, 2023). By combining these frameworks, the prototype can be assessed not only from a technical standpoint, such as responsiveness, feature implementation, and task flow, but also from a user-centered perspective that considers perception, expectation, and embodiment. This dual-method approach reveals where the prototype successfully facilitates intuitive interaction (e.g., when photogrammetry enhances spatial grounding) and where limitations persist, such as inconsistent affordance signaling or lack of fine-grained control. The findings help surface critical insights into how photogrammetry-based VR tools might advance creative workflows, offering both expressive freedom and contextual accuracy. This evaluation underscores the importance of aligning system behaviors with perceptual cues and interaction expectations to support more fluid, legible, and usable immersive design environments.

Chapter 4) Research Methodology: Case Study Approach (No User Testing)\

4.1 Overview and Rationale

This research adopts a practice-led methodology structured through an analytical case study approach. Rather than employing quantitative usability testing or survey-based evaluation, the study centers on the iterative development and critical examination of a Unity-based VR prototype. Within creative technologies research, the act of making functions not only as a means of production but also as a method of inquiry. In this context, the prototype operates both as an artefact and as an investigative instrument, enabling direct engagement with the affordances and constraints of immersive design workflows.

The central focus of the study is the persistent tension between creative expressiveness and technical precision in contemporary VR design platforms. This tension is examined through practical experimentation rather than abstract comparison. Existing tools such as Gravity Sketch and Open Brush are analyzed in relation to their interaction structures, constraint systems, and interoperability limitations. The prototype developed in this research does not seek to replace these systems but to explore an alternative workflow informed by identified gaps

The prototype emphasizes a photogrammetry-based interaction pipeline, enabling the capture and integration of real-world scanned geometry within an immersive environment. This approach is investigated as a grounding mechanism for scale calibration and spatial alignment, rather than as a validated precision solution. The implementation allows examination of how physically referenced geometry influences embodied modelling and dimensional awareness within VR.

Although the study does not include formal user testing or performance benchmarking, evaluation is structured through the application of usability heuristics and affordance theory. These frameworks provide analytical criteria for assessing interaction feedback, error prevention, constraint visibility, spatial legibility, and embodied precision. The resulting analysis is qualitative and reflective in nature. Findings are not intended to be statistically generalizable but to articulate design tensions, system behaviors, and integration constraints observed through iterative development.

By positioning the prototype as a critical artefact within a practice-led case study, the research contributes to an exploratory examination of photogrammetry integration in immersive design workflows. The study advances discussion surrounding interaction embodiment, input stabilization, and workflow grounding, while explicitly acknowledging the need for future empirical validation through structured user evaluation.

4.2 Tool Evaluation through Analytical Case Study

The evaluation of contemporary VR design platforms, specifically Gravity Sketch and Open Brush, was conducted through a comparative desktop-based case study approach. Rather than incorporating participant-based testing, the analysis drew upon a combination of academic research, industry reports, developer documentation, tutorial demonstrations, and practitioner discourse sourced from technical forums and community platforms. This triangulated review provided insight into documented workflow behaviors, reported limitations, and recurring usability concerns across professional and enthusiast contexts.

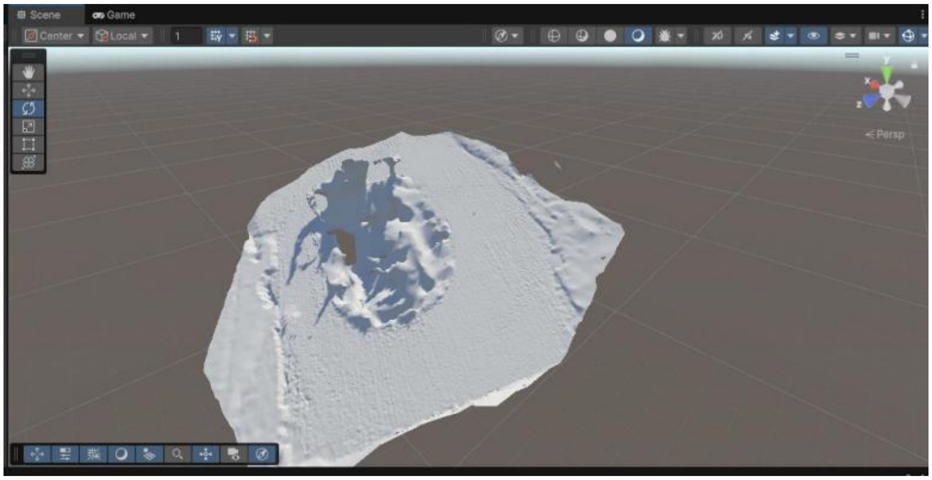
Gravity Sketch was examined for its structured modelling features, including snapping systems, surface manipulation logic, and compatibility with CAD exchange formats such as STEP and IGES. While these features indicate alignment with industrial workflows, documented limitations relating to input stabilization and fine-grained dimensional control suggest constraints in achieving high-precision modelling fidelity.

Open Brush was analyzed in relation to its gesture-based interaction paradigm and accessibility. Although the platform supports expressive spatial drawing and rapid conceptualization, it provides limited constraint-based modelling tools, measurement systems, or structured export options required for production-oriented workflows.

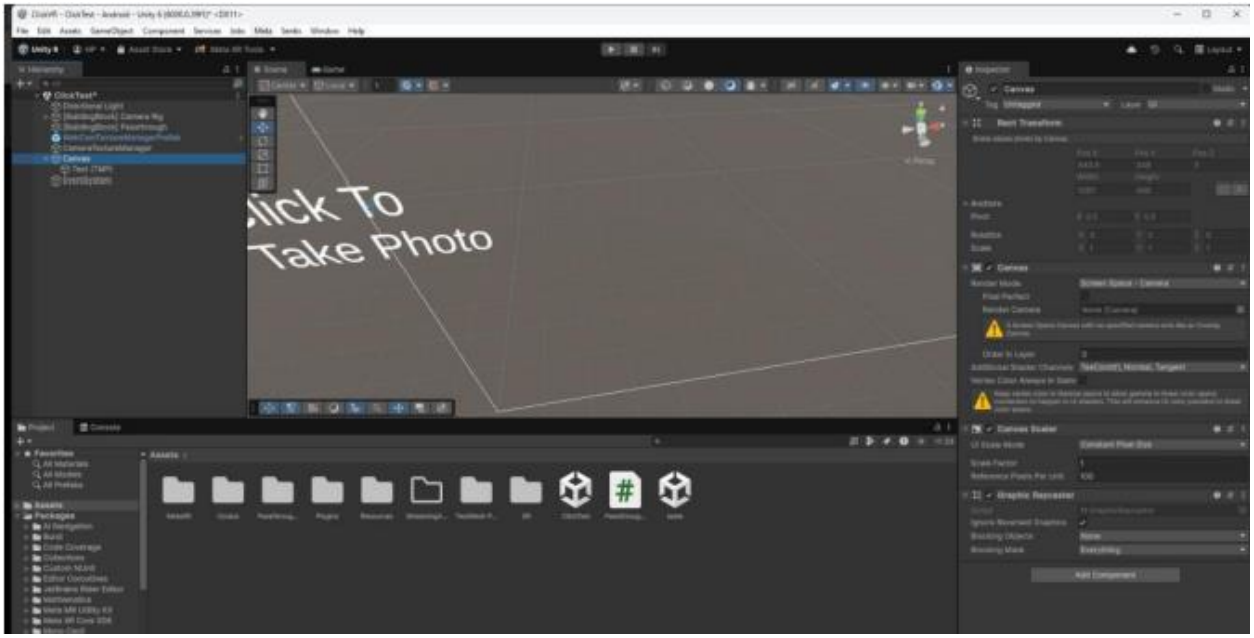
Both platforms were compared with established desktop modelling environments, including Rhinoceros 3D and Blender, in terms of precision control, workflow continuity, and interoperability. This comparative analysis informed the conceptual direction of the Unity-based prototype developed in this study. The prototype does not seek to replicate or replace existing tools, but rather to explore alternative workflow configurations that respond to identified tensions between expressive interaction and technical control.

