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3D Sketching Application Scenarios

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The technology needed to enable 3D sketching has become more accessible due to the availability of consumer VR devices and companies have released software that enables users to sketch and design in 3D such as Tilt Brush [1], Gravity Sketch [2], and Quill [3]. Research tools have also been made available for other disciplines to work with such as the Lift-Off and Hyve systems. In the previous chapters of this part, we presented information about how interacting with a 3D sketching system can be realised ([Chapter 8](#)) and how the sketched information can be represented internally ([Chapter 7](#)). This chapter shifts the focus from the sketching system and the interaction techniques to existing projects in various application domains. We present the created artefacts and use-cases to provide an overview of how different domains *use* mid-air 3D sketching.

After presenting some general findings regarding the advantages and effects of 3D sketching on creativity, we present systems from a variety of different disciplines including art, modelling, movie-making, architecture, visualisation design & research, medicine, and cultural heritage.

9.1 Conceptual design and creativity

Traditional sketching is a central part in early conceptual design and allows to quickly produce initial ideas. Many researchers believe that immersive sketching can be beneficial in this stage as designers can create and see their ideas in 3D without requiring additional sketching techniques. Israel et al. [4] investigated how 3D sketching affects the early conceptual design stages by performing expert discussions and user studies. They concluded several benefits of 3D sketching.



Figure 9.1: Example drawings around a mannequin. Students in the VR condition sketched more novel ideas compared to the pen-and-paper condition. Image taken from [6].

Spatiality: seeing a sketch as a 3D object

1-1 proportions: being able to create and see the object at the same size it could be constructed in

Association: to design and create objects where they could be used or relative to existing objects

Formability: the option to adjust and change virtual models

Israel et al. argue that the biggest advantage is the sketching process itself as it enables the user to recognise the spatiality and spatial thinking involved in creating the 3D sketch. On the other hand, Israel et al. also note that traditional sketching has advantages in other areas so that “sketching on paper will not be replaced”.

The Lift-Off System by [5] provides a possibility to combine the two methods. Here, users can first use pen-and-paper sketching to create initial design ideas. These sketches are then placed in VR and the user can lift individual lines from the image into mid-air. Between the lines created this way, surfaces can be generated to create a full model. The authors used their system to create several animal models from sketches such as a moose, a fish, or a lion’s head and also let an architect try out this system to design a cabin.

To compare creativity between pen-and-paper sketching and immersive sketching, Yang et al. [6] performed a study in which participants had to generate wearable technology ideas around the model of a human given in the scene or on paper as shown in Figure 9.1. They found out that participants in



Figure 9.2: Long exposure photograph of Picasso using a light pen to draw lines in mid-air. ©Gettyimages.

the VR condition had better focus and better flow while working on the task, indicating greater creativity. Participants in the pen-and-paper condition on the other hand were more relaxed. However, their ideas were more similar to each other compared to the ideas in the VR condition. Yang et al. hypothesise that the ability to view the scene from different viewpoints might lead to the higher amount of novel ideas.

9.2 Art

The ability to define persisting lines in mid-air is a revolutionary opportunity for the art community. Artists have used various techniques to create the



Figure 9.3: An artist suggesting the shape of an artwork by sketching lines in mid-air. Image from [8].

perception of depth in their images but immersive sketching enables new possibilities for 3D art. Using a light pen and long-exposure photography, it has been possible for some time to create an image of strokes performed in 3D. Picasso, for example, used this method to visualise 3D sketches [7]. However, the sketches created this way are always somewhat elusive since the artist can not see the lines while sketching and the static viewing perspective has to be specified beforehand. The immersive sketching systems presented in this chapter allow to create lasting sketches that are visible to the artist, are editable, and can be viewed from multiple positions.

Examples of art created with Tilt brush can be seen for example on the website of the “Artist in Residence” program run by Google¹. Compared with models created for games or for personal fabrication, artistic sketches don’t need, or even benefit from, the absence of watertight 3D meshes. Instead, the strokes can be used to suggest the form rather than completely specify it, thereby engaging the viewer in the interpretation of the artwork.

A classical distinction regarding art is the perception of art as either the “process” of creating an artwork or the finished artifact itself. A third view could be the focus on the perception of the viewer while interacting with the artwork. In the area of immersive sketching, this has for example been made part of the art installation by Rubin and Keefe [9] in their “Hiding Spaces”. This VR system features 3D painted mid-air objects in

¹ <https://www.tiltbrush.com/air/>

front of virtual backgrounds. As the viewer moves through the exhibit, the background morphs based on the viewing movement of the user making them part of the experience.

