6

Introduction to 3D Sketching

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What if designers' marks and movements while sketching could transcend the page and exist in 3D space? This chapter addresses this exciting question through a fresh discussion of the science, techniques, and applications of sketching in 3D space. Although 3D spatial relationships are often depicted in traditional 2D sketches, this chapter focuses specifically on a different form of sketching that may be new to many readers. Here, sketching in 3D space refers to a type of technology-enabled sketching where

1. the physical act of mark making is accomplished off-the-page in a 3D, body-centric space,
2. a computer-based tracking system records the spatial movement of the drawing implement, and
3. the resulting sketch is often displayed in this same 3D space, example, via the use of immersive computer displays, as in virtual and augmented realities (VR and AR).

Although such technologies have only recently matured to the point where practical limitations such as costs and maintenance among others, are no longer major issues, it is already clear from the early work reviewed here that sketching in 3D space has serious potential to transform for product design and other design fields.

To better understand this potential, let us first reflect on the role of some existing 3D design tools, for example, physical prototyping and compare this to sketching. When we interact with a physical 3D prototype of a product, architectural space, or other design idea, we are able to make body-centric spatial judgements. We can measure lengths from a first person perspective, and understand form, scale, light, and more. We get to experience the design.

Unfortunately, physical prototypes also have some limitations. Some designs are expensive, impossible, or time consuming to prototype in physical form or at a natural scale, and they are also difficult to edit and annotate.

Traditional 2D sketching, so well documented in previous chapters, provides a complementary tool. Sketching is expressive while also being immediate and easily editable. Sketching enables rapid exploration. We can, for instance, make 20 sketches, throw out 19, and be very happy about how the design process is proceeding. Yet, traditional 2D sketches never quite capture the experience of holding or standing within a physical prototype. We cannot use 2D sketches to make body-centric judgements about scale and other spatial relationships. Even if a sketch beautifully captures a 3D likeness, it does this only from a single vantage point.

Sketching in 3D space promises to overcome these limitations by combining the best of both worlds. In theory, this leads to a medium that provides designers with both the expressiveness, immediacy, and edit-ability of traditional 2D sketching as well as the body-centred spatial awareness, presence, and multiple perspectives afforded by traditional 3D design tools, such as prototyping.

There are already many sketching in 3D space success stories described in literature. Artists have transported us to playful virtual worlds [66] and explored new forms of digital 3D sculpture that preserve rather than hide evidence of a real human hand behind the form [24]. Architects have translated their initial 2D design sketches into life-size virtual sketches they can iteratively refine in life-size virtual environments [35]. Scientists have prototyped 3D multivariate data visualisations [53] and even selected bundles of fluid flow in immersive data visualisations by sketching 3D lassos [68]. Engineers have prototyped new medical devices [36].

Today, the underlying technologies that are required to enable applications like these come mostly from the fields of virtual and augmented reality. This chapter introduces the novice reader to the underlying technologies for display and rendering in 3D space in Section 6.1.1, and the spatial tracking and environmental sensing technologies in Section 6.1.2.

In recent years, AR and AR technologies have become more widely available through commercial outlets and consequently, there is a wider availability of tools that allow for sketching in 3D space. Suffice to say that if readers have access to a VR or AR headset and its corresponding applications manager, they are likely to find at least one 3D sketching application. These applications provide a great starting point for new users, but designers can benefit from understanding a bit more of the history, science, and use cases for sketching in 3D space.

This chapter, therefore, aims to provide designers with two primary resources. First, in Section 6.1, we trace the origins of 3D sketching, including the underlying technologies that make it possible. Second, in Section 6.2 we present the opportunities and challenges of immersive sketching with a discussion grounded in perceptual and human-computer interaction research. From this discussion, we learn what currently works well, and hence the existing opportunities, as well as what does not work well and hence the remaining challenges in the field. The groundwork laid here is built upon in the subsequent chapters. Chapter 7 documents options and best practices for converting input to geometrical representations, covering the four core topics of tracking, filtering, sampling, and mesh creation. Chapter 8 presents what we believe to be the most complete account of 3D sketching interaction devices and techniques ever assembled, including complete references to research and best practices on sketching sub-tasks, strategies and interactive algorithms for increasing control, and matching interaction techniques to the affordances provided by VR/AR hardware. Finally, Chapter 9 brings all these pieces together to present some compelling applications of 3D sketching, organised according to themes that range from conceptual design and creativity to scientific data visualisation.

Since AR and AR hardware has only recently begun to move out of the research lab in the form of commercially successful hardware platforms, most designers today have only been exposed to the concept of 3D sketching through the small set of apps already available in the app stores for the most popular one or two hardware platforms. By covering each of these topics in depth, as informed by the history, current practice, and active research topics within the VR/AR, human-computer interaction, visualisation, and computer graphics research communities, we hope this chapter and the subsequent chapters on 3D sketching provide designers with an approachable and also uniquely complete account of sketching in 3D space.

