

UNLOCKING SPATIAL FLUENCY: A SCAFFOLDED APPROACH TO VR VISUALISATION IN FOUNDATIONAL DESIGN EDUCATION

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ABSTRACT

This paper presents a scaffolded pedagogy for teaching Virtual reality (VR) sketching and modelling to engineering students for product design and development. The approach addresses a common barrier for non-design learners: difficulty using traditional freehand sketching to externalise ideas. The framework deliberately progresses from foundational analogue 2D exercises (line control, shape-to-form reasoning, and object deconstruction into geometric primitives) to immersive 3D ideation and surface development using Gravity Sketch as the sole VR platform. By enabling students to work at 1:1 scale and iterate through reversible actions, the VR environment reduces intimidation and supports the development of spatial awareness and controller fluency. Students learn to generate concepts, refine surfaces for product casings, and communicate curvature, proportion, and ergonomic intent directly in three dimensions, improving the speed and clarity of design discussions. Implemented over a 16-week semester with 50 engineering students, the course culminated in individual projects demonstrating that an analogue-to-VR progression can build practical spatial and visual reasoning skills essential for contemporary product development workflows.

Keywords: Visual thinking, VR sketching, spatial reasoning, virtual reality (VR), design education

1 INTRODUCTION

Engineering students increasingly operate in digital-first environments, yet many struggle to externalise early-stage ideas because conventional entry routes—freehand sketching and traditional CAD carry steep learning demands. Freehand sketching can be imprecise [1] for communicating three-dimensional form and typically requires years of practice to reach clarity, while CAD tools often impose a high cognitive load during ideation, shifting attention from exploration to command execution. As immersive technologies mature, VR sketching offers an alternative pathway that can reduce these barriers by enabling students to think and create directly in 3D [2]. This paper investigates spatial fluency as a key capability for bridging the analogue–digital gap in concept development. We define spatial fluency as the practical competence to interpret, manipulate, and communicate form natively in three dimensions, without relying on 2D translation [3]. Through an empirical, credit-bearing intervention with non-design engineering students, examines how a structured analogue-to-VR workflow, centred around Gravity Sketch for product-oriented sketching and modelling, supports ideation, spatial communication, and proof-of-concept visualisation [4]. The study contributes an actionable pedagogical structure and evidence of how immersive sketching can expand access to design capability within engineering education [5].

2 BACKGROUNDS

Virtual Reality (VR) is increasingly shaping how early-stage concepts are explored, evaluated, and communicated in product development. Immersive environments allow learners to work with form at varied scales, test proportions and ergonomics through embodied movement, and iterate in three dimensions with immediate feedback [6]. Prior work on immersive prototyping positions VR as a practical medium for advancing concepts earlier in the pipeline, particularly when physical prototyping is slow or resource-intensive [7] & [8]. Yet, educational adoption remains uneven, partly because commercial tools are typically introduced as software training rather than as structured learning experiences with explicit outcomes [9].

A strong motivation for VR-based instruction is the documented role of three-dimensional spatial visualisation in engineering and design performance [1]. Sorby emphasises the need to strengthen spatial ability among non-design learners, as it underpins the interpretation and manipulation of 3D form. VR sketching has been described as a bridge between ideation and prototyping because it enables learners to construct, assess geometry & volume within an immersive space [4]. Evidence from applied domains such as automotive concept design further suggests VR sketching can improve spatial fidelity and reduce iteration time [10]. In response, the course was delivered in a workshop-style format, emphasising guided demonstrations, short practice cycles, and iterative critique. Sessions progressively moved from foundational sketch habits to immersive form exploration, enabling students to build competence through repeated making, feedback, and refinement within a concept-oriented VR workflow.

3 METHODOLOGIES

This study employed an instructional intervention design to evaluate a scaffolded pedagogical approach for developing VR sketching capability and creative confidence [7] among students from non-design backgrounds. The intervention was structured as a short intensive course progressing from analogue sketching foundations to VR-based ideation, modelling, and final rendering, with instructional support gradually reduced as students gained competency. The study involved 50 undergraduate engineering students with no formal design background [7], divided into 10 batches of five students to enable close facilitation and iterative feedback. All participants completed the same sixteen-week instructional sequence. Each 45-minute session emphasised incremental skill development through repeated practice, guided exercises, and structured critique, enabling students to build confidence and spatial fluency before advancing to more complex tasks. The intervention followed a scaffolded learning strategy in which demonstrations, guided exercises, and instructor feedback were progressively replaced by independent exploration as learner competence increased [4]. Scaffolding was implemented through: (a) sequencing skills from basic drawing control to volumetric reasoning and digital production; (b) a structured transition from analogue sketching to immersive VR workflows involving VR sketching, 3D modelling, and texture application; and (c) continuous progress monitoring to support diverse learner entry points. This approach allowed students to engage directly with VR-based form development without prior VR sketching experience. To evaluate the intervention, an anonymous post-study survey was conducted using Google Forms. The survey captured participant feedback, learner experiences, and reflections on the course structure and VR workflow. The responses informed post-study analysis and contributed to refinements in the pedagogical framework. The pedagogical pipeline unfolded across seven sequential stages (Figure 8 below).

