Combining 2D and 3D Modeling

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Abstract
Creating and modeling 3D objects faces many challenges in all currently available environments. Especially accuracy and precision of drawing and sketching in mid-air without constraints is often a problem. We present some of the most important papers in the area of combining 2D and 3D modeling in AR and VR environments and categorize each paper's methodology considering their implementation setup, approaches, and results. We identify strengths and challenges and discuss them in our final results. We demonstrate that different approaches are more suitable for different use cases and that imprecise 3D sketching still remains an issue.

Introduction
The research fields of augmented reality (AR) and virtual reality (VR) have their roots in the 1960s, more than 50 years ago [13]. Sketch-based modeling has been extensively researched as an intuitive approach of making 3D models during the last several decades. While traditional 2D sketching has been ingrained in our consciousness, abilities, and training since childhood [15], the rise of consumer-grade augmented and virtual reality (AR/VR) devices has recently enabled us to digitally transcend the limits of the sketch canvas, providing artists with the unprecedented ability to sketch 3D curves directly in the air. Numer-

ous research projects and products, such as Tiltbrush[1] and Gravity Sketch[2], are centered on sketching in mid-air to produce 3D objects in both VR and AR. Both technologies enable users to create and examine 3D models immediately. Despite their novelty, contemporary mid-air 3D drawings lack the precision and constraints required for conceptual design. This is primarily due to our ergonomic inability to draw accurately and in-depth at arbitrary 3D scales, orientations, and without a physical platform to support and steady our sketching action [2]. Surprisingly, both traditional and digital 2D sketching techniques effectively solve this issue. They provide greater control and precision over sketch strokes and are ergonomically superior in comfort. However, the biggest problem with 2D sketching is conveying the absolute 3D depth from a single viewpoint using only a flat surface.

Several approaches and tools have been created to investigate various conceptual choices for creating 3D models by combining 2D and 3D modeling [10, 1, 5, 3]. According to their surveys, in augmented reality, users can define and sketch on a drawing plane, and sketches on the actual drawing surface are then projected onto the AR drawing plane. As a result, users benefit from the expressiveness of free mid-air sketching while simultaneously having the precision of a real drawing surface available. Therefore, we've compiled some of the most important papers in this field in one document.

Structure

In the following, after an overview of background and related work, we subsequently present some of the most relevant paper's proposed setup, techniques, and results. In the discussion, we will categorize chosen papers based on their contributions and challenges in similar order they encountered. Later in the conclusion and future work part, we presented possible research opportunities in the field of combining 2D and 3D modeling.

Background and Related Work

In this section, we give a short summary of papers in the domain of combined 2D and 3D modeling and sketching, in AR or VR environments, using props like tablets, pen styluses, tabletops, smartphones or Desktop PCs.
SpaceTop by Lee et al. [6], uses a see-through desktop monitor to combine 2D and 3D spatial interactions. The user can click, type and draw with a mouse and keyboard placed behind the see-through monitor and then manipulate the created 2D elements in 3D space. This method however lacks the immersion that the integration of VR or AR provides. Making VR Work by Mine et al. [8] uses a VR environment and two 6DoF-tracked hybrid controllers combining physical buttons with a touch display. Special emphasis in the development was put on the reduction of fatigue and exhaustion during the usage of the system. TabletInVR by Surale et al. [12] developed a vocabulary of interaction techniques, describing the usage of a tablet combined with 6DoF-tracked barehand mid-air input. The vocabulary's usefulness was then tested in a VR environment.
In the following sections, we describe some papers that are not mentioned in this section in more detail.

Mockup Builder

Mockup Builder [3] by Bruno R. De Araujo et. al. introduces a semi-immersive environment for conceptual design, creating virtual mockups from 2D sketches on a surface in the form of a 2D tabletop. The work provides several on-and-above-the-surface interaction techniques using bimanual finger and hand gesture inputs. Combining above-the-table finger and hand tracking with multi-touch on its sur-

[1]Tiltbrush - https://www.tiltbrush.com/
[2]Gravity-Sketch - https://www.gravitysketch.com/

face allows for more expressive operations on the mockup. Switching between bimanual interaction on the surface and continuous interaction above the surface, together with asymmetrical and symmetrical hand operations are the key features of the Mockup Builder.