4.3 Iterative Unity Prototype Development

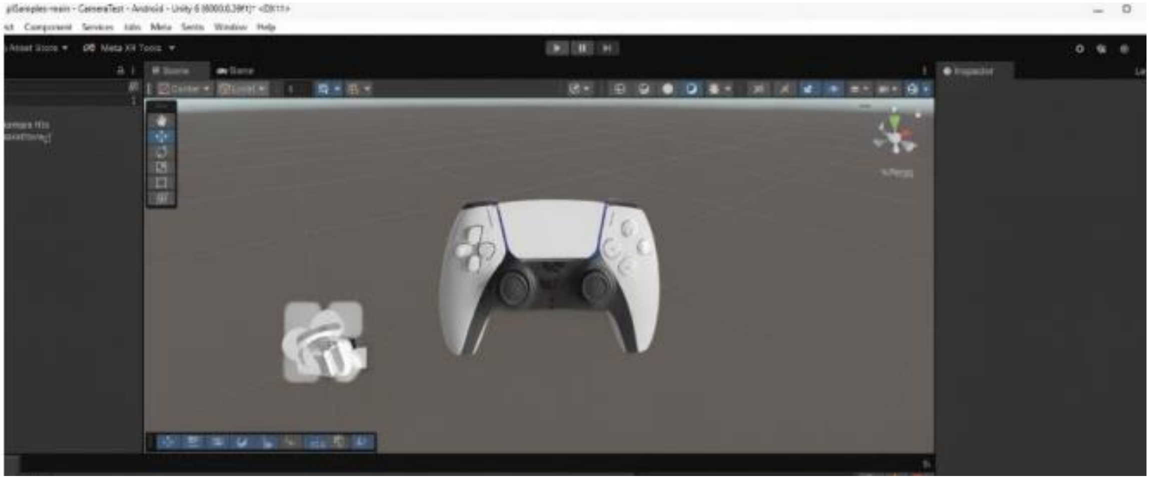
In parallel with the desktop-based evaluation of existing VR design platforms, a custom immersive prototype was developed through an iterative, version-controlled workflow in Unity. This practice-led development process functioned as a method of inquiry, enabling systematic exploration of interaction constraints identified in commercial tools. Each iteration focused on isolating and examining specific usability or workflow tensions rather than producing a finalised production-ready system. The application was deployed on Meta Quest 3 hardware to investigate spatial interaction, feedback behavior, and system responsiveness within a standalone immersive context.



Version 1 established the technical foundation of the prototype using Unity's XR Interaction Toolkit. Core functionality included scene navigation, teleportation, and an object loader capable of importing .obj files. Photogrammetry assets were generated externally using Meshroom. Early scans revealed geometric inconsistencies resulting from insufficient image coverage and irregular capture angles. This initial version functioned as a feasibility study of the photogrammetry-to-Unity pipeline rather than as an evaluative precision benchmark.



Version 2 incorporated object manipulation through Unity's XR Grab Interactable system. Revised image capture protocols were introduced to improve photogrammetric fidelity; however, issues related to depth resolution and edge definition persisted. Within the immersive environment, freehand placement revealed alignment instability, prompting the implementation of grid-based snapping anchored to local spatial references. This iteration highlighted the interaction challenges associated with mid-air positioning and constraint visibility.



Version 3 refined the photogrammetry workflow through controlled lighting conditions, standardized camera trajectories, and denser image datasets. Resulting models were optimized prior to Unity import, enabling scale, rotation, and repositioning through gesture-based interaction. While geometric stability improved, this version was primarily evaluated in relation to spatial embedding and dimensional referencing rather than sub-millimeter accuracy validation.

Each iteration was documented through annotated screenshots, version logs, and structured development notes to support reflective analysis. The iterative process served not as proof of performance improvement, but as a structured examination of how photogrammetry integration influences embodied interaction, spatial calibration, and workflow continuity within immersive environments. Insights derived from development informed the final system configuration and shaped broader reflections on the feasibility and limitations of grounding immersive design workflows in real-world geometry.

4.4 Plugin and SDK Selection

The selection of software development kits (SDKs) and plugins was informed by hardware compatibility with Meta Quest 3, modular integration with Unity, and support for performance-optimized immersive interaction. Each component was chosen to serve a distinct role within the development pipeline, balancing creative flexibility with system stability.

Unity XR Interaction Toolkit provides the core architecture for VR interaction, including locomotion, object selection, and manipulation mechanics. Its event-driven model enabled rapid prototyping of user interactions using established Unity conventions.

Meta XR All-in-One SDK was integrated to access native Quest 3 functionality, including controller input mapping, hand tracking, haptic feedback, and passthrough features. This ensured tighter alignment between software behavior and hardware-specific affordances, particularly for testing nuanced gesture interactions and device-level feedback systems.

The OpenXR Plugin was included to ensure long-term portability and platform interoperability. By adhering to OpenXR standards, the project remains adaptable to future hardware or cross-device deployment scenarios without requiring extensive rework.

Meshroom served as the primary photogrammetry engine for generating 3D assets from real-world object scans. As a result, obj files were decimated and cleaned in Blender to optimize mesh complexity before Unity integration, ensuring smooth runtime performance within the constraints of mobile VR.

Together, this modular toolchain enables the implementation of precision-focused, photogrammetry-driven workflows while maintaining performance stability on standalone VR hardware. Access to Quest-native input data via Meta’s SDK was especially critical in prototyping interaction techniques that required fine-grained manipulation and gesture fidelity.