Our focus in this chapter, regardless of the interpretation of art—either as the final artifact or as the process of creating the artifact—is the interaction with the immersive sketching system. Therefore, we describe how artists have been *using* immersive sketching systems to create their artwork and do not discuss related areas such as copyright or sampling of digital art. Using an immersive VR sketching system is interesting from an artist's perspective as the artist is leaving the real environment to a large degree, grounding her- or himself in the virtual environment. Chittenden [10] looked at this detachment and sees similarities to the “adventure chronotope”. Yet, even in this new environment, 3D sketches are unmistakably human creations. In 3D sketching, the human hands can leave a trace that, like a digitally sampled voice in electronic music, provides clear evidence, perhaps even an identifiable artistic style or mark, of the physical art-making process. This has potential to engage both artists and viewers in new ways with digital media. Indeed, even concepts, such as sampling, derivative works, and copyright take on new meaning when considering a spatial, digital medium that translates physical movements of the artist so directly. In this regard, 3D sketching is decidedly different from traditional digital 3D modeling tools.

Art can be created in many inventive ways and artists often use existing methods in novel way to realise their artworks. For example, Grey [11] used the surface drawing system [12] to create a trace around a human person. The resulting model looked nothing like the person but viewing the tracked lines from different perspectives produced interesting shapes. The author used the model in different compositions such as “Rockman” shown in Figure 9.4 and “Visitation”. A similar approach is seen in the Artwork by Nam and Keefe [13]. Here, the viewing angle of the person looking at the screen determined how the digital drawing would be shown. Additionally, the artist creating the drawing was recorded from multiple angles. This allowed to show the creation process from these different angles synchronised with the viewing position of the digital drawing while the viewer looks at the artwork.

There are many ways to create a 2D painting but many early projects for immersive modelling focused on creating cylindrical lines or ribbons in mid-air. To gain more expressiveness and options, Mäkelä [14] added particle clouds and meshes to the mix and also replaced the wand controller with a finger tracking device to easily adjust the size and position of strokes simultaneously in real time. Using this setup, he re-created an image of



Figure 9.4: The “Rockman” model created by Grey [11] using the surface drawing system.

Rembrandt in VR. More recently, Lisa Padilla² used Tilt Brush to create portraits of celebrities such as Stephen Curry, Andy Warhol, or Mark Zuckerberg (Figure 9.5).

To increase the possibilities for mid-air drawing, Eroglu et al. [15] designed techniques for the creation of fluid artworks similar to smoke photography, paper marbling, or ink dripped into water. The “particles” can be manipulated by hand gestures with the controller as shown in Figure 9.6 or by blowing as shown in Figure 9.7, where the blowing is detected by a microphone that the user is wearing.

Focusing on the experience creating mid-air drawings, Seo et al. [16] presented “Aura Garden”, a VR setup in which users can paint their own light sculptures using a custom wand as shown in Figure 9.8. These sculptures

² <https://www.flickr.com/photos/lisap/44473512285/>

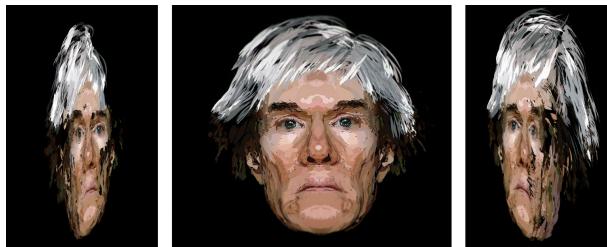


Figure 9.5: Different perspectives at a VR Portrait of Andy Warhol by Lisa Padilla. Created in TiltBrush. Printed with permission.



Figure 9.6: Movements of the hand are tracked to control particles. Images from [15].

remained for the next user to see. While observing visitors of the exhibit, the authors noted that different professions led to different usages of the system. For example, photographers created detailed shapes that they would then look at from different angles while dancers enjoyed to visualise their own movement.

In most cases, the creation and consumption of the artworks is separated in both time and space. For their Hybrid Campus Art project, Pakanen et al. [17] combined both of them. Participants could use TiltBrush to create virtual models directly on the University Campus. These models were then placed in a virtual mirror world of the campus and could be viewed on a screen that was located in the same area. The intention of the authors was to also “add value to mirror worlds”.

9.3 Modeling for fabrication

While many artists like to only suggest the form of a model through individual strokes as seen in the previous section about art, other domains require solid mesh models. One example is the design of objects that are intended to be printed out using a 3D printer. There are techniques that create 3D models for this purpose for example by using commercially available tools such as



Figure 9.7: A microphone detects if the user blows air at the particles. Image from [15].



Figure 9.8: Light sculpture created in Aura Garden. Light beacons indicate the location of sculptures of other users. Image from [16].