6.1 Tracing the technological origins of 3D sketching

In this section, we will dive into the historical development of immersive reality, tracing the roots of the technology that makes immersive 3D sketching possible.

Head-mounted displays were pioneered by Sutherland [70] in 1968. Incidentally, a few years before his work on head-mounted displays (HMDs), Sutherland also invented the first digital sketching system. His Sketchpad [69] system is widely considered to be the precursor of modern sketching tools as well as CAD/CAM systems, and further, was one of the first programs that could be fully controlled by a graphical user interface (GUI). It is interesting to note that immersion and digital sketching share the same roots.

Coming back to immersive realities, Sutherland's pioneering AR system utilised a see-through stereoscopic AR display mounted on a bulky HMD tethered to the ceiling as illustrated in Figure 6.1(a). Objects were rendered on a scanline-based cathode-ray tube (CRT) displays which was the leading display technology at the time. Just a glance at contemporary VR devices suggests how far the technology has come. Modern VR headsets such as the Oculus Rift S [54] and Vive Pro [31] weigh less than 500 grams, utilise standardised cables available on any modern PC, and have high-resolution organic light-emitting diode (OLED) displays running at 80–90 frames per second. While Sutherland's device could only display primitive wireframe objects, modern devices can render complex photorealistic scenes with ease. Furthermore, modern VR and AR systems allow six degrees of freedom (DoF) tracking of the HMD as illustrated in Figures 6.1(b) and 6.1(c). That is, both the 3D position and the orientation about the three spatial axis are precisely tracked. Precise and low-latency tracking of the headset is required not just for an enhanced sense of presence in the immersive environment, but is essential to prevent disorientation and cybersickness as discussed in Section 6.2.2.2. For interaction, users either utilise similarly tracked controllers, or make use of recently developed algorithms for bare-hand tracking. Section 8.2.2 presents a discussion on the differences between these interaction devices.

Here, we present the technical advancements that have made this transformation possible. The idea is to give a broad overview of the area, as an exhaustive summary of all VR/AR technological advancements is beyond the scope of this book. We categorise these advancements into the following areas.

6.1.1 Display technologies and rendering

Immersive VR environments can be simulated using a stereoscopic head-mounted display, first demonstrated by Sutherland [70], or a multi-projected environment, such as the cave automatic virtual environment (CAVE) [13]. Our focus is on HMDs, the dominant modality for modern VR. In the past few decades, VR HMD designers have gained from the

(a) 1968 HMD (b) Modern HMD: Oculus Rift S (c) Modern HMD: HTC Vive Pro

Figure 6.1: Sutherland's pioneering AR HMD [70] was bulky and tethered to the ceiling (a). In contrast, modern HMDs afford freedom of movement and interaction via 6-DoF headset and controller tracking (b, c). Some modern devices such as the Oculus Rift S use inside-out tracking (b), while others like the Vive Pro (c) use outside-in tracking which requires external wall-mounted trackers. © (b) Facebook, and (c) HTC.

improvement in display technologies, leading from CRTs to flat-panel liquid crystal displays (LCDs) and then on to flat as well as curved displays based on light-emitting diodes (LEDs). Apart from the obvious impact on the quality of virtual environments that can be displayed, these advancements have also reduced the power consumption and weight of HMDs, further contributing to the recent explosion of consumer interest in VR.

Another important factor impacting immersion is the display's field of view (FoV). Human eyes have an approximate FoV of 210° horizontally and 150° vertically [71]. Hardware designers have been chasing for an improved immersion via higher FoVs from as early as the 1989 Howlett‘s Cyberface system [46], however, even modern VR devices typically only achieve 110–130° horizontal FoV [73] falling short of what the real world affords. Nevertheless, technological improvements are constantly being made to further push the FoV boundaries [56].

One final technological advancement that has led to high-resolution displays in modern VR systems is the miniaturisation of LCD and LED display machinery. With increasing pixel density, hardware designers are now able to integrate high-resolution screens in compact wearable devices. For example, the Vive Cosmos Elite has a resolution of 1440×1700 pixels per eye [73].

Rendering complex scenes on these high-resolution displays while maintaining acceptable frame rates requires massive amounts of computational power. Immersion also requires realistically simulating lighting and shading based on physical principles which can be daunting even for modern graphics processing units (GPUs). As a result, techniques for focusing computational power for synthesising the most perceptually-salient regions of the scene is an active area of research. An important technique for VR HMDs is foveated rendering [55], which synthesises lower details in the periphery compared to the user's point of focus on the *fovea*. While current commercial devices only offer "fixed" foveated rendering, which renders the edges of the display at a lower resolution, mounting eye tracking sensors on HMDs is being actively researched to enable true foveated rendering [81].