3.1 Analog Foundations (Paper-and-Pencil Sketching)

The course began with low-stakes analogue sketching to develop baseline visual confidence and hand-eye coordination. Learners practiced line control and contour drawing before advancing to shape-to-form development (e.g., transforming 2D shapes into 3D forms). Students also engaged in analogue deconstruction, in which complex real-world objects were observed and mentally decomposed into geometric primitives (e.g., cubes, spheres, cylinders, lamps, and organic shapes, etc.). The focus was on “seeing structure” rather than producing aesthetically refined sketches, thereby reducing performance pressure while strengthening volumetric understanding (See Figure 1 below).

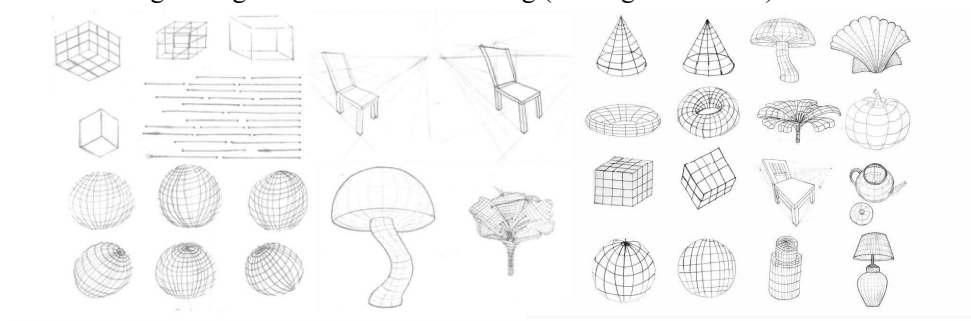


Figure 1. Example of visualising primitive geometry

3.2 VR Tool Familiarisation (2D-to-3D Transition)

After establishing basic volumetric reasoning, learners were introduced to a VR sketching platform (e.g., Gravity Sketch). Familiarisation followed a structured progression: students recreated contoured volumes and simple everyday objects in 3D space, practicing scale, placement, and orientation. This stage emphasised continuity with Stage 1 by transferring already-learned concepts (volume, proportion, primitives) into the immersive environment (see Figure 2 below).

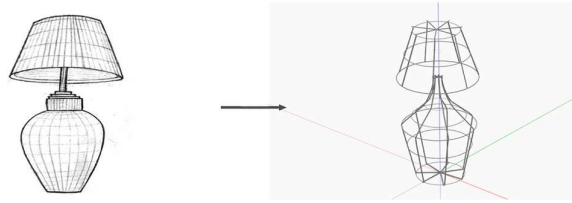


Figure 2. Analogue to 3d conversion

3.3 Concept Framing (Moodboard and Inspiration Board)

To anchor exploration and prevent tool-driven divergence, students developed a Moodboard/inspiration board aligned with a concept they wished to explore (See Figure 3 below). This activity was conducted through iterative discussion and critique, including feedback from senior faculty. Boards typically included references related to form language, style cues, contextual use, and material/texture inspirations [11].



Figure 3. Mood board with the setting of the Concept

3.4 VR Ideation and Volumetric Concept Sketching

Students then engaged in rapid ideation directly within VR. The emphasis was on generating multiple volumetric alternatives through quick exploratory sketching, iterating on shapes, proportions, and configurations, and progressively converging toward a selected form direction. Outputs from this phase included multiple candidate concepts and one refined concept for further development (See Figure 4 below).

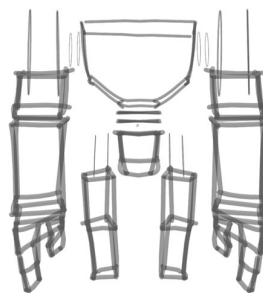


Figure 4. Example of VR Sketching

3.5 VR Modelling (Surface Development and Refinement)

Following concept selection, learners transitioned from sketching to VR-based modelling (See Figure 5 below). Instruction focused on constructing and refining surfaces, improving form coherence, and managing surface interactions (e.g., continuity and intersections). This stage aimed to convert exploratory sketches into more stable model-like representations suitable for subsequent detailing and export.