4.5 Ethical Considerations

The OpenXR Plugin was included to ensure long-term portability and platform interoperability. By adhering to OpenXR standards, the project remains adaptable to future hardware or cross-device deployment scenarios without requiring extensive rework. Meshroom served as the primary photogrammetry engine for generating 3D assets from real-world object scans. Resulting, obj files were decimated and cleaned in Blender to optimize mesh complexity before Unity integration, ensuring smooth runtime performance within the constraints of mobile VR. Together, this modular toolchain enabled the implementation of precision-focused, photogrammetry-driven workflows while maintaining performance stability on standalone VR hardware. Access to Quest-native input data via Meta's SDK was especially critical in prototyping interaction techniques that required fine-grained manipulation and gesture fidelity.

4.6 Summary

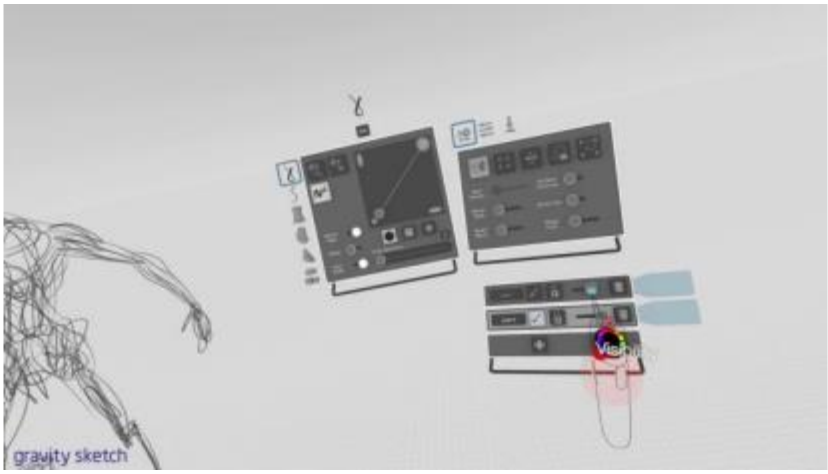
This research employed a hybrid methodology that integrated desktop-based analytical evaluation with practice-led Unity prototyping. This dual approach enabled a critical and reflective examination of current immersive design tools while simultaneously engaging in the creative development of an alternative system. By iteratively building within a VR environment, the research directly explored the functional boundaries of interaction precision, affordance signaling, and photogrammetry integration. Insights were drawn not only from firsthand development but also from an extensive review of expert commentary, industry documentation, and practitioner discourse.

The act of making functioned as both method and inquiry, consistent with the aims of an exegesis in the creative technologies discipline. This alignment with practice-led research traditions allowed for the generation of situated, experience-based knowledge—grounded in material engagement with tools and systems rather than abstract critique alone. In doing so, the methodology supported both conceptual reflection and technical innovation, establishing a foundation for the subsequent analysis of the prototype's design outcomes and implications for immersive workflows.

Chapter 5) Case Study: Assessing Precision in VR Design Tools – Gravity Sketch vs. Open Brush

5.1 Introduction

Virtual reality design platforms have introduced new interaction paradigms for three-dimensional modelling and spatial exploration. Immersive environments enable embodied navigation and gestural manipulation that differ fundamentally from traditional desktop-based workflows. Among contemporary tools, Gravity Sketch and Open Brush represent contrasting approaches to immersive design.



Gravity Sketch incorporates structured modelling features and compatibility with external CAD systems, positioning it closer to industrial and product design contexts. In contrast, Open Brush, derived from Tilt Brush, prioritizes expressive spatial drawing and intuitive interaction, with less emphasis on constraint-based modelling or parametric control.

This case study presents a comparative, framework-informed analysis of these two platforms. Rather than conducting empirical benchmarking or precision measurement, the evaluation examines documented interface structures, interaction models, constraint visibility, and interoperability features. The analysis is guided by usability heuristics and affordance theory to assess how each system supports or constrains precision-oriented workflows within immersive environments.

By examining the structural differences between these platforms, the case study clarifies the extent to which immersive tools currently reconcile creative flexibility with technical control. The findings inform the subsequent development of the research prototype and contribute to a broader discussion concerning workflow integration and dimensional grounding in VR-based design systems.

5.2 Tool Overview

Virtual reality design platforms vary considerably in how they negotiate the balance between expressive interaction and structured modelling. Gravity Sketch and Open Brush represent two distinct approaches within the immersive design landscape. This case study provides a comparative analysis of their interface structures, modelling constraints, and interoperability features in relation to precision-oriented workflows. The evaluation is qualitative and framework-informed rather than performance-benchmarked.

Gravity Sketch is positioned toward industrial and product-oriented design contexts. It supports controlled surface modelling, curve manipulation, and export compatibility with CAD exchange formats such as STEP and IGES. These features indicate alignment with structured workflows, particularly when models are transferred into external systems such as Rhinoceros 3D, SolidWorks, or Autodesk Fusion 360. However, despite its structured toolset, limitations remain in achieving micro-level input stability and constraint visibility within immersive interaction. The reliance on handheld controllers introduces variability that may affect fine-grained dimensional adjustments.

Gravity Sketch also incorporates real-time collaborative features, enabling shared spatial modelling sessions. While such capabilities support distributed ideation and review, they do not directly resolve precision-related constraints. Furthermore, the interface complexity and learning curve may present accessibility challenges, particularly for users unfamiliar with immersive modelling paradigms.

In contrast, Open Brush prioritizes expressive, brush-based spatial creation. Originally derived from Tilt Brush, it emphasizes gestural fluidity and immediate visual feedback. This makes it well-suited to conceptual exploration, immersive illustration, and creative experimentation. However, Open Brush provides limited support for constraint-based modelling, dimensional referencing, or structured alignment systems. The absence of snapping, numerical input, and parametric logic restricts its applicability within precision-driven workflows. Export options are primarily mesh-based formats such as GLB or FBX, which may require additional restructuring when integrated into CAD or digital content creation pipelines.

Collectively, the comparison indicates that while both platforms demonstrate distinct strengths, neither fully reconciles embodied creative interaction with structured precision control. Gravity Sketch moves toward technical interoperability but retains interaction constraints, whereas Open Brush enables expressive modelling with minimal constraint systems. This contrast reinforces the broader research problem: how immersive design tools might better integrate spatial embodiment with dimensional stability and workflow continuity.

5.3) Comparative Analysis

Precision and Control:

In precision-oriented workflows, Gravity Sketch demonstrates closer alignment with structured modelling paradigms than Open Brush. Gravity Sketch supports Bézier curve manipulation, surface continuity controls, and export compatibility with CAD exchange formats such as STEP, IGES, and FBX. These features enable interoperability with external systems including Rhinoceros 3D and SolidWorks, facilitating transition from immersive ideation to downstream refinement.

The platform also incorporates orthographic views and alignment tools intended to improve geometric consistency. However, despite these structured features, fine-grained dimensional control remains constrained. The absence of direct numerical input and sub-millimetre editing precision limits its capacity for tolerance-sensitive modelling. Minor variations in hand stability or tracking accuracy may influence surface continuity and edge alignment, particularly during detailed refinement tasks. As a result, exported models may require additional adjustment within desktop-based CAD environments.