Compared to VR, augmented reality displays need to tackle the additional challenge of combining the real world with the virtual. While projection-based AR has been a widely-studied area as well, see for example, [59], we will focus on headset-based and mobile AR. Modern AR devices such as the Magic Leap 1 [51] and Hololens 2 [52] use an optical see-through display. Such display systems include beam-splitters to combine the real-world image with the reflection of an image produced by a stereoscopic display [9]. In contrast, mobile AR is video-based, that is, the technology overlays virtual images over an image of the real world captured through a video camera. While optical see-through AR offers a better sense of immersion, since the user can directly see the physical world, a temporal delay between the real world and virtual objects is always present. This delay occurs because any immersive experience requires sensing and processing the real world and manipulating the virtual world in response. However, the real world can change by the time the virtual objects respond to it, and therefore successfully executing immersive see-through AR requires extremely low-latency sensing hardware and processing algorithms.

6.1.2 Spatial tracking and environment sensing

The second necessary ingredient for realising an immersive environment is spatial tracking. Six degrees of freedom (DoF), namely three translational DoF for position and three rotational DoF for orientation, are typically tracked by HMDs and handheld controllers. Rolland et al. [64] provides a survey of a variety of magnetic field based sensors have historically been utilised for 6-DoF tracking for immersive environments. Magnetic tracking is unaffected by occlusion and optical disturbance, but their short range limits their utility and these tracking devices have fallen out of favour in recent years. Another common tracking technique is through inertial tracking, which utilises inertial measurement unit (IMU) sensors such as accelerometers, gyroscopes, and magnetometers. These IMU sensors are mounted on an HMD or other objects that require tracking, and directly measure linear acceleration and angular orientation. Unfortunately, IMU sensors are susceptible to drift: accumulated error over time [12]. This is especially true for positional tracking, which requires integrating linear acceleration over time to get velocity, which is then integrated to get change in position. Therefore, VR/AR devices typically use IMU sensors in combination with other sensing techniques [10].

The third tracking method involves computer vision and has been actively researched since the early 1990s [5, 75] and has shown rapid advancement recently [22, 16]. Vision-based tracking can make use of either the infrared (IR) portion of the electromagnetic spectrum, or the visible light portion. IR-based tracking typically requires an external source of IR light, which is then reflected by IR reflectors on the HMD and controllers [75]. This configuration can be reversed as well such that the HMD contains the light source while the external *trackers* are equipped with cameras [61]. Such systems are called inside-looking-out and outside-looking-in, respectively, sometimes shortened to inside-out and outside-in as shown in Figures 6.1(b) and 6.1(c). Inside-out systems capturing visible light can completely do away with external markers by tracking prominent real-world features such as edges, textures, high-level descriptors such as SIFT [49], and features learned via neural-networks [79]. Recently, computer vision algorithms have also been applied for hand-pose tracking and gesture recognition [48], enabling natural bare-handed input in immersive environments.

It should be noted that computer vision-based tracking is typically accurate but suffers from high latency and low update rates. In contrast, inertial and magnetic sensing have low latency and extremely high update rates. As a result, modern devices tend to use a combination of computer vision, inertial, and/or magnetic sensors [25].

In this section, we looked at how display and rendering advancements let us visualise beautiful scenes and models in VR/AR and at the advancements in 3D tracking which allow positioning marks freely in 3D. However, tracking and hardware innovations by themselves do not transform immersive reality into a creative platform. The next section looks at the novel interactions made possible by modern VR/AR and how an artist can harness immersive environments for creative sketching.

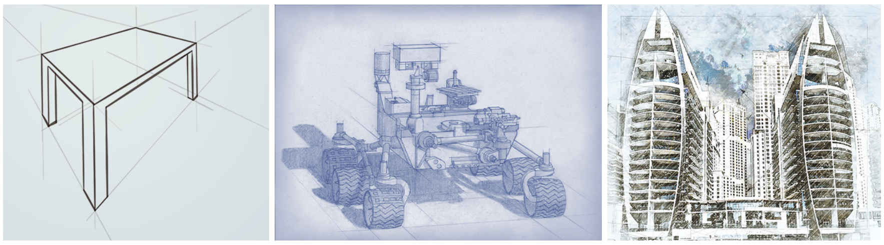
6.2 Opportunities and challenges of immersive sketching

The exciting and unprecedented creative potential of immersive realities is driven by developments in two broad domains, namely, technological innovations resulting in the design of high-fidelity hardware, and creative user interface design utilising the novel interactive capabilities afforded by the said hardware. We looked at the technology driving VR/AR in the previous section; this section discusses the novel interactive affordances enabled by the technology. Our focus here is on broad capabilities; specific research projects and devices are described in more detail in Chapter 8. However, we will not just look into the exciting new creative opportunities of VR/AR, but also delve into the sensorimotor and perceptual challenges that arise during the creative use of these technologies. Following this, we will briefly look at research into the learnability of immersive 3D sketching and modelling, before concluding with a discussion of collaborative 3D creation in immersive realities.