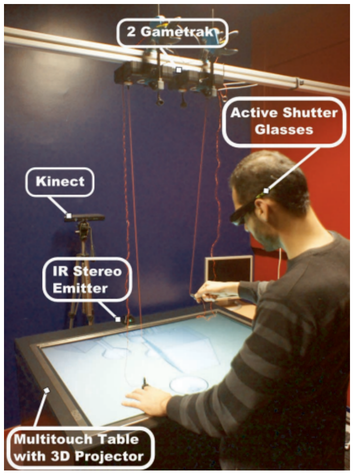

Figure 1: Overview of the setup as shown in [3]

Setup

The setup (Fig 1) consists of a stereoscopic multi-touch display, a Kinect and two Gametraks used to track the hands and fingers above the table. Head tracking and locating the dominant hand are achieved by the Kinect's skeleton detection algorithm, while finger tracking is used through multi-touch on the surface and Gametraks above the surface. The stereoscopic visualization is created through the back-projection-based system under the table and the active shutter glasses from 3D Vision NVIDIA. The IR Stereo Emitter uses an IR wavelength different from the multi-touch table. For on-the-surface inputs, a camera is set up under the table and for above-the-surface inputs, the Gametraks compute the 3D position of the fingers. Gametrak strings are attached to the fingers to compute the rotation and position of the fingers. Also switch buttons on each index finger allow the detection of pinching actions.

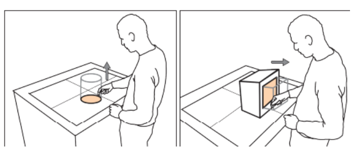

Figure 2: Lifting up a 2D image into 3D space (left) and extruding a face along the normal (right) as shown in [3]

Approach

The suggested modeling approach for creating, modifying and editing 3D models consists of multiple modeling operations. To work properly with models, the models are represented by boundary representations. The boundary representations are made of faces, edges and vertices, which are created by decomposing the topology of the object. The boundary representation can be selected to modify the model in 3D space according to the selected part(face, edge or vertice). Using multi-touch on the surface, sketches can be created and afterwards 'pulled up' to create a stereoscopic visualization of that 2D sketch as a 3D model. They present five different operations to operate on the model, based on the push and pull approach, which Google Sketchup[11] or Sesame[9] is also using.

- Displacing the topological features, to change the geometry of the object without altering its topology
- Extruding a face along the normal, which extends the topology with new side faces accordingly to the selected face (Fig. 2 on the left side)
- Extruding a face along a created path in mid-air or on the surface, also creating new side faces
- Splitting faces, by drawing linear or curvilinear strokes, enabling the creation of more complex forms
- snapping operation, which switches between surface and mid-air editing

These operations are all performed by using asymmetric hand operations, meaning that switching between sketching, object transformation and world manipulation is done implicitly. But they also show three symmetric hand operations, which are using the non-dominant hand (NDH) to complement the actions of the dominant hand (DH).

- The NDH can be used to select a mode for the DH (Fig. 3 on the left side). Next to the NDH, an item menu shows up, representing the different modes available at the given moment
- The NDH can be used to build constraints for the DH using geometrical features. For example using the height of an already existing object as the maximum height for the new object in creation (Fig. 4 on the left side)

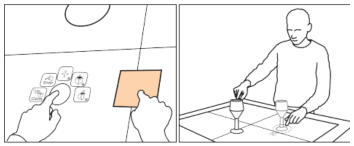

Figure 3: Selecting a mode through the item menu (left) and duplicating an object (right) as shown in [3]