Gravity Sketch [2] to create such models directly. In 2007, the Front Design Studio released a video on YouTube showing how they designed furniture by recording mid-air brushstrokes and printing them out using a 3D printer [18]. However, in their system, the designers were not able to see their strokes during the design process. Other projects investigate how the models created by brushstrokes in VR applications such as Tilt Brush [1] can be used to achieve models that can be sent to a 3D printer.

The SurfaceBrush system by Rosales et al. [19] describes an algorithm that interprets the individual brushstrokes in relation to the surrounding brushstrokes to generate surfaces as shown in Figure 9.10. This way, a solid model based on the brushstrokes is generated.

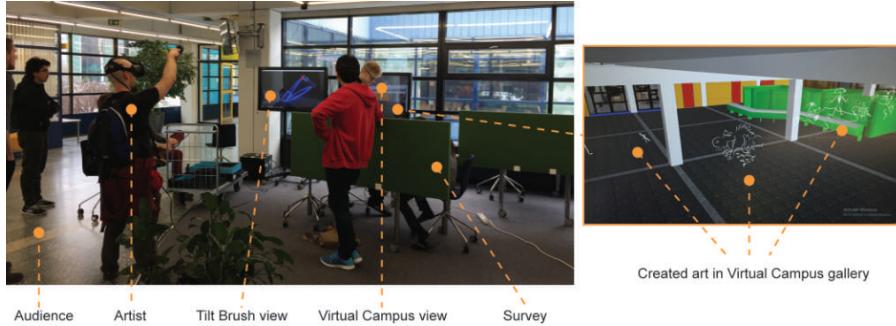


Figure 9.9: Setup of the “Hybrid Campus” project. Both the creation of virtual objects in place as well as the visualisation for an audience are co-located on the campus. Image from [17].



Figure 9.10: Combination of input brushstrokes and the resulting solid model. Image from [19].

Using a different approach, Giunchi et al. [20] use the user’s brushstrokes as search input through a model database. For example, the user creates a rough sketch of a chair and the system searches through its database to find the closest matching existing model. The user can then also adjust the sketch and run the search again.

9.4 Dynamic storytelling

The previous projects aim to create a model that in its finished state is static. However, 3D sketching can also be used in more dynamic scenarios such

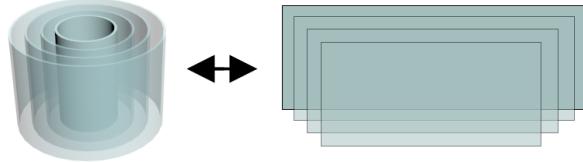


Figure 9.11: The 360 degree surrounding around the VR wearer (left) is separated into different depth layers and flattened into individual planes that can be used to sketch on a tablet. Image from [21].

as movies and animations. Movies in VR are hard to plan and prototype as traditional planning techniques for camera movement and control have issues when applied to scenarios in which the user controls the viewing direction and can turn 360 degrees at any point. Henrikson et al. [21] address this problem by using 360 degree sketching planes that can be viewed within a VR headset as shown in Figure 9.11. This setup allows for simultaneous work. For example, while the director is wearing the VR headset and watching the scene, an artist can directly implement his comments by adjusting the sketch on a tablet. The director himself can also add notes through a tablet similar to drawing tablets. Different depths in the VR environment are achieved by different 360 degree layers that the user can easily switch between.

Mid-Air interaction can also be used to assist in the creation of 3D animations such as the path of an airplane or wind blowing in a specific pattern. Arora et al. [22] implemented and evaluated the “MagicalHands” system which tracks hand gestures to describe animations. They gave the system to four artists and let them create scenes with animations. The resulting scenes included the setting of a scary storytelling, a paper airplane race, and an explanation how rain is forming. They found out during the use of the system that tracking the coarse hand posture might be sufficient precision for the general interaction so that it is not necessary for more precise tracking.

9.5 Architecture

Mid-air sketching also has the potential to be used in different disciplines for which it is not directly apparent. One example is architecture. Traditional sketching, physical mockups, and even desktop-based modelling tools, like Google SketchUp, all play a critical role in modern architectural design. 3D sketching complements these by providing options to quickly create a

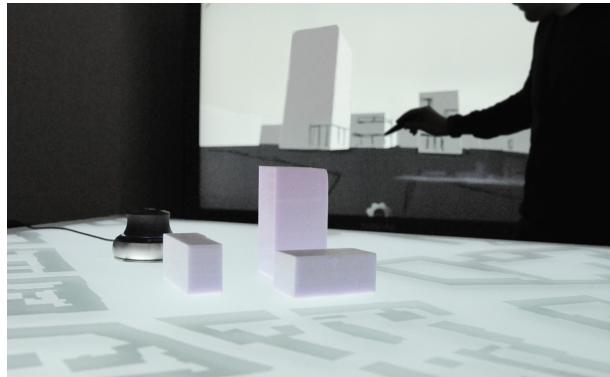


Figure 9.12: Overview of the architectural drawing system. The position of the objects on the multitouch table is synced with the visualization on the touchscreen. Drawings on the touchscreen are applied to the 3D model depending on the chosen drawing mode. Image from [23].