6.2.1 Novel interaction capabilities and creative avenues

As noted earlier, artists and designers have traditionally sketched on a 2D surface using either a physical sheet of paper or a drawing tablet. The resulting stroke-marks are then displayed on a 2D surface either on the sheet of paper itself or on a digital screen rendering the stroke, respectively. In other words, in traditional sketching systems, both the input *creation*) and the output *visualisation* are in the two-dimensional domain. Immersive environments fundamentally transform the creation as well as the visualisation process, lifting both to the third dimension. This is especially relevant for designing 3D objects meant to be physically fabricated and used in the real world.

Three-dimensional input functionality is enabled by tracked controllers, allowing designers to forgo the mental projection from 3D to 2D and directly execute 3D strokes mid-air. As a result, designers do not need to worry about sketching aids such as perspective grids and scaffolding [19, Ch. 2] as illustrated in Figures 6.2(a) and 6.2(b). Moreover, a single3D sketch can convey the full geometric details of the designed object. This is unlike 2D sketching, where a single sketch only depicts the shape as seen from a particular viewpoint as illustrated in Figure 6.2(b), and depicting complex shapes often requires multiple sketches from different viewpoints [63, Ch. 6]. Another advantage of 3D sketches is their inherent spatiality. For instance, 3D sketches provide designer with an opportunity to use their own body to



(a) Need for scaffolds (b) Challenging geometry (c) Lack of scale

Figure 6.2: Working in 2D often requires sketching aids such as scaffolds and perspective grids (a, b), complex objects are difficult to describe in a single 2D sketch (b), and the medium lacks an immersive sense of scale which can benefit the design and illustration of large architectural structures (c). © Rahul Arora (CC BY 4.0), NASA/JPL-Caltech (free to use), and ArtTower (free to use).

assess the scale of the sketch, thereby allowing them to immediately perceive the spatial impact of their designs [33].

While heightened spatial awareness of the designed object for professional designers is important, an even greater potential for impact is communication with relatively untrained stakeholders with lower levels of spatial ability. That is, designers often need to communicate their ideas with non-designer peers and end clients, who may not have had the same training. Immersive displays also improve this communication process, since users without a design background no longer have to take the mental leap of interpreting a 3D shape from purely 2D information [39]. Thus, 3D sketches lower the barrier to entry for understanding early stage designs and those untrained in spatial thinking can also gain a faithful understanding of the visualised concept [57]. At the same time, immersive sketching can reduce the designer effort required to communicate concepts to clients since even loosely drawn ideation sketches can potentially be communicated to the end client.

The third benefit of immersive sketching that we will look into is *scale*. Immersive environments provide the designer with a potentially-infinite 3D canvas to draw in, enabling the drawing of large objects in real-world scale as illustrated in Figure 6.2(c). For example, a furniture designer can draw a table in 1:1 scale, instead of drawing a vastly scaled-down version on a sheet of paper. Designers of virtual worlds for games and movies can conceptualise the whole environment in scale, judging proportions with respect to their own bodies, or they can immerse themselves in a virtual space such as a car or a specific room. Design-focused commercial tools such as Gravity Sketch [23] and Shapes XR [72] equip users with readily-accessible measurement tools to aid their sense of real-world scale. Immersion can thus help not just in assessing the visual and aesthetic aspects of a design, but its functional aspects as well [2]. For instance, questions about a new car seat design fitting tall drivers or the reachability of a new steering wheel design for short drivers can be answered with higher confidence when designing in context using an immersive environment.

See-through augmented reality can take designing in context a step further by allowing designers to draw *in situ*, placing the drawing in the context of the physical world. For example, interior designers can decorate a real-world room, tools can be sketched over the user's hands, and virtual buildings can be positioned around existing buildings in a city [40, 4]. To some extent, this novel creative capability is also supported by video-based AR on mobile devices and "VR" devices which allow a pass-through mode via an HMD-mounted camera. Access to the real world is useful not just for drawing *around* physical objects, but also for drawing *on* and *with* them. That is, physical objects can also be employed as constraints for anchoring strokes [4] or as props [34], respectively. Edges, contours, and textures in the real world can also act as visual guidance for sketches [74].