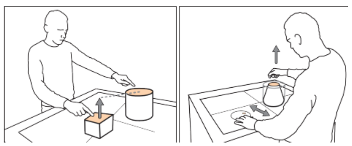

Figure 4: Limiting the height of an object using another one (left) and scaling with the NDH while extruding with the DH (right) as shown in [3]

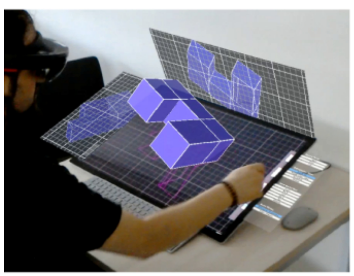

Figure 5: Orthographic views of a 2D projection of the model, one of which is tilted for greater visibility to the user shown in [10]

- The NDH can be used to create continuously updated constraints for the DH (Fig. 4 on the right side)

All these operations together allow the modeling of complex models.

Results

They presented a semi-immersive approach for designing 3D models on and above the surface using various techniques. They tested their prototype and got promising results. The approach seems to be faster than usual approaches like Rhino3D Modeler. Also, it feels very intuitive to work with, since you can seamlessly change from sketching, object transformation and world manipulation. The asymmetric bimanual system might cause confusion and might need time to get used to it since you have to use your non-dominant hand a lot. The necessary need for a menu is also a downside, since it increases visual overlap and clutter.

DesignAR

DesignAR [10] introduced an immersive work environment by combining touch and pen-enabled design workstations with Augmented Reality (AR) head-mounted displays (HMD).Within this immersive work environment, users can use pen and touch input to interact with the AR objects. In addition, DesignAR not only allows the use of AR space but also extends the device screen beyond its display border to present stereoscopic 3D objects. Their method focuses on ensuring a seamless integration of AR content with the display, placing a strong emphasis on the spatial alignment between the two. They categorize AR objects into three levels of spatial proximity: level one (L1) refers to being aligned and placed precisely on display (Fig 5), level two (L2) refers to the idea of having anything placed on or around the display's edges (Fig 6), and lastly, level three (L3) refers to the idea of a display that is spatially independent (Fig 7). L1 and L2 offer a tight coupling relation between AR and the physical environment and invoke the perception of display and AR information being seamlessly integrated. L1 and L2 minimize the lack of immersion and address the possibility of more content space above and beyond the display screen. On the contrary, L3 lacks the tight coupling of the previous two (L1 and L2) but still share a semantic connection to the display, so changes to one affect the other. L3 uses mid-air interaction and provides a real-world reference to 3D objects that can be positioned directly on display by using an AR HMD to understand better how those objects integrate into the environment.

Setup

Their setup consists of an interactive display, AR head-mounted display, a dedicated messages exchange server, and a virtual camera. Their dedicated server issues a session ID during registration of either display or HMD, which ensures the synchronization between them. Although DesignAR only uses a single display and HMD, it opens the door to connect an arbitrary number of displays and HMDs by integrating the publish and subscribe machine network protocol for messages in the future within multiple device configurations. To appropriately depict the model from the user's perspective, an extra virtual camera has been used to sync with the current location and orientation of the HoloLens. To some extent, there are some setup similarities to the well-known fish-tank [14] approach with DesignAR.

Approach

Bimanual touch and pen input are used by DesignAR for interaction within L1. The display's frame surrounding the edge is set aside for touch interaction with AR objects in L2. They have chosen to employ mid-air interaction for all L3

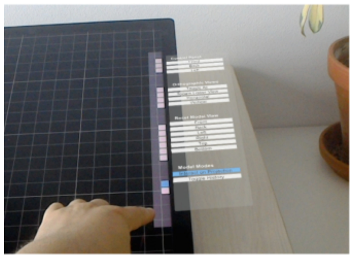

Figure 6: Menu offloaded in AR space, with display borders employed for interaction shown in [10]

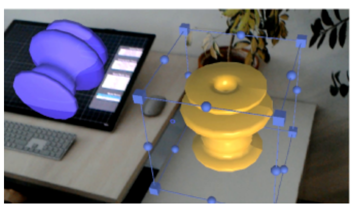

Figure 7: A real-world reference (yellow) of the modeled object (blue) placed directly in the environment shown in [10]

substances.