building layout before stepping inside a prototype and annotating the design. For example, the Lift-Off system was used by an architect to design a cabin over multiple sessions with the system [5]. For a dynamic planning scenario, Schubert et al. [23] combined a sketching tool with a physical 3D working model of a cityscape on a multitouch table shown in Figure 9.12. The multitouch table was used to arrange the tangibles representing the buildings and a touchscreen beside the table showed a rendering of the scene. Sketches on this touchscreen could be integrated into the virtual model in different ways. The first, 2D, is similar to tracing on a paper. The sketch stays relative to the camera and is not connected to the scene. Adding half a dimension, the 2.5D mode has two sub-modes. In the “Object Mode”, lines drawn are projected onto the 3D objects in the scene, in the “Extended Mode”, a infinite supporting plane from a selected surface allows to sketch continuations from an already existing plane, for example, to connect two objects or to extend an object. In both 2.5D modes, the drawings are connected to the objects in the scene and keep their relationship when the camera or object is moved. The final mode is the 3D sketching mode. Here, the user can sketch 2D models on the screen and they are converted into 3D mesh models that are placed in the scene as shown in Figure 9.13.

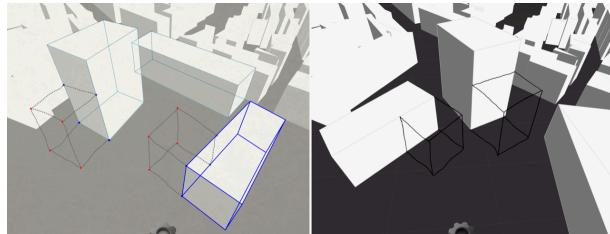


Figure 9.13: Example of the 3D drawing mode. 2D sketches on the screen are converted into 3D models that are placed in the scene. Image from [23].

9.6 Visualisation design and research

Visualising information in 3D can be helpful in many disciplines. While artists have the skills to visualise data, interpreting what a set of data means and what data is relevant also requires expert knowledge in the current research domain. Often, artists are employed at the end to create visualisations for the findings of the researchers. However, including visual artists early rather than later during the evaluation can help researchers to *understand* the data and *find* results. Keefe et al. [24] introduced the process of Scientific Sketching to enable the collaboration between researchers and artists to visualise research data. They based this process on the experience they had gathered before when working with visual artists to investigate archaeological dig sites and the fluid dynamic of flying bats by visualising the data in VR [25]. They found that artists can convey the data well but require the critique and assistance from researchers along the way. For the scientific sketching process, they formulate four steps: Paper sketching, VR sketching, VR prototyping, and implementation. Similar to the process suggested in the “Lift-Off” system, the paper sketching step allows for quick exploration of ideas using traditional methods. In the next step, the VR sketching, the ideas can be transferred into the third dimension to both test different spatial arrangements and give people the option to critique these arrangements. The VR prototyping step adds more refinement and interactivity as well as animated elements to the visualisation. The resulting visual requirements can now be implemented in the final step. The final visualisation is then dependent on the underlying research data and not on manual control. While it is important that the artist can prototype many visualisations in the early stages, it is important to include the real data as well. Otherwise, this might lead to a situation in which the artist has created a good visualisation for

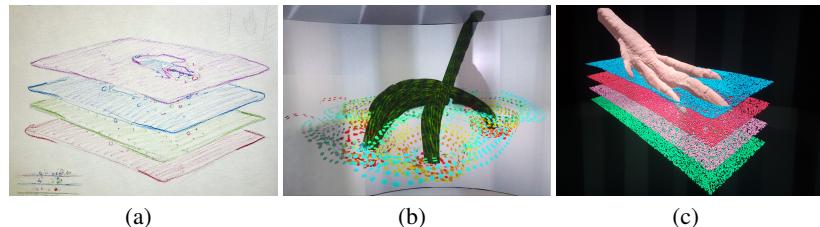


Figure 9.14: The visualisation of dinosaur foot movement at different stages of the scientific sketching process. Starting with a paper sketch (a) the artists generate prototype visualisations in VR (b) and suitable visualisations are implemented to run dependent on the research data (c). Images from [26].

a single sample of data but that this visualisation is not able to visualise different sets or the change over time. This process was for example used by Novotny et al. [26] to analyse the foot movement of dinosaurs based on fossil scans. They let two VR visualisation design courses work on the visualisation and according to the researchers, the process and the result provided a significant benefit to the standard desktop based analysis. To analyse the data, the researchers and artists used different visualisations such as a particle visualisation to track the movement of different particles during the foot movement as shown in Figure 9.14.