These constraints reflect a broader limitation across immersive interaction systems. While embodied spatial navigation enhances intuitive understanding of form, fine motor precision remains dependent on hardware fidelity and interaction stabilization mechanisms (Jerald, 2016; LaViola et al., 2017).

In contrast, Open Brush prioritizes expressive, brush-based modelling over structured constraint systems. Its interface emphasizes immediacy and visual feedback, supporting conceptual sketching, illustrative workflows, and immersive ideation. However, it provides limited support for grid alignment, snapping precision, unit-based measurement, or parametric logic. Although recent updates have introduced basic transform and axis-locking features, these remain comparatively limited when assessed against constraint-based modelling environments.

Export functionality in Open Brush is primarily mesh-based, supporting formats such as GLB and FBX. The absence of parametric data retention or engineering-grade exchange formats restricts integration into precision-driven production pipelines. Consequently, immersive sketches often require restructuring or reinterpretation when transferred to technical modelling systems.

The comparison indicates that Gravity Sketch moves toward structured interoperability while retaining interaction-level precision constraints, whereas Open Brush enables accessible creative exploration with minimal geometric control. Neither platform fully reconciles embodied gestural interaction with tolerance-sensitive modelling requirements. This contrast reinforces the central research inquiry concerning how immersive systems might better integrate expressive spatial interaction with structured dimensional stability.

Workflow Integration:

Gravity Sketch demonstrates closer alignment with hybrid workflows that combine immersive ideation and desktop-based refinement. The platform enables designers to initiate conceptual form of development within a spatial VR environment before transferring geometry into conventional CAD systems for further detailing, validation, or production planning.

Compatibility with external software such as Rhinoceros 3D, SolidWorks, Autodesk Fusion 360, and Autodesk Alias support this transitional workflow. Export formats including STEP, IGES, and FBX facilitate geometry transfer into downstream environments. While this interoperability improves continuity between immersive and desktop stages, exported models may still require refinement depending on surface tolerances and project complexity. Thus, the workflow can be described as interoperable rather than fully seamless.

Gravity Sketch’s capacity to retain surface definitions and hierarchical structure in certain workflows supports structured refinement. However, the degree of downstream editability varies depending on modelling technique and export configuration and should not be interpreted as direct equivalence to native CAD authoring environments.

In contrast, Open Brush was not developed with engineering-oriented interoperability as a primary objective. Its export options, typically OBJ, GLTF, and FBX, prioritise visual representation over parametric or constraint-based modelling logic. These formats preserve surface appearance and brush geometry but do not embed editable dimensional relationships or tolerance data. Consequently, integration into precision-driven pipelines often requires restructuring within external modelling systems.

Open Brush therefore aligns more closely with conceptual visualization, immersive illustration, and exploratory ideation rather than tolerance-sensitive production workflows. Its strengths lie in rapid spatial expression and intuitive gestural interaction rather than structured interoperability.

Taken together, the comparison suggests differentiated roles within the immersive design ecosystem. Gravity Sketch demonstrates partial alignment with hybrid technical workflows, while Open Brush supports exploratory creative practice. Neither platform fully resolves the integration challenges between immersive modelling and precision-dependent downstream production systems. This distinction reinforces the broader research focus on how immersive environments might better support continuity between ideation and structured refinement.

User Experience and Accessibility:

The user experience between Gravity Sketch and Open Brush is different, and that really shapes how each tool feels to use. Gravity Sketch is packed with features and has a lot of potential for professional work, especially in industrial or product design. But that depth also makes it a bit overwhelming at first. If you are not already familiar with 3D modeling or do not have some kind of structured tutorial to follow, it is easy to feel lost. The interface is not always intuitive, and even basic tasks can take some trial and error to figure out. That learning curve can push beginners away before they even get a chance to see what the tool is capable of. I genuinely think some built-in onboarding tools, like step-by-step tutorials, adaptive UI elements, or even a beginner mode that gradually unlocks features, could make an enormous difference here.

Open Brush, on the other hand, sits at the opposite end of the spectrum. It is incredibly easy to pick up. The brush-based interface is super visual, the feedback is instant, and it feels more like painting or playing than learning software. That makes it perfect for artists, hobbyists, or anyone who just wants to jump in and start creating without dealing with menus or toolbars. But the other side is that it lacks structure. There is no snapping, no real measurement system, and no way to enforce symmetry or alignment, which means it falls short for technical or production-level design. If you are trying to do anything that requires clean geometry or precision, you quickly hit a wall.

So, one tool gives you power but not ease, and the other gives you ease but not power. Neither quite bridges that gap, and that’s a big reason why I started thinking about what a hybrid solution might look like, something that could combine Open Brush’s approachability with Gravity Sketch’s depth, without making users feel like they have to choose one or the other.

Learning Curve and Community Support:

When it comes to learning curve and community support, both Gravity Sketch and Open Brush have solid followings, but they serve diverse types of users and offer various kinds of help. Gravity Sketch has built up a strong community of industrial designers, VR creators, and product developers. There is a ton of usergenerated content, like tutorials, workflow breakdowns, and time-lapse builds, scattered across YouTube, Discord servers, and online forums. That kind of community is super valuable, especially when you are trying to figure out a new feature or pick up best practices. But at the same time, the tool does not offer a clear or structured path for learning. There are not many official courses, certifications, or guided modules, which can make it hard for new users to get up to speed quickly, especially if they are not coming from a design background.

Open Brush has a different vibe. Because it is open-source and more art-focused, its community is made up of a lot of illustrators, experimental artists, and creative coders. People constantly share their work, custom brushes, and mods on social media and platforms like GitHub. It is welcoming and creative, which makes it easy to dive in and start playing around. But since the tool is geared more toward expressive creation than technical workflows, it lacks the kind of structured documentation that professionals might expect, especially if they are trying to bring it into a commercial pipeline or use it in a collaborative production environment.

So, while both platforms have active and enthusiastic communities, the kind of support you get—and the kind you might need depends on what you are trying to do. If you are learning for fun or expression, Open Brush feels open and inviting. If you are aiming for professional-level work, Gravity Sketch has the depth, but not always the guidance. That gap in formal learning is something I kept in mind while designing my prototype wanted to be powerful, but also easier to learn and grow with.

Professional Applicability and Future Potential:

When it comes to professional use and future potential, both Gravity Sketch and Open Brush offer interesting strengths, but in diverse ways. Gravity Sketch already feels like it is on track to become a serious tool for industries that rely on both creativity and technical precision, like product design, automotive, or even architecture. It has the foundation: support for CAD-compatible exports, parametric curves, and multi-user collaboration. But to fully establish itself in those professional pipelines, it still needs some upgrades. Features like better hand tracking, more stabilization when working on small-scale details, and a UI that you can customize depending on your workflow would push it to the next level. If those things get addressed, I could easily see it becoming a standard tool in engineering-focused design teams.