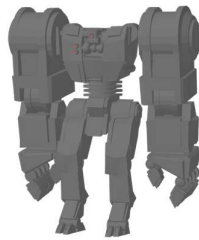


Figure 5. Example of VR Modelling

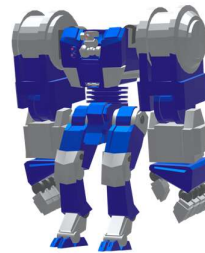


Figure 6. Texture preview with lighting

3.6 Detailing and Texturing

Once primary form decisions were finalised, students were introduced to detailing and texturing workflows (See Figure 6 above). Learners explored secondary features and surface qualities to improve visual clarity and communicative fidelity. Texturing was intentionally positioned after form stabilisation to ensure that surface qualities complemented, rather than substituted for, unresolved geometry [8].

3.7 Export and Rendering

In the final stage, students exported their VR-generated 3D files and used Blender to produce presentation-ready renders (See Figure 7 below). Instruction included file import, basic model preparation as needed, lighting and camera setup, and composition for final visualisation. This stage completed the pipeline from early ideation to shareable outputs.

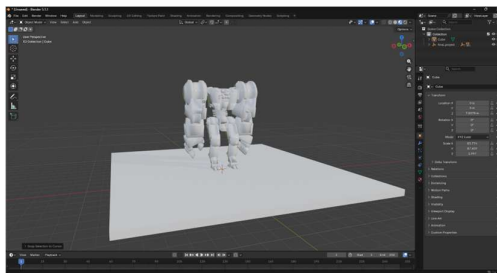


Figure 7. Finalisation of composition to render in Blender

Progress was tracked throughout the intervention to support mastery-based movement across stages. Early sessions involved higher instructional support (demonstrations, step-by-step guidance, corrective feedback), while later sessions emphasised learner independence and self-directed iteration. Batch-based delivery enabled facilitators to observe difficulties (e.g., spatial reasoning, tool control, or concept convergence) and provide targeted feedback. The pedagogical pipeline visualisation can be viewed in (See Figure 8 below).

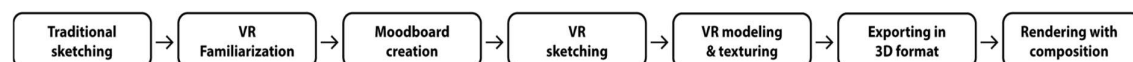


Figure 8. Finalisation of composition to render in Blender

4 RESULTS

Students' most significant learning gains were observed during the transition from unstable 2D sketching to immersive VR sketching, modelling, and final rendering. Gravity Sketch served as the

primary platform due to its support for spatial sketching and surface-oriented (NURBS) modelling, enabling students to create clean, editable geometries aligned with product-design workflows [3]. The learning process followed a progressive structure. Initially, students converted basic geometric forms into simple 3D models. From the second week onwards, they translated inorganic objects composed of basic shapes into VR-based 3D forms, strengthening their ability to convert orthographic sketches into perspective representations. From the third week onwards, students advanced to modelling organic forms, improving their understanding of surface flow, contours, and curvature. Sketching curved forms in VR required greater controller fluency and spatial coordination, enhancing embodied interaction with form generation. Pedagogically, this phase focused on developing controller fluency, including tool handling, stroke control, and navigation, alongside spatial awareness related to scale, depth, and volumetric judgment. Students demonstrated improved understanding of volume, proportion, and structural logic through continuous instructor observation. Increased confidence in line work, reduced sketch jitter, and improved contouring and proportional scaling prepared them for VR-based ideation tasks [12]. Building on these foundations, students developed exploratory conceptual briefs inspired by forms encountered in films, games, and popular media. Rough 2D sketches were imported into VR to establish three-dimensional bounding volumes, grounding concept exploration within explicit spatial constraints. Within Gravity Sketch, students explored concepts through 1:1-scale spatial sketching and refined them into higher-precision surfaces suitable for product casings [9]. Students who struggled with perspective sketching on paper benefited from embodied VR ideation, as they could rotate, scale, and evaluate forms directly in 3D space, enabling faster iteration and clearer visualisation. This was particularly valuable for engineering students, for whom three-dimensional form representation was not a natural part of prior training. Concepts were subsequently exported to Blender for texturing, lighting, and rendering, resulting in high-fidelity digital twins representing refined concept configurations rather than exploratory sketches. A comparative synthesis highlights the strengths of the VR-based workflow (See Figure 9 below). Conventional CAD-first instruction often prioritises precision and configuration while underemphasising experiential and aesthetic exploration. Conversely, purely VR-led approaches may encourage expressiveness without ensuring configurational feasibility. The proposed workflow balanced both approaches by combining immersive ideation with structured refinement. Features such as 1:1-scale feedback and low-risk iteration tools, including undo/redo functions, encouraged students to explore more complex configurations than they would typically attempt within conventional CAD workflows [4].