9.7 Medicine

In the medical field, immersive sketching can help in many different ways as well. Similar to modelling tasks described in Section 9.3, seeing the model of new equipment such as an operating table in its real environment can help to uncover issues that have not been detected before. Johnson et al. [27] used the “Lift-Off” system to design new equipment and then have medical professionals look at the models in the real size and setting. This uncovered issues that have not been thought of previously. An example are hinges that are in the way of the doctor when walking around the table. But 3D sketching can be used in more cases such as communication and education. In the same project, Johnson et al. also enabled doctors to create models of injuries such as fractures to explain the diagnosis and treatment to patients as shown in Figure 9.15. The doctors said that while the modelling process itself would not be desirable for them, the option to annotate the model would be used to



Figure 9.15: A doctor describes the injury and treatment by showing and annotating a 3D model. Image from [27].

explain the procedure. An interesting observation of the communication of doctors with the patients was that the doctors spend more time to explain the surrounding elements of an injury, for example to explain the effect it had on muscles surrounding a fracture. This included areas that were not even visible in the traditional 2D data normally used in the communication with the patient. The researchers conclude that providing 3D models of injuries in their context within the body can help doctors communicate with the patients.

The relationships and processes within the body are hard to learn and effects of changes are not easy to predict. Saalfeld et al. [28] investigated how 3D sketching can help in understanding such relationships by designing a semi-immersive system with 6-DoF sketching capabilities that is aimed at medical educators and students to understand the vascular structure. Users can sketch blood vessels and add disturbances such as saccular aneurysms. The system would then animate the blood flow through these vessels enabling the teacher or student to In an evaluation, the researchers focused on the creation of blood vessel sketches and they did not study if and how the new visualisation improves learning retention.

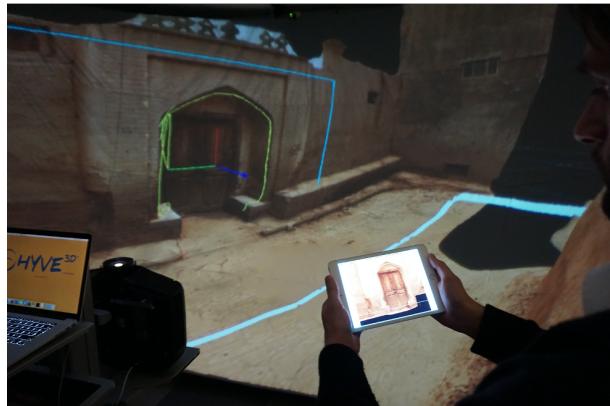


Figure 9.16: User can navigate the virtual space using a tablet and annotations made on the tablet are added to the 3D model. Image from [29].

9.8 Cultural heritage

Virtual environments have a great potential in the area of cultural heritage since it is possible to visualise environments and structures that do not exist anymore. Virtual environments can also be used to provide information and annotate specific areas on artworks without having to mark the statue or painting itself. Making the possibility to annotate models available for everyone also creates new ways to involve people in generating cultural heritage. Schnabel et al. [29] used the Hyve3D system and its sketching capabilities (explained more closely in [Section 8.2.2.2](#)), to navigate through a scan of the old town of Kashgar. Multiple users could sketch on their tablets to annotate their current view in the 3D world, as shown in [Figure 9.16](#) and [Figure 9.17](#), for example to provide explanations of interesting structures or ‘errors’ in the scanning data. The authors explain that this process could enable the creation of new stories either about the old town or its scan in particular.

Virtual reality also becomes an interesting part of theatre installations [30] and mid-air sketching can be used in this context to prototype and design sets. The virtual rooms of the play “Draw Me Close”³ for example, have been created using mid-air sketching techniques as shown in [Figure 9.18](#).