Despite numerous advantages and novel creative avenues opened up by sketching in 3D, it also comes with its own set of issues. We look at the most important challenges in the next section.

6.2.2 Challenges in control and perception

Creating directly in 3D presents a host of novel challenges, which we divide broadly into three categories, namely issues related to control and precision of 3D strokes, challenges in perceiving objects in stereoscopic 3D, and ergonomic problems encountered by users of 3D sketching systems.

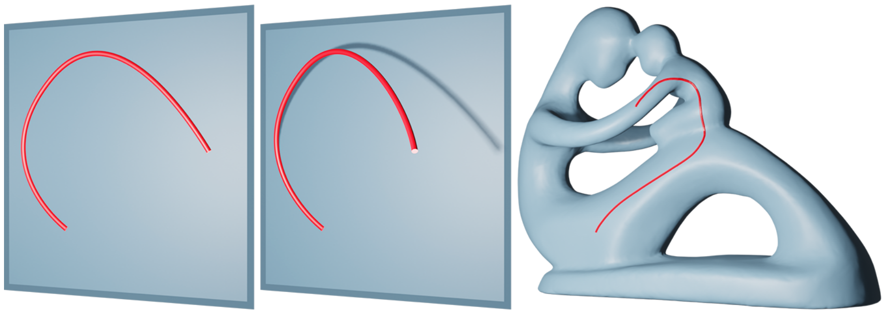
6.2.2.1 Control and Precision Issues

In traditional 2D sketching, a drawing surface provides a physical constraint which helps artists anchor their strokes as shown in Figure 6.3(a). Lacking such a physical constraint, mid-air 3D drawing can be difficult to control and prone to inaccuracy [3, 37]. Keefe et al. [37, 38] indicate that haptic feedback can be useful for reducing control errors, but the range and form-factor of current haptic devices can be limiting. Arora et al. [3] further suggest that

3D drawing imprecision is not limited to out of plane meandering, that is, attempts to draw a specific planar stroke mid-air was observed to be less accurate than one drawn on a physical surface even when the mid-air stroke was projected onto the intended drawing plane. The 3D drawing inaccuracies are also affected by the orientation of drawn strokes with respect to the user, with strokes in the fronto-parallel plane exhibiting the least inaccuracies, while the depth axis is the hardest to sketch precisely [37, 7]. Furthermore, while 3D sketching allows the creation of non-planar or *space* curves in a single step, as shown in Figure 6.3(b), such curves tend to exhibit even higher levels of inaccuracy [3]. One may argue that this deficiency is not important since CAD is dominated by planar curves and non-planar curves are rarely utilised [67, 80]. However, we hypothesise that the proliferation of planar curves in CAD is partially due to limitations imposed by the traditional 2D devices. Therefore, it is important to build novel tools to improve the non-planar curve creation workflow in immersive systems.

Follow-up studies [4, 74] indicate that even sketching directly over physical objects in AR can be prone to precision issues. Drawing over real-world objects is useful for conceptualising decorations and augmentations for those objects. In these cases, sketching precisely is difficult when the object's surface has high curvature regions as illustrated in Figure 6.3(c), unwieldy surface texture, or when it is a fixed or difficult-to-manipulate object, thus forcing the designer to draw in uncomfortable orientations [3, 4, 74]. Lastly, sketching in context of the real-world can be challenging if the strokes are either too large or too small and there is a sweet spot for the size of 3D strokes to ensure accuracy. Specifically, consider an example scenario of drawing strokes larger than a typical human's arm span. This requires the user to move their whole body while drawing, making it extremely difficult to control the stroke. Even drawing long straight lines becomes difficult as the stroke follows the natural arc of the human arm. On the other hand, small 3D strokes, of the order of a centimetre, are visibly impacted by the jitter caused by the lack of a physical sketching surface.

Section 8.1.1 discusses recent research that attempts to alleviate these challenges by taking cues from the 2D sketching domain, while filtering mechanisms for utilising imprecise 3D inputs are described in Section 7.1.



(a) Drawing on a plane (b) Lifting in 3D (c) Drawing on surfaces

Figure 6.3: Traditional 2D sketching is limited to a drawing plane (a), while immersive 3D sketching allows lifting marks off the plane to directly create non-planar curves (b), including drawing directly over highly curved physical or virtual objects (c). However, navigating high curvature regions and unusual drawing orientations imposed by such curves can make the execution ergonomically challenging. Fertility model (c) courtesy Aim@Shape repository.