Every operation in L1 that adds new geometry to the model is carried out with a pen. Multi-touch input is used to carry out additional tasks, such as selection or view modification. The choice to model using a pen was made for two reasons: First, the considerably finer pen tip enables more precise interaction, such as drawing or view adjustment, avoiding the fat finger issue. Second, it relies on the behavioral notion of the pen as a specific tool for creating new strokes. There are toggle buttons on to the display to perform different interaction techniques like translation,rotation and scale. For translation, user can use drag gesture to move the object towards x and y axes with one finger and to move the object towards z-axes with two fingers.A uniform scale is performed with a pinch gesture. They highlight that all interactions take place via the display's axes rather than the model's local axes. Therefore, the user's actions on display are consistent with the model's resulting transformation.

Results
They demonstrated a prototype where they used different techniques to create 3D models and described faced challenges that have been created by using the Unity 3D engine, which runs on both the display and the head-mounted display. Their implementation is not tested in fully fledged 3D modeling applications but based on their hypothesis, they are assuming that it is possible to develop fully-fledged 3D modeling by deep dive into this approach.

SymbiosisSketch

SymbiosisSketch [1] is a hybrid sketching method that combines drawing in the air (3D) with drawing on a drawing surface (2D) to generate detailed 3D drawings in an augmented reality (AR) environment. Users sketch on a 2D

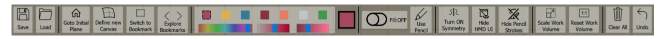

Figure 8: 2D UI toolbar [1]

tablet and a 3D tablet interchangeably inside an ergonomically comfortable canonical volume, which is translated to arbitrary size in AR.

Setup
The system is composed of three key hardware parts: an augmented reality Head-Mounted Display (HMD), a tablet for 2D modeling, and a digital pen with 6 degrees of freedom equipped with motion tracking markers to write in the mid-air (fig 10).The same pen has been used to write on the tablet (fig 9), as writing on the tablet is natively supported by the hardware.In addition, they used Microsoft HoloLens as their AR HMD, which has spatial mapping capabilities and can generate a crude 3D representation of the physical environment as a triangular mesh.

Approach
Multiple modeling operations are used in the proposed modeling technique for creating and altering 3D models.
In this approach, the user usually holds the pen with their dominant hand and the tablet with their non-dominant hand, although the tablet can also be placed on a table. The tablet mainly serves two purposes. To begin, it provides an orthographic view of the environment and allows user to display their drawings on a 2D canvas within this view. Additionally, the tablet has a toolbar that can be activated through pen or touch input (fig 8). They have presented different modeling techniques and also explained the reason for choosing specific ones against the remaining others. They used tube rendering techniques to provide homogeneous sketch appearances and to differentiate curves from drawing canvases when rendering 2D and 3D strokes. They used either

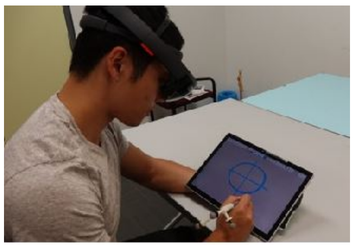

Figure 9: Setup: The user puts on the HoloLens and draws with a motiontracked pen, on a tablet as shown in [1]