³ https://www.nfb.ca/interactive/draw_me_close_en/

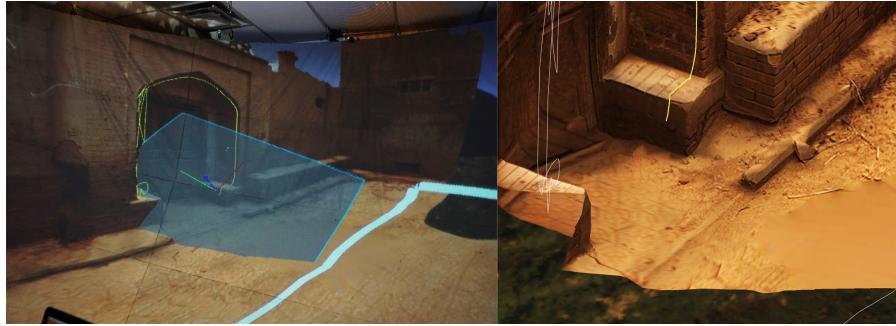


Figure 9.17: The viewing position of a user is shown with a cursor in the 3D model (left). Right: the view of the user from the cursor on the left. Images from [29].



Figure 9.18: VR sketch of the house of the play “Draw Me Close”.

9.9 Summary

The projects show that 3D sketching can be used in a variety of domains and for many different use cases. One central intention is to “create” a 3D object or scene that can be used later, for example for 3D printing or as an artwork. Other potential uses of 3D sketching are communication and education. Being able to highlight a particular part in a scene or visualise a 3D path can help to bring points across, for example, in medical contexts among others, and being able to manipulate 3D models and see the effects live can assist in understanding consequences of these changes. We believe that the potential of using 3D sketching as a tool has not yet been reached and that many processes can be improved by employing 3D sketching techniques.

9.10 Conclusion

We conclude for this whole part of the book that 3D sketching is a uniquely powerful and widely applicable tool for designers. Although it is often marketed today as a new technology, taking into account the long history of 3D Sketching, as presented in [Section 6.1](#), reveals a, perhaps more accurate, assessment that what we are witnessing today is instead the maturing of a technology that has been under development for more than three decades.

The longstanding interest in 3D sketching can be attributed, in part, to the many opportunities the hardware and software provide. In other words, the affordances provided by 3D tracking and spatial displays lead naturally to a medium that simultaneously combines an ability to make body-centric 3D spatial judgements with the fluidity, immediacy, and creativity of traditional 2D sketching.

With this fundamental potential identified, it is worth noting that the medium does also present challenges to overcome. At the top of this list, presented in [Section 6.2](#), is controlling 3D mark making, a challenging topic because the applications of 3D Sketching are so broad. The most straightforward application of the technologies leads to a style of loose, fluid sketching that is a natural fit for 3D gesture sketches and early conceptual design work. Yet, this is not as appropriate for more deliberate styles of drawing or model making where artists and designers wish to have precise control over proportion, line quality, and form. Fortunately, there are many possible solutions to achieving this level of control as described in the deep dive into interaction devices and techniques together with input processing algorithms in [Chapter 8](#). Compiling and discussing this picture of the state of the art leads us to conclude on behalf of the 3D Sketching research community that we have now reached the point where the goal should no longer be to create the “best” general 3D Sketching system or interaction technique. Instead, the tools and techniques have reached a point of maturity where we are fortunate to be able to instead focus on, “the best technique for the job at hand”.

This brings us to the many possible applications of 3D sketching. We hope that our review of compelling work to date inspires designers to think creatively about how 3D Sketching in Space might be used in their practice. The cornerstone application for many designers will likely be conceptual design and modelling for fabrication or building. However, also consider the role 3D sketching can play in art, dynamic storytelling, data visualisation, medicine, and cultural heritage, where we see some of the most creative

applications to date. Whatever the application, it is clear the 3D sketching in space is now in a renaissance period, and we look forward to seeing how designers will employ these exciting techniques now that it is possible for them to move beyond the research lab and into regular practice.