6.2.2.2 Visual and Perceptual Factors

In the real world, humans perceive depth using a variety of perceptual cues, including monocular cues such as lighting, shading, occlusion, and defocus blur; binocular cues such as stereopsis, proprioceptive cues of accommodation and convergence; and dynamic cues such as motion parallax [30]. Virtual objects rendered by HMDs only offer a subset of these cues and the depth perception is, therefore, diminished as compared to the real world. For example, stereopsis and motion parallax are achieved near-trivially by modern hardware due to the presence of stereoscopic displays and stereo rendering. Occlusion can also be easily achieved in VR via depth-ordering techniques, at least for opaque objects. However, quality of other depth percepts such as lighting and shading may be contingent on the availability of computational resources for rendering the virtual environment in real-time.

In AR environments, occlusion can be also be challenging since correctly occluding and disoccluding the real world requires precise environment sensing. Unfortunately, currently available AR devices suffer from limitations such as limited sensing precision, large initialisation lead times, and wildly inaccurate shape estimation when scanning specular (shiny) surfaces.

In some instances, both AR and VR immersive environments can even offer conflicting depth percept cues, causing user discomfort [21]. One important and well-studied problem is the *vergence-accommodation conflict*, caused by the mismatch between the depth indicated by the rendered objects, and the actual depth of the displays [28]. While the eyes accommodate to the screen located at a distance of a centimetre or from the user, they converge onto the distance indicated by the rendered objects, which is often much larger.

An important characteristic of depth cues is their distance dependence [14]. Notably, occlusion is an extremely relative depth discrimination cue for nearby objects (0–2 m away). Since typical 3D sketching modalities involve sketching in the user's vicinity, this suggests that correctly inferring occlusions and disocclusions is an important puzzle to solve for a truly immersive AR sketching experience.

An additional challenge is the dominance of curves as the preferred geometric modelling primitive for creative sketching which we discuss in Chapter 7. Perceiving depth in the real-world typically involves surfaces, which convey additional depth cues via lighting, shading, and textures. Unlike 3D surfaces, thin curves cannot effectively communicate depth to a viewer via these cues. Furthermore, our focus is on an artist's workflow: an artist must be able to precisely position their head and hands in relation to existing strokes to continue drawing accurately. Unfortunately, as demonstrated by Lubos et al. [50], even reaching out to precise positions in three-dimensions can be challenging. Their study involved participants trying to reach out and select flat-shaded disks in 3D, where, flat shading implies that the discs could not convey texture and shading details. The results of their experiment shows that errors due to sensorimotor inaccuracies in 3D hand positioning is a minor factor in comparison to errors due to depth misperception [50]. Recent works [6, 8, 3, 37] further characterise 3D selection inaccuracy, demonstrating that the dominant inaccuracy is along the depth axis. For further details on perceptual issues in immersive systems, especially in AR, we refer the reader to the excellent ontology by Drascic and Milgram [18].

Using novel algorithms, interfaces, and hardware design, various remedies for these perceptual issues have been suggested in literature. We will look into these solutions in Section 8.2.2 and Section 8.2.2.2.

6.2.2.3 Ergonomics and User Comfort

In Section 6.2.2.1, we noted that the physical drawing surface in traditional 2D sketching provides a physical constraint that mid-air sketching lacks. This lack of constraint does not just impact stroke precision, but the removal of a physical surface to support the user's hand and arm also increases the strain on the user's muscles [42, 82]. Furthermore, techniques have been developed to minimise strain when drawing in 2D. For example, artists are taught to draw using larger muscles controlling the shoulder and elbow joints rather than smaller muscles controlling the wrist [63, Ch. 1]. Formal sketching guidelines are yet to be developed for mid-air sketching, and it is unclear if it is even possible to sketch in three-dimensions with the same level of efficiency and comfort that artists currently enjoy in 2D. Still, some generic guidelines for VR design such as prototyping interfaces in VR, embracing the 3D interaction space while still maintaining familiar user interface metaphors, and designing with ergonomics in mind, have started to appear [32].

Numerous lab studies and artist interviews have indicated that fatigue remains an issue in mid-air sketching and modelling [3, 37, 17, 43]. Professional artists state that spending long hours sketching in VR can induce neck and shoulder pain [3]. Experiments also suggest that traditional drawing plane orientations utilised by draftsmen and digital artists are close to optimal, and that mid-air drawing fatigue can be partially mitigated by sketching tools that allow users to draw in these desired orientations by, for example, providing methods for efficiently repositioning the scene [3].

A number of solutions have been suggested to mitigate this added fatigue. A haptic rendering device has been shown to deduce mid-air drawing fatigue [37]. Unfortunately, the range of current commercially-available haptic rendering devices can be extremely limiting, supporting only a distance of around a fifth of a meter or less [1], thereby destroying the large-scale drawing affordance of mid-air sketching. It must be noted, however, that wireless devices do exist as research prototypes as in Section 8.2.2.2. Utilising a graphic tablet for sketching while mapping the strokes to an immersive visualisation space is another solution [4, 17]. However, the need for manipulating a tablet in 3D space, or holding it still in space can also be a demanding task. Even holding a mobile device steadily mid-air can induce fatigue [43]. Finally, Arora et al. [3] suggest that artists should reposition the scene in order to draw in certain desirable orientations, called *sketchable* orientations. Interestingly, the suggested optimal orientations are similar to those utilised by traditional draftsmen. We will return to this discussion in

Section 8.2.2.2 and discuss some ideas for improving the ergonomics of immersive sketching in detail.