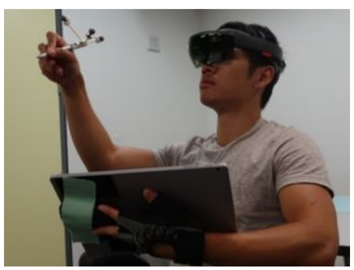

Figure 10: Setup: The user puts on the HoloLens and draws with a motiontracked pen, in mid-air as shown in [1]

a planar rectangle or a surface patch expressed as a height field over a planar rectangle to generate drawing canvases (both flat and curved). Users can define and use an unlimited number of drawing canvases during design, but only one canvas can be activated at a time. The orthographic viewport of the active drawing canvas is always projected by the 2D tablet's viewport, allowing users to draw on the tablet and project their strokes into that canvas in 3D. To avoid frequent view manipulation of the chosen canvas, a continuous boundary topology has been used. Their tool offers many widgets like translation, scale (planar canvas only), move, and rotation to manipulate active canvas. Their method for scaling the workspace gets rid of problems with precision and lets users design large 3D objects with all of the details.

SymbiosisSketch also allows users to interact with and draw relative 3D objects in the physical world, and their survey results show that defining curved canvases by using physical objects as proxies or by scaling the workspace can significantly reduce the amount of direct interaction with the objects, potentially influencing final design outcomes. A pencil tool has been used to draw strokes of a pre-defined thickness and color. To draw solid objects users need to use close strokes. To make stroke smoothing and reparametrization, they used a real-time smoothing procedure which ensures strokes are more suitable for canvas fitting and rendering. This technique also helps to remove additional jitter from the mid-air 3D strokes. By determining the mid-point of the shortest line segment between the pen and head rays, the system actively calculates the approximate intersection while creating, translating, and scaling the 3D location in the workspace.

Results

The system was evaluated by both professional and amateur designers based on task completion time and the total number of strokes drawn. The survey results indicated that the total number of strokes was higher when using the symbiosis sketch, considering the task completion time criteria. A similar trend was observed in the second task of 3D modeling using a combination of 2D and 3D interfaces, with participants in the symbiosis sketch drawing 75 percent more strokes than in other systems. The authors reported that the qualitative feedback collected from the participants indicated that they found the symbiosis sketch to be helpful.

DualCAD

In DualCAD, by Milette and McGuffin [7], users can switch between AR-HMD mode and an external desktop monitor at runtime. A 6DoF-tracked Smartphone serves as an additional input display for stylus and multitouch input. This method combines the precise input with the mouse, which desktop CAD applications provide, and an immersive AR environment that lets you view the scene in 3D space. The phone serves as a selection, transformation and creation tool for polygons in the 3D scene.

Setup

The setup for DualCAD consists of a Meta 1 Developer Kit AR Glasses. These glasses have a 23 degrees Field of View (FOV), 960x540 pixels resolution, front-facing depth and RGB cameras. For the phone the Samsung Galaxy Node 4 was chosen, due to its larger display compared to normal smartphones and the pen stylus. The main CAD program runs on a laptop and the phone communicates via Bluetooth with it. Unity 3D is used to render the 3D scene and the Polhemus Patriot sensor tracks the movement of the phone and the HMD.

Approach

DualCAD enables switching at runtime between a Desktop Mode for the 2D and an Arcade Mode for 3D input. That allows the creation of objects in 3D space with the smartphone and their refinement with the mouse in the more precise CAD environment on the external Desktop screen. The Desktop mode provides a traditional GUI that lets the user create, select, annotate, change colors, group, and un-group. By using the smartphone and the see-through HMD, the user accesses Arcade Mode. The smartphone is tracked in 6Dof and held in the non-dominant hand (NDH). The user interacts with the smartphone with the dominant hand (DH). Tracking the DH index finger in 3D enables the user to interact directly with the scene instead of doing it through the smartphone. A smartphone was chosen because most people own one and today they all have tracking technology embedded. Modern smartphones have a high resolution which compliments the low resolution of the HMD and the phone recognizes multi-touch gestures and offers more stable sketching and handwriting in contrast to mid-air.

The smartphone is the basis of two major interaction workflows, Draw-and-Drop and Touch-and-Draw.