References

- [1] Google. Tilt Brush. <https://www.tiltbrush.com/>, 2020.
- [2] Gravity Sketch. Gravity Sketch. <https://www.gravitysketch.com/>, 2020.
- [3] Facebook. Quill. <https://quill.fb.com/>, 2020.
- [4] J. H. Israel, E. Wiese, M. Mateescu, C. Zöllner, and R. Stark. Investigating Three-dimensional Sketching For Early Conceptual Design—results From Expert Discussions And User Studies. *Computers & Graphics*, 33(4):462 – 473, 2009. ISSN 0097-8493. doi: <https://doi.org/10.1016/j.cag.2009.05.005>. URL <http://www.sciencedirect.com/science/article/pii/S0097849309000855>.
- [5] B. Jackson and D. F. Keefe. Lift-Off: Using Reference Imagery and Freehand Sketching to Create 3D Models in VR. *IEEE Transactions on Visualization and Computer Graphics*, 22(4):1442–1451, 2016.
- [6] X. Yang, L. Lin, P. Y. Cheng, X. Yang, Y. Ren, and Y. M. Huang. Examining Creativity Through A Virtual Reality Support System. *Educational Technology Research and Development*, 66(5):1231–1254, October 2018. ISSN 1042-1629, 1556-6501. doi: [10.1007/s11423-018-9604-z](https://doi.org/10.1007/s11423-018-9604-z). URL <http://link.springer.com/10.1007/s11423-018-9604-z>.
- [7] Pablo Picasso. Pablo Picasso Draws With Light: The Story Behind an Iconic Photo, January 2012. URL <https://www.life.com/arts-entertainment/behind-the-picture-picasso-draws-with-light/>. Library Catalog: www.life.com Section: Arts & Entertainment.
- [8] D. F. Keefe. From Gesture To Form: The Evolution Of Expressive Freehand Spatial Interfaces. *Leonardo*, 44(5):460–461, 2011. Publisher: MIT Press.
- [9] C. B. Rubin and D. F. Keefe. Hiding Spaces: A CAVE Of Elusive Immateriality. In *ACM SIGGRAPH 2002 conference abstracts and applications on - SIGGRAPH '02*, page 192, San Antonio, Texas, 2002. ACM Press. ISBN 978-1-58113-525-1. doi: [10.1145/1242073.1242205](https://doi.org/10.1145/1242073.1242205). URL <http://portal.acm.org/citation.cfm?doid=1242073.1242205>.
- [10] T. Chittenden. Tilt Brush Painting: Chronotopic Adventures In A Physical-virtual Threshold. *Journal of Contemporary Painting*, 4(2):381–403, October 2018. ISSN 2052-6695. doi: [10.1386/jcp.4.2.381_1](https://doi.org/10.1386/jcp.4.2.381_1). URL http://www.ingentaconnect.com/content/10.1386/jcp.4.2.381_1.

- [11] J. Grey. Human-Computer Interaction In Life Drawing, A Fine Artist's Perspective. In *Proceedings of the Sixth International Conference on Information Visualisation*, pages 761–770, London, UK, 2002. IEEE Comput. Soc. ISBN 978-0-7695-1656-1. doi: 10.1109/IV.2002.1028866. URL <http://ieeexplore.ieee.org/document/1028866/>.
- [12] S. Schkolne, M. Pruett, and P. Schröder. Surface drawing: Creating Organic 3D Shapes with the Hand and Tangible Tools. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '01)*, pages 261–268, New York, New York, USA, 2001. ACM Press. ISBN 1581133278. doi: 10.1145/365024.365114. URL <http://portal.acm.org/citation.cfm?id=365114><http://portal.acm.org/citation.cfm?doid=365024.365114>.
- [13] J. Nam and D. F. Keefe. Spatial Correlation: An Interactive Display of Virtual Gesture Sculpture. *Leonardo*, 50(1):94–95, February 2014. ISSN 0024-094X, 1530-9282. doi: 10.1162/LEON_a_01226. URL http://www.mitpressjournals.org/doi/10.1162/LEON_a_01226.
- [14] W. Mäkelä. Working 3D Meshes and Particles with Finger Tips, towards an Immersive Artists' Interface. In *Proceedings of the IEEE Virtual Reality Workshop*, pages 77–80, 2005.
- [15] S. Eroglu, S. Gebhardt, P. Schmitz, D. Rausch, and Torsten W. K. Fluid Sketching—Immersive Sketching Based on Fluid Flow. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 475–482, Reutlingen, March 2018. IEEE. ISBN 978-1-5386-3365-6. doi: 10.1109/VR.2018.8446595. URL <https://ieeexplore.ieee.org/document/8446595/>.
- [16] J. H. Seo, M. Bruner, and N. Ayres. Aura Garden: Collective and Collaborative Aesthetics of Light Sculpting in Virtual Reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, pages 1–6, Montreal QC, Canada, 2018. ACM Press. ISBN 978-1-4503-5621-3. doi: 10.1145/3170427.3177761. URL <http://dl.acm.org/citation.cfm?doid=3170427.3177761>.
- [17] M. Pakanen, P. Alavesa, H. Kukka, P. Nuottajärvi, Z. Hellberg, L. M. Orjala, N. Kupari, and T. Ojala. Hybrid Campus Art: Bridging Two Realities Through 3D Art. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia - MUM '17*, pages 393–399, Stuttgart, Germany, 2017. ACM Press. ISBN 978-1-4503-5378-6. doi: 10.1145/3152832.3156613. URL <http://dl.acm.org/citation.cfm?doid=3152832.3156613>.
- [18] FRONT. Sketch furniture by front. <https://www.youtube.com/watch?v=8zP1em1dg5k>, 2007.
- [19] E. Rosales, J. Rodriguez, and A. Sheffer. SurfaceBrush: From Virtual Reality Drawings to Manifold Surfaces. *ACM Transactions on Graphics*, 38(4):1–15, July 2019. ISSN 07300301. doi: 10.1145/3306346.3322970.