Another important consideration is the strain induced by the HMD itself. In an immersive environment, *sensory conflict* caused by the mismatch between the simulated reality and our expectation of reality can induce simulator sickness [60]. In VR, this can be caused, for example, by the disruption of well-trained interaction between senses due to the low refresh rates of the immersive display, as compared to the expectation of the human brain [45]. In AR, *swimming* artifacts caused by poor environment sensing can induce sickness [29]. Fortunately, both rendering and sensing have been rapidly improving, raising the hope that VR/AR-sickness can be largely avoided. For a more thorough discussion on VR-induced cybersickness, see Davis et al. [15]. It must be noted that while the *sensory conflict* theory is the most widely accepted explanation for VR-induced simulator sickness, competing theories suggesting the lack of a *rest frame* aligned with the user's inertial frame of reference [58, 76] and *postural instability* caused by the body's attempts to learn to stabilise in a novel virtual environment [62] are also being actively researched.

Lastly, while lighter than their historical counterparts, the weight of immersive reality HMDs still causes a significant strain on the user's head and neck. Innovations in headset design and computational miniaturisation can help combat this problem.

6.2.3 Learnability considerations

In Section 6.2.2.1, we talked about studies which show that humans do not enjoy the same degree of control and precision at 3D sketching as they do at traditional 2D sketching. Even experienced artists encounter a host of difficulties when creating in immersive 3D. However, an important point to note is that these *experienced* artists are experienced at traditional 2D sketching, or at other forms of visual creation which have existed for a long time. In contrast, mid-air 3D sketching is a novel medium and most artists have not been exposed to it before. Therefore, the question of the *learnability* of 3D sketching is of paramount importance.

As a species, humans have been sketching in 2D for millennia [47]. Every professional designer has had years of formal training and experience sketching in two-dimensions. Is it fair then, to compare human sketching abilities in the novel mid-air 3D domain to the long-learned 2D sketching?

Of more practical importance is the question of training artists to get better at 3D sketching and understanding how quickly this skill can be acquired.

The learnability of immersive sketching was first studied by Wiese et al. [77]. In a study with 25 design students as participants, they observed that even short training sessions of 10–30 minutes produced an observable improvement in 3D sketching quality. Barrera Machuca et al. [7] noted that higher spatial ability, as measured via standard tests [41, 20], was correlated with better 3D shape depiction when using immersive sketching. This suggests that the spatial reasoning and imagination skills acquired by artists and designers during formal training and practice can transfer over to 3D sketching as well.

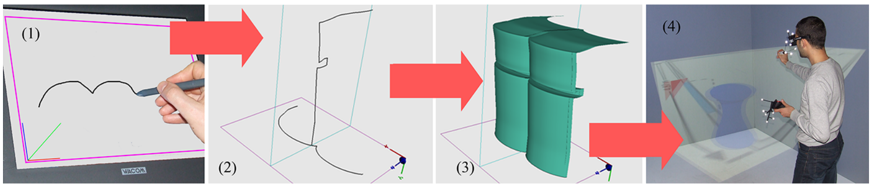
Much work is still needed to gain a deeper understanding of 3D sketching learnability. Not many learnability studies have been performed so far, and even the ones that have been performed only study participants over short periods of time. Only a long term study that looks at participants' progress over weeks or months can reveal the true potential of 3D sketching. With the learnability considerations in mind, we now move on to a discussion of collaborative creation in immersive realities.

6.2.4 Considerations for collaborative creation

Design rarely happens in isolation the synthesis of a useful real-world object requires designers to collaborate with peers, engineers, managers, and clients to brainstorm ideas, offer and receive feedback, and ideate iteratively. It is, therefore, crucial to examine the collaborative aspects of immersive sketching. How can designers communicate sketches created in VR/AR? How does immersion aid this communication? What are the hindrances to a successful collaboration in immersive sketching? In this section, we will look at a few interactive tools designed to aid collaboration in immersive design. We shall also identify the challenges these tools aim to solve, and how the target applications dictate which collaboration tools users desire.