Open Brush, on the other hand, does not aim for technical precision right now, and that is okay. Its strength lies in rapid ideation, visual storytelling, and expressive sketching. But it still has potential to grow. If the platform introduced some basic precision tools like alignment grids, snapping options, or even cleaner export formats that play well with other software, it could start to appeal to a broader group of users, including those working in pre-visualization or concept development. Its open-source nature also gives it room to evolve quickly if the community or contributors decide to take it in that direction.

So, while Gravity Sketch is already moving toward becoming a professional staple, and Open Brush is more of a creative sandbox, both have room to expand their role in the design ecosystem. Each one could benefit from borrowing ideas from the other, whether it is adding structure to creativity or making technical workflows more intuitive and engaging.

5.4) Recommendations for Enhancement

The comparative analysis highlights several areas where immersive design platforms could evolve to better support precision-oriented workflows. These recommendations are not presented as validated solutions, but as speculative design directions informed by the preceding evaluation.

One potential direction involves AI-assisted input stabilization. Both Gravity Sketch and Open Brush rely on mid-air gestural input, which remains susceptible to minor hand tremors and tracking variability. Adaptive filtering or predictive smoothing systems could reduce input noise while preserving gestural intent. Such systems may improve geometric consistency during detailed operations, particularly in contexts requiring controlled surface continuity.

A second area concerns the integration of structured precision tools within expressive environments. Open Brush, in particular, provides limited support for grid alignment, snapping constraints, or unit-based measurement. Introducing optional constraint layers or modular toolsets may enable users to toggle between exploratory and structured interaction modes. From a usability heuristic perspective, increasing visibility of constraints and providing clearer feedback mechanisms could enhance task legibility without compromising creative flow.

Interoperability also remains a critical consideration. Expanding export compatibility with structured exchange formats such as STEP or IGES, or improving geometry translation pipelines into desktop systems such as Rhinoceros 3D or SolidWorks, could strengthen continuity between immersive ideation and downstream refinement. However, such integration would require careful attention to parametric data retention and constraint mapping to avoid loss of structural logic.

Finally, onboarding and interface scalability warrant attention. Feature-rich platforms such as Gravity Sketch may benefit from adaptive interface layers that respond to user expertise or task specificity. Guided workflows, contextual prompts, or tiered tool access could reduce cognitive load while preserving access to advanced functionality. Prior research on immersive interaction suggests that reducing mental friction supports sustained engagement and precision retention.

5.5) Conclusion

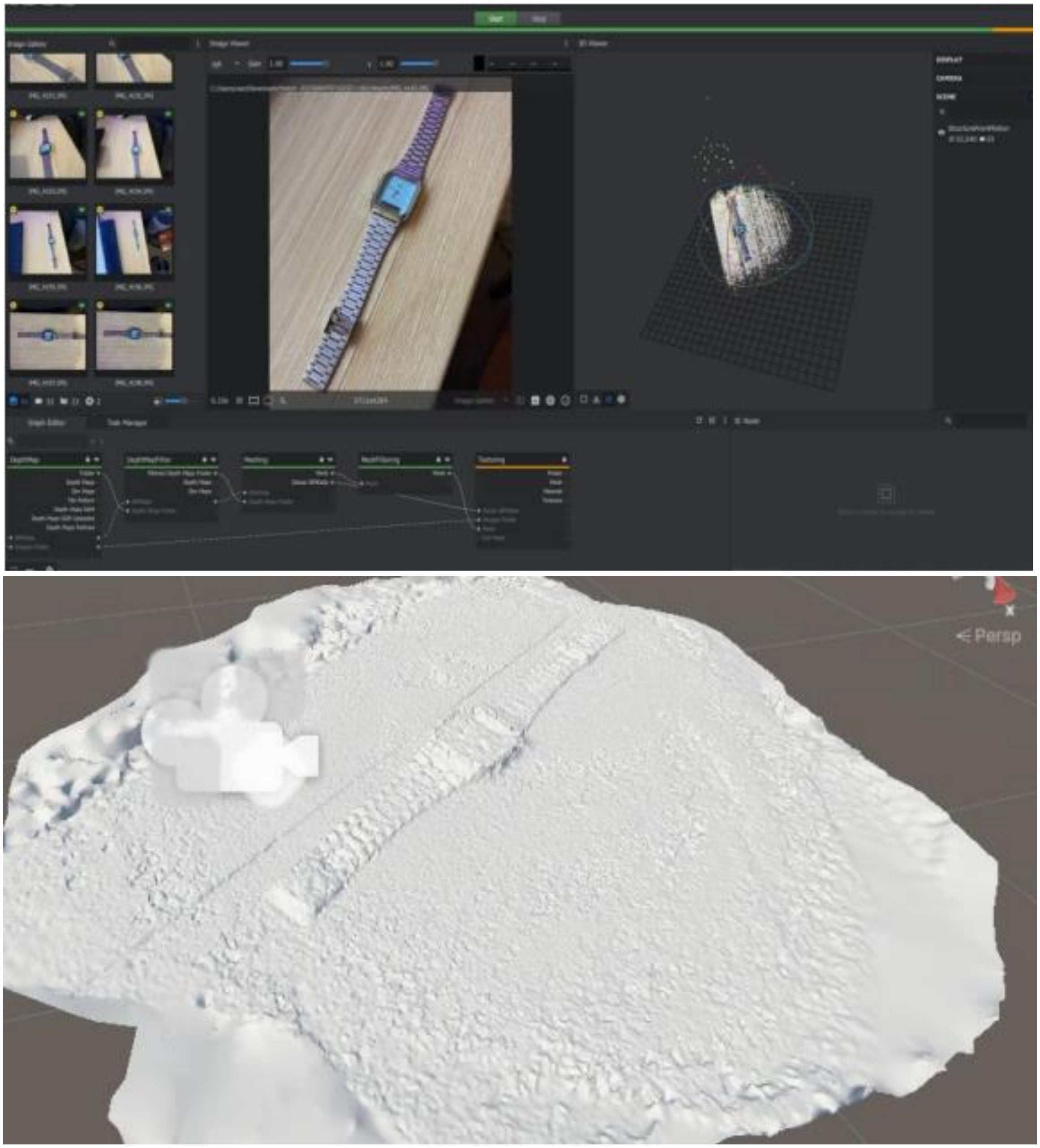
Gravity Sketch and Open Brush represent two distinct orientations within the immersive design landscape. Gravity Sketch demonstrates partial alignment with structured modelling workflows through its export compatibility and surface control tools, whereas Open Brush prioritises expressive immediacy and accessibility.

Each platform is effective within its intended scope. Gravity Sketch supports interoperability with CAD-adjacent systems but retains interaction-level precision constraints and interface complexity. Open Brush enables rapid spatial ideation but lacks structured constraint systems and parametric data retention required for precision-driven workflows.