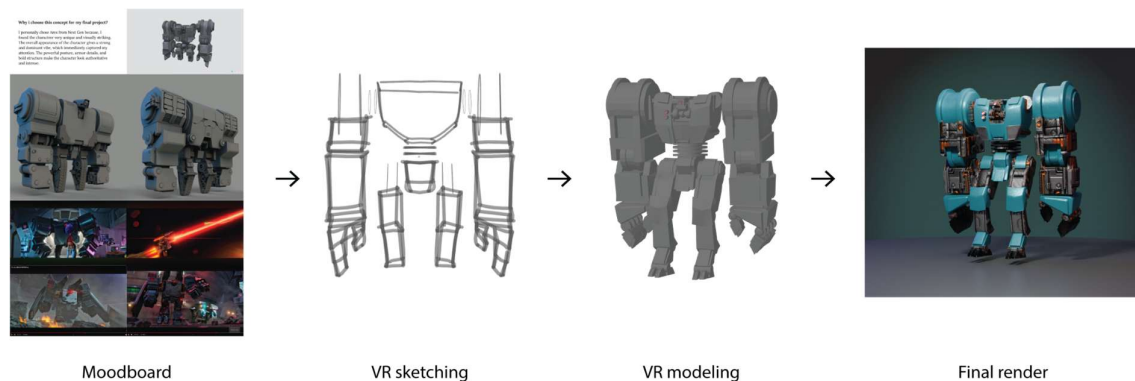


Figure 9. Full workflow from mood board to render

5 DISCUSSIONS & CONCLUSION

This research challenges the positivist assumption that design knowledge is primarily abstract or symbolic. Instead, it adopts a constructivist and embodied epistemological perspective in which knowledge develops through situated action and experiential engagement. By sketching and modelling in VR at a 1:1 scale, students engage with space beyond geometric representation, experiencing form through bodily movement, spatial awareness, and continuous interaction between the hand, tool, and design. This embodied interaction supports spatial fluency, understood as a practical “knowing-how” that enables learners to think and operate directly in three-dimensional space without relying on 2D translation methods [3]. In this context, VR functions not only as a tool but as a medium that reshapes learning by making spatial reasoning immediate, interactive, and embodied. Three major outcomes

emerged from the intervention. First, students demonstrated increased creative confidence. The intimidation associated with the blank page gradually diminished, and learners initially hesitant to sketch progressed toward generating complex VR-based forms through a scaffolded workflow moving from analog deconstruction to immersive refinement. Second, communication of spatial intent improved significantly. Instead of relying solely on ambiguous 2D drawings, students demonstrated curvature, thickness, ergonomics, and spatial relationships directly in 3D space, enabling clearer critique and faster iteration [4][2]. Third, the workflow enabled high-fidelity proof-of-concept outputs. Models exported to Blender for texturing, lighting, and rendering resulted in digital twins that met product-configuration expectations even among engineering students with limited design training. These findings suggest that immersive workflows can effectively bridge conceptual ideation and digital realisation. However, these benefits coexisted with practical and ergonomic constraints affecting broader adoption. Some students struggled with immersive navigation and initiating ideation directly in 3D space, reporting disorientation and unfamiliar motor demands. Others experienced eye strain, headset discomfort, and visual fatigue, particularly students with astigmatism, high-powered spectacles, or recurring headaches. Extended use also caused lens fogging for participants wearing glasses. Technical and infrastructural limitations further affected workflow efficiency. Tethered cable systems used for instructor monitoring and real-time feedback occasionally restricted movement and introduced risks of physical obstruction. Limited laboratory space also constrained freedom of movement within the immersive environment. Additional ergonomic concerns were observed among female students with long hair or hair accessories, as headset straps interfered with proper fitting and comfort. Maintaining hygiene standards required regular headset sanitisation using alcohol-based wipes and ensuring devices remained fully charged before each session. Furthermore, the 45-minute session duration limited prolonged exploration, controller fluency, and sustained immersion. Overall, the study highlights the potential of VR-based workflows in supporting design learning by enabling students to think, sketch, and develop ideas directly in three-dimensional space. While the approach demonstrated promising outcomes in creativity, spatial understanding, and digital visualisation, the findings also emphasise the need to improve accessibility, comfort, and practice duration to create a more inclusive and effective immersive learning environment.

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