In the study by Herman and Hutka [27], expert 2D artists were introduced to 3D creation in VR to observe how they adapt to the novel medium. They noted artists' expectations for the interface, functionality, and applications, as well as their mental models for creation in 2D and VR. While artists also imagined using VR for creating initial mock-ups and for collaborating with 3D artists who build 3D models based on their 2D concept art, communicating the design to end-clients was considered as the most important use case for VR. As we have noted earlier, immersion

(a) Hyve-3D (b) An et al. [2] (c) *Storyboarding*



(d) VR4D

Figure 6.4: Collaborative design using immersive systems. In Hyve-3D [17], individual tablets act as 3D cursors for interacting with a shared immersive design space. An et al. [2] target the prototyping of functional user experiences (b). Henrikson et al. [26] support asymmetric collaboration for storyboarding 360° movies (c). VR4D [11] connects a VR user to a tablet user for collaborative sketch-based CAD (d).

improves spatial awareness for designers and non-designers alike, but has a larger impact on the spatial awareness of non-designers. Therefore, artists in Herman and Hutka's study found VR extremely useful for communicating with clients, who do not have formal training in design. Experimental research has confirmed that immersive environments can improve spatial awareness [44] and aid non-professional users in comprehending 3D content [65], thus aiding designer to client communication.

Other studies have looked more closely at designers actively collaborating in immersive settings for applications ranging from architectural and interior design [17, 11] to experience prototyping for the design of automotive interiors [2] to storyboarding for VR movies [26].

To aid designer collaboration for architectural design, Dorta et al. [17] created the Hyve-3D system, which equips designers with individual tablets for interacting with a shared anamorphic projection-based immersive 3D space for architectural design. As shown in Figure 6.4(a), the tablet acts as an individual *3D cursor*, allowing users a personal window for visualisation as well as creation. The individual tablets allow users to co-design while optionally looking at the shared immersive visualisation for communication. Unfortunately, Hyve-3D does not allow mid-air sketching or any other technique for creating non-planar geometry, as all strokes are executed on the tablet and are constrained to be planar.

VR4D [11] explores the collaboration between users who do not share an immersive space. In their system, one user dons a VR HMD, while the other holds a drawing tablet. As shown in Figure 6.4(d), collaboration is enabled by dividing the design duties between the users. While the tablet user creates geometry by **sketching** 2D curves (1) and building surfaces of extrusion and revolution (3), the immersed user **reviews** the created geometry (2), provides verbal **feedback**, and handles scene **layout** (4). In addition to the shared workspace, VR4D aids collaboration by rendering a rectangle representing the tablet user's drawing plane in VR, and by relaying the sketched strokes to the VR user in real-time. Henrikson et al. [26] employ similar metaphors for 360° storyboard design. In their system, the artist holds the tablet, while the director wears the HMD as shown in Figure 6.4(c). Collaboration aids include real-time visualisation of artist's strokes for the director, maintaining a consistent FoV across both modalities, a shared ground plane with a radial grid to aid verbal communication, and overlays indicating the current view for both users. Furthermore, when receiving feedback from the director, the artist can choose to couple the two views, allowing the director's HMD to dictate the tablet's viewport as illustrated in Figure 6.4(c)(bottom).

An et al. [2] take this metaphor a step forward by imagining multiple members of a design team in a collaborative design setting. In their study, designers are provided with a barrage of VR and AR headsets, drawing tablets, and physical props as shown in Figure 6.4(b). Team-members play different roles and utilise the device or prop most suitable for their assigned role. The studied design task is experience prototyping of automotive interior interfaces. Using a combination of shared and isolated experiences, the designers collaborate to design the shape of the car interiors and the functionality of the interface.

The lesson to takeaway from these case studies is that while VR provides novel opportunities for collaboration, specific design domains need a careful treatment for their particular demands. However, some general solutions can potentially be applied across domains. For example, Xia et al. [78] recently developed a set of techniques for helping resolve spatiotemporal conflicts in virtual scene design in a collaborative immersive setting. This system helps reduce conflicts by letting users work on parallel copies of scene objects, and aiding collaborative interactions among variably-sized *avatars* corresponding to individual users. It will be interesting to adapt such techniques for 3D design sketching.

6.3 Summary

In this chapter, we delved into the historical background of 3D sketching, looking into the technology underpinning contemporary 3D sketching hardware. We further discussed the novel creative opportunities enabled by this exciting medium and how researchers are designing novel tools to exploit these opportunities. But we also discussed the flip side of the coin—the challenges in control and precision, ergonomics, and perception which can hinder creativity in immersive environments. Fortunately, significant research has already gone into novel interaction techniques and input devices that help mitigate these problems, and are comprehensively described in Chapter 8. But before describing these solutions, the next chapter further describes mechanisms for processing 3D sketch inputs, further laying the groundwork that will allow the reader to understand existing 3D sketching systems, modify and augment them, and even build their own 3D sketching tools.

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