This contrast illustrates the broader tension identified throughout this thesis: immersive environments enhance embodied spatial exploration, yet fine-grained technical control remains unevenly supported. Neither platform fully resolves the integration challenge between intuitive gestural modelling and tolerance-sensitive refinement.

The findings do not suggest that immersive tools should replace established desktop systems. Rather, they indicate the need for continued development toward more coherent hybrid workflows. Enhancements such as adaptive constraint visibility, improved input stabilisation, and expanded interoperability may incrementally strengthen alignment between immersive ideation and structured modelling environments. Gravity Sketch and Open Brush therefore serve as indicative case studies of the current state of immersive design tools. Their strengths and limitations highlight both the progress made and the structural challenges that remain. The future role of VR in professional design will likely depend not on replacing existing systems, but on refining the relationship between embodied spatial interaction and established precision-based methodologies.

Chapter 6: Proposed Solution



Photogrammetry In Meta Quest 3 -Harshil Pandya

6.1 Summary

This section introduces a hybrid prototype workflow developed in response to gaps identified in the preceding literature and comparative case study. Specifically, it explores the relationship between immersive ideation and technical structuring within VR design tools. Rather than positioning the system as a validated solution, the prototype functions as a practice-led investigation into how photogrammetry might be integrated into immersive workflows.

The proposed implementation combines mixed reality image capture, external 3D reconstruction, and real-time asset import within a Unity-based VR environment. This configuration was developed to examine whether embedding real-world scanned geometry within immersive modelling spaces could support improved spatial referencing and dimensional grounding. The emphasis is exploratory rather than confirmatory.

Beyond its technical structure, the prototype investigates VR as a spatial interface for embodied interaction. By enabling users to scan and reconstruct physical objects and import them into an immersive workspace, the system examines how externalised geometry influences spatial perception and design iteration. This process allows designers to observe and manipulate objects from multiple perspectives within a shared spatial frame, supporting reflective interaction with form and scale.

It is important to clarify that the prototype does not claim to resolve precision limitations within immersive design tools, nor does it demonstrate measurable improvements in workflow efficiency. Instead, it serves as a critically evaluated proof of concept that explores how photogrammetry may contribute to bridging the conceptual gap between expressive ideation and structured modelling. The insights generated are interpretive and situated within the constraints of a practice-led methodology.

6.1.1 Overview of the Approach.

A recurring limitation identified in existing VR design tools concerns the difficulty of integrating expressive spatial interaction with structured dimensional reference. While platforms such as Gravity Sketch support immersive form exploration, their capacity to incorporate real-world reference geometry remains constrained. In response to this observation, a practice-led prototype was developed to investigate the integration of photogrammetry within an immersive workflow.

The prototype utilises the mixed reality capture capabilities of Meta Quest 3 in combination with a Unity-based development environment. Image data captured within the headset is processed externally using Meshroom, an open-source photogrammetry pipeline. Offloading reconstruction tasks to an external system avoids computational strain on standalone VR hardware while enabling higher-fidelity model generation.

Once reconstructed, the resulting 3D geometry is re-imported into the immersive environment as an interactive asset. This workflow was designed to examine how real-world scanned objects might function as spatial reference anchors within VR-based design exploration. Rather than replacing existing creative tools, the prototype investigates how scanned geometry may coexist with freeform modelling practices.

The Unity-based implementation also provides flexibility for future feature integration, such as alternative input modalities or constraint-based interaction layers. However, these possibilities remain speculative and were not empirically evaluated within this study. The purpose of the prototype is exploratory: to assess the feasibility and interaction implications of embedding photogrammetry within immersive design workflows, rather than to present a finalized or validated system.

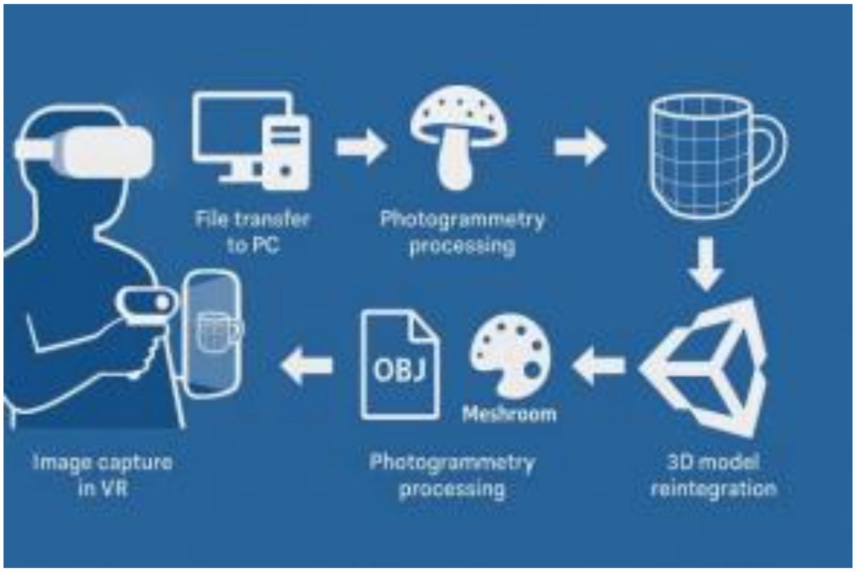
6.1.2 Conclusion of Approach

In summary, the prototype represents an exploratory investigation into how photogrammetry may be integrated within immersive design workflows. Rather than presenting a definitive solution, the system functions as a practice-led inquiry into whether real-world object capture and external reconstruction can be meaningfully embedded into a VR-based design environment.

By combining mixed reality image capture, external processing, and in-environment asset integration, the prototype examines how scanned geometry might contribute to spatial referencing and contextual grounding during immersive ideation. The emphasis is not on demonstrated improvements in precision or efficiency, but on understanding the interaction implications of introducing physically derived geometry into a virtual workspace.

The approach therefore suggests a potential pathway toward more integrated hybrid workflows, where creative exploration and structured modelling coexist within the same spatial context. However, further empirical validation and user-based evaluation would be required before broader claims regarding workflow enhancement or professional applicability could be substantiated.

6.2 System Architecture



1) On Device Capture (Quest 3 + Unity MR):
Unity script captures a configurable number of high-resolution screenshots of the physical object via passthrough. Images are saved as .jpg to persistent storage.
2) Cloud-Based Reconstruction: The application zips the captured images and uploads them via HTTPS to a server running Meshroom CLI. The server pipeline executes photogrammetric reconstruction, yielding an optimized .obj mesh plus accompanying. mtl and textures. A RESTful response returns a URL pointing to the generated files.
3) Runtime Download & Import: Unity downloads the .obj (and associated files) at runtime. A lightweight OBJ-importer script reconstructs the mesh in the scene, applies materials, and positions it within the designer's shared MR coordinate frame.

6.3 Design Goals

The prototype was developed with the intention of exploring how immersive VR environments might better accommodate both expressive interaction and structured modelling practices. Rather than resolving this tension, the system was designed to investigate whether elements of freeform ideation and constraint-based precision could coexist within a shared spatial workflow.