- [20] D. Giunchi, S. James, and A. Steed. 3D Sketching for Interactive Model Retrieval in Virtual Reality. In *Proceedings of the Joint Symposium on Computational Aesthetics and Sketch-Based Interfaces and Modeling and Non-Photorealistic Animation and Rendering*, Expressive '18, New York, NY, USA, 2018. Association for Computing Machinery. ISBN 9781450358927. doi: 10.1145/3229147.3229166. URL <https://doi.org/10.1145/3229147.3229166>.
- [21] R. Henrikson, B. Araujo, F. Chevalier, K. Singh, and R. Balakrishnan. Multi-Device Storyboards for Cinematic Narratives in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology - UIST '16*, pages 787–796, Tokyo, Japan, 2016. ACM Press. ISBN 978-1-4503-4189-9. doi: 10.1145/2984511.2984539. URL <http://dl.acm.org/citation.cfm?doid=2984511.2984539>.
- [22] R. Arora, R. H. Kazi, D. M. Kaufman, W. Li, and K. Singh. MagicalHands: Mid-Air Hand Gestures for Animating in VR. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 463–477, New Orleans LA USA, October 2019. ACM. ISBN 978-1-4503-6816-2. doi: 10.1145/3332165.3347942. URL <http://dl.acm.org/doi/10.1145/3332165.3347942>.
- [23] G. Schubert, E. Artinger, V. Yanev, F. Petzold, and G. Klinker. 3D Virtuality Sketching: Interactive 3D-sketching Based On Real Models In A Virtual Scene. In Mark Johnson Jason Kelly Cabrinha and Kyle Steinfeld, editors, *Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, volume 32, pages 409–418. The Printing House Inc, WI, 2012.
- [24] D. F. Keefe, D. Acevedo, J. Miles, F. Drury, S. M. Swartz, and D. H. Laidlaw. Scientific Sketching for Collaborative VR Visualization Design. *IEEE Transactions on Visualization and Computer Graphics*, 14(4):835–847, July 2008. ISSN 1077-2626. doi: 10.1109/TVCG.2008.31. URL <http://ieeexplore.ieee.org/document/4447665/>.
- [25] D. F. Keefe, D. B. Karelitz, E. L. Vote, and D. H. Laidlaw. Artistic Collaboration In Designing VR Visualizations. *IEEE Computer Graphics and Applications*, 25(2):18–23, March 2005. ISSN 0272-1716, 1558-1756. doi: 10.1109/MCG.2005.34. URL <https://ieeexplore.ieee.org/document/1405949/>.
- [26] J. Novotny, J. Tveite, M. L. Turner, S. Gatesy, F. Drury, P. Falkingham, and D. H. Laidlaw. Developing Virtual Reality Visualizations for Unsteady Flow Analysis of Dinosaur Track Formation using Scientific Sketching. *IEEE Transactions on Visualization and Computer Graphics*, 25(5):2145–2154, May 2019. ISSN 1077-2626, 1941-0506, 2160-9306. doi: 10.1109/TVCG.2019.2898796. URL <https://ieeexplore.ieee.org/document/8672601/>.
- [27] S. Johnson, B. Jackson, B. Tourek, M. Molina, A. G. Erdman, and D. F. Keefe. Immersive Analytics for Medicine: Hybrid 2D/3D Sketch-Based Interfaces for Annotating Medical Data and Designing Medical Devices. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces - ISS Companion '16*, pages

- 107–113, Niagara Falls, Ontario, Canada, 2016. ACM Press. ISBN 978-1-4503-4530-9.
doi: 10.1145/3009939.3009956. URL <http://dl.acm.org/citation.cfm?doid=3009939.3009956>.
- [28] P. Saalfeld, A. Stojnic, B. Preim, and S. Oeltze-Jafra. Semi-Immersive 3D Sketching of Vascular Structures for Medical Education. In *Eurographics Workshop on Visual Computing for Biology and Medicine*, pages 123–132, 2016.
 - [29] M. A. Schnabel, S. Aydin, T. Moleta, D. Pierini, and T. Dorta. Unmediated Cultural Heritage via Hyve-3D: Collecting Individual and Collective Narratives with 3D Sketching. In *Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2016*, volume 21, pages 683–692, 2016.
 - [30] S. Atkinson and H. W. Kennedy. Extended Reality Ecosystems: Innovations in Creativity and Collaboration in the Theatrical Arts. *Refractory: A Journal of Entertainment Media*, 30(2018), 2018. ISSN 1447-4905.