A central design objective involved reducing the fragmentation between exploratory sketching and structured refinement stages. The prototype examines whether users can transition between loose conceptual manipulation and more controlled positioning within the same immersive context, without necessitating platform switching. This goal is exploratory and reflects an inquiry into workflow continuity rather than a demonstrated optimization.

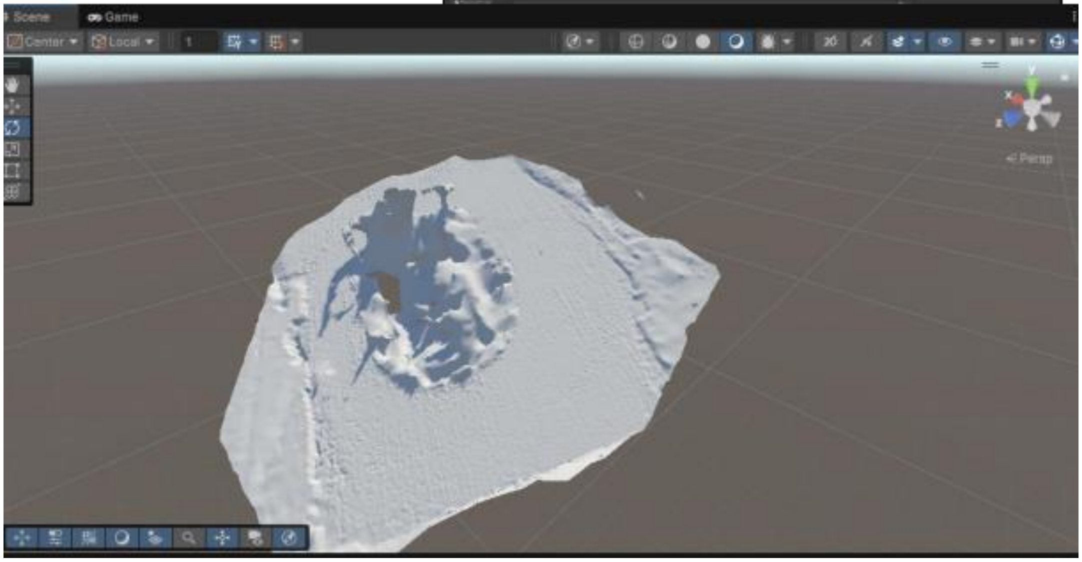
Interface adaptability was also considered during development. The system explores the possibility of layered tool access, where basic interaction remains accessible while more structured functions such as snapping, grid alignment, or numeric input may be introduced as optional constraint mechanisms. The intention is not to impose rigidity, but to examine how precision-supporting tools can be made visible without disrupting embodied interaction.

Interoperability was treated as a functional consideration. The prototype supports export pathways compatible with common formats such as FBX, GLTF, and STEP. However, these exports were implemented to assess technical feasibility rather than to establish seamless cross-platform integration. Downstream compatibility remains dependent on external software environments and workflow configuration.

The integration of photogrammetry serves as an additional investigative component. By enabling scanned physical objects to be imported as spatial references, the system examines whether real-world geometry can function as contextual anchors within immersive design sessions. The effect of this integration on perceived accuracy or confidence was not empirically measured and is therefore interpreted qualitatively.

Overall, the prototype's design goals centre on exploring whether immersive VR tools can incrementally support both expressive spatial ideation and structured interaction within a unified environment. These goals remain investigatory and do not claim to demonstrate validated improvements in professional workflow performance.

6.4 Mock-Up Prototype



The prototype developed for this research, ClickVR, was designed to investigate how photogrammetry might be integrated into immersive design workflows. Rather than attempting to replicate comprehensive 3D sketching or sculpting systems, which proved performance-intensive on the Meta Quest 3, the development focus shifted toward the import and spatial manipulation of photogrammetry-derived assets within VR.

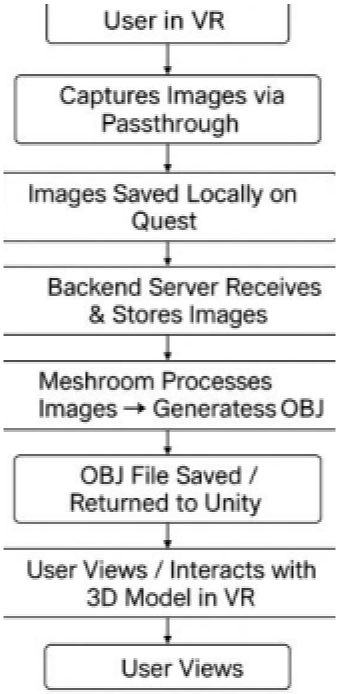
Initial design intentions included implementing native drawing and modelling features directly inside the immersive environment. However, performance testing revealed hardware constraints. Running real-time drawing systems alongside image capture, rendering, and interaction layers introduced noticeable latency and reduced interaction stability. These findings led to a strategic narrowing of scope, prioritising photogrammetric asset integration as the central investigative function.

Within ClickVR, users capture reference images of physical objects using the headset's passthrough camera system. The images are transferred externally and processed using Meshroom, which generates a reconstructed OBJ model. Once processed, the model is imported back into the Unity environment and placed within the immersive workspace. Users can then scale, rotate, and reposition the scanned object spatially within the scene.

Rather than constructing models from abstract primitives, this workflow enables designers to begin from geometry derived from physical context. The prototype examines whether such grounded reference objects may influence spatial judgement and iterative refinement during immersive sessions. However, any claims regarding improved decision-making or dimensional accuracy remain interpretive, as no empirical user testing was conducted.

The interface was intentionally minimal, exposing tools contextually in order to reduce cognitive load and maintain interaction clarity. ClickVR does not attempt to replace existing immersive modelling platforms. Instead, it functions as a proof-of-concept exploration of how photogrammetry-based inputs may coexist with immersive spatial design environments.

The reliance on Meshroom introduces practical constraints. As an open-source photogrammetry engine, it does not support real-time reconstruction and remains sensitive to image quality, lighting conditions, and coverage consistency. Early iterations produced incomplete or low-fidelity reconstructions when capture protocols were inconsistent. Processing times varied depending on dataset size, often requiring several minutes per scan. Additionally, generated OBJ files frequently required decimation and optimization in external tools such as Blender prior to Unity import. This additional step interrupts the continuity of a fully VR-native workflow and highlights the infrastructural limitations of current consumer hardware ecosystems.



6.4.1 Justification

The rationale for this prototype emerges from the recurrent tension identified throughout the literature and comparative analysis: immersive VR tools often prioritise either expressive interaction or structured precision, but rarely integrate both within a single coherent workflow. The development of ClickVR was therefore guided by an exploratory intention to examine whether elements of these modes could coexist within a shared spatial system.

Rather than positioning the prototype as a definitive solution, it functions as an investigation into hybrid workflow possibilities. Conceptually, the system explores a fluid, non-destructive interaction model in which users may transition between exploratory manipulation and more structured positioning without leaving the immersive environment. Features such as adaptive interface layering and constraint-based interaction were considered as potential mechanisms for managing this transition. However, these elements were not empirically evaluated and should be interpreted as investigatory design directions rather than validated improvements.

The approach also draws on prior research concerning cognitive load, usability in immersive systems, and the balance between flexibility and control. By attempting to reduce friction between ideation and refinement phases within a single environment, the prototype examines whether immersive tools can support progressive structuring of design intent. Claims regarding improved workflow smoothness or precision remain interpretive and are not supported by user-based performance metrics.

Ultimately, the justification for this approach lies in its capacity to function as a research artifact. It provides a practical context through which the broader research question, concerning the integration of embodied creativity and technical constraint in VR, can be examined within the limits of a practice-led methodology.

6.5 Implications and Future Directions

The integration of photogrammetry within an immersive design workflow raises several implications for the evolving relationship between spatial ideation and structured modelling. While the prototype does not demonstrate validated improvements in precision or efficiency, it provides a situated example of how real-world geometry may be embedded within VR-based environments. The introduction of scanned objects as spatial references suggests potential pathways for grounding immersive exploration in physically derived scale and proportion.

Future development could examine the integration of automated mesh optimisation or AI-assisted reconstruction workflows. Systems capable of identifying topological inconsistencies, suggesting surface refinements, or assisting with retopology inside immersive environments may reduce post-processing fragmentation. However, such possibilities remain speculative and would require empirical evaluation to determine their impact on workflow stability or cognitive load.

Collaborative extensions also present a potential area for investigation. Distributed photogrammetry capture and shared immersive reconstruction sessions may enable geographically dispersed users to contribute to spatial modelling environments. The feasibility and usability of such systems would depend on network infrastructure, real-time processing capabilities, and interface clarity.

Hardware advancements may further influence the evolution of immersive design workflows. Emerging input modalities such as haptic feedback systems, pressure-sensitive gloves, and eye-tracking headsets may alter how users engage with constraint-based manipulation in VR. Nevertheless, the implications of these technologies for precision modelling remain under-researched and warrant systematic study.

Beyond individual modelling tasks, photogrammetry-supported VR environments may have relevance for design review, contextual prototyping, or spatial validation scenarios. However, claims regarding professional scalability or industry-wide adoption exceed the scope of this study and would require longitudinal, user-based investigation.

Overall, the prototype contributes a proof-of-concept exploration of how photogrammetry can be positioned within immersive workflows. Rather than asserting reliability or production readiness, the findings highlight areas for continued research at the intersection of embodied interaction, real-world geometry capture, and structured design refinement.

Chapter 7: Conclusion & Future Directions:

This thesis set out to investigate a central tension within immersive design technologies: how virtual reality tools might negotiate the relationship between embodied creative exploration and the structured precision required in professional design workflows. Rather than positioning VR as a replacement for established desktop-based systems, this research examined its current affordances, constraints, and developmental trajectory through a practice-led and critically reflective methodology.

Through comparative analysis of Gravity Sketch and Open Brush, situated within broader discussions of input fidelity, interoperability, and immersive interaction frameworks, the study identified a persistent structural divide. Gravity Sketch demonstrates partial alignment with CAD-adjacent workflows through export compatibility and surface control tools, yet remains constrained by interaction-level precision limitations. Open Brush supports expressive, intuitive ideation but lacks constraint-based modelling features and parametric interoperability necessary for precision-sensitive applications. Neither platform fully reconciles embodied spatial interaction with tolerance-driven refinement.

A key contribution of this research lies in the exploratory integration of photogrammetry within an immersive workflow. The ClickVR prototype did not demonstrate measurable improvements in efficiency or dimensional accuracy. Instead, it functioned as a proof-of-concept investigation into how real-world scanned geometry might operate as contextual anchors within VR environments. The findings suggest that photogrammetry may offer a pathway for grounding immersive ideation in physically derived spatial references. However, the implications of this integration remain interpretive and require empirical validation.

The analysis also highlighted the evolving role of hardware and interaction technologies. Developments in gesture tracking, haptic systems, and input stabilisation may influence future precision capabilities in immersive environments. Nevertheless, their impact on professional modelling workflows remains under-examined and cannot be assumed.

Across all findings, the central research question was revisited: to what extent can VR design tools support both creative exploration and technical exactitude? The evidence indicates that current tools partially address this goal but remain structurally segmented. Immersive platforms are effective for early-stage ideation and spatial understanding, yet underdeveloped in relation to constraint-driven modelling and precision-sensitive downstream workflows.

Rather than prescribing definitive solutions, this thesis outlines areas for continued investigation. These include adaptive interface layering, improved interoperability between immersive and CAD environments, expanded photogrammetry pipelines, and systematic evaluation of cognitive load in immersive modelling contexts. Importantly, future research should incorporate empirical user testing, longitudinal performance studies, and cross-platform validation to assess the practical implications of hybrid workflows.

Ultimately, the future role of VR in professional design practice is unlikely to depend on replacement of traditional tools. Instead, it may involve incremental refinement of hybrid ecosystems in which immersive ideation and structured desktop-based modelling coexist. This exegesis contributes a critically evaluated prototype and a framework-informed analysis of current limitations, positioning immersive VR not as a resolved solution but as an evolving design medium with both promise and constraint.

Chapter 8: Critical Reflection

The development of this thesis involved not only conceptual investigation but also significant technical experimentation. Early assumptions regarding the capabilities of consumer-grade hardware, particularly the Meta Quest 3, proved to be overly optimistic. Initial expectations included the possibility of native photogrammetry or depth-sensing integration within the headset environment. However, iterative testing and consultation of developer documentation revealed structural limitations. The device does not support built-in structured light or LiDAR-based scanning and provides only RGB passthrough capture functionality. This realisation necessitated a shift toward an external reconstruction pipeline using Meshroom.The prototype therefore evolved through an iterative and constraint-driven process. Development required engagement with fragmented documentation, evolving SDK ecosystems, and interoperability challenges between Unity, standalone VR hardware, and external reconstruction tools. Practical issues such as passthrough image extraction and file transfer workflows required custom scripting and procedural workarounds. These constraints shaped the direction and scope of the prototype.

While the development trajectory was non-linear, this iterative process aligns with the principles of practice-led research. Failures, technical limitations, and workflow breakdowns became analytical data points rather than setbacks. Understanding infrastructural constraints proved central to articulating the broader limitations within immersive design ecosystems.

Importantly, this hands-on engagement sharpened awareness of the practical boundaries of current consumer VR systems. The research therefore benefited from direct confrontation with hardware, software, and interoperability constraints, grounding theoretical claims in material experimentation. In this sense, the act of making functioned as a methodological lens through which the feasibility and structural challenges of immersive photogrammetry integration were critically examined.

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