Draw-and-Drop

The user can draw polygons directly on the smartphone surface, as shown in figure 11(a), thus providing a stable and more precise way of sketching than in mid-air. After sketching the polygon, the user can extrude it into 3D space. The extrusion height is defined by sliding the DH index finger across the phone's display, as shown in figure 11(b,c). The extruded object stays attached to the phone, and the user can place it in the 3D scene by orienting the phone inside of it 11(d). By pressing a button on the phone with the NDH, the object is released and placed in the scene, as shown in figure 11(e).

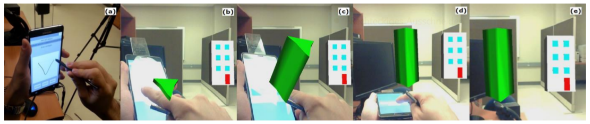

Figure 11: Example for a Draw and Drop operation [7]

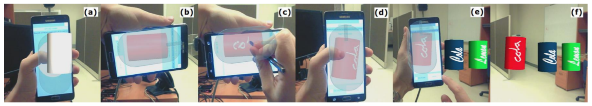

Figure 12: Example for a Touch and Draw operation [7]

Touch-and-Draw

The user can modify an existing object by using the phone as a proxy for the virtual object. To select an object, the phone needs to be placed inside of it in such a way that a part of the surface is visible on the phone display, which can be seen in Figure 12(b). To modify the object, the user needs to draw on the phone display and the resulting drawing is projected onto the texture map of the object12(c). Rotating the object is done by dragging the fingers across the display.

Selection and Transformation

A ray is casted from the DHs index finger or from the phone itself, making it a virtual wand, enabling the selection of objects in the 3D scene. Object Transformations, are classified as direct and indirect. Direct Transformations are accomplished by positioning the smartphone on the object, pressing a button to select it and then rotating the object by moving the phone itself. It is also possible to use the index finger. By casting a ray, the user selects a distant object and transforms it by touching the smartphone display. This type of transformation is called indirect. To select different interactions like coloring or annotations a marking menu is used. This menu is activated by drawing a stroke on the phone.

Results

The system was tested by presenting it to 5 users. The participants found the switching between the two modes very helpful. The Workflows of Touch-and-Draw and Drop-and-Draw prevent fatigue, by making it possible to hold the phone near the body during the usage. On the other hand, the participants complained about the divided attention between the 3D scene and the information displayed on the smartphone and the sometimes incorrect gesture recognition in mid-air, which was caused by false tracking of the index finger. In the future the combination with tabletop displays or Mockup Builder [3] are feasible and the search for more precise hand recognition algorithms could make the system more valuable.

VR-SketchIn

Drey et al. [4] developed VRSketchIn, an application using a 6DoF-tracked pen and tablet as 2D input devices, allowing an interchangeable usage of 2D input with the tablet and pen as well as 3D mid-air gestures with the pen. The Focus of this paper is the definition of a design space consisting of Interaction Metaphors. VRSketchIn then implemented some of the interaction techniques defined in their Design Space and tested them with participants from different fields of work.

Setup

To implement VRSketchIn an HTC Vive Pro HMD and a Wacom Intuos Draw tablet are used. The pen is custom made, by combining the graphical Pen from the Wacom tablet with buttons from a Logitech R400 Presenter to ensure wireless button input, which is needed when drawing mid-air. 14 cameras from OptiTrack are used with an accuracy of a minimum 1mm. The mid-air interactions are tracked in a 4x4 meter area. To combine the 2D sketching with the tablet, with 3D mid-air sketching done with the pen, a custom software was created using Unity 3D.

Approach

VRSketchIn conducted expert Interviews with artitst, illustrators, designers and engineers before creating the Design Space. Based on those interviews the focus of the Design Space and VRSketchIn was set onto sketching, because in all identified workflows of the different fields, sketching seems as the most promising to benefit from combination of 2D and 3D drawing. The main focus group are artists, illustrators and the more creative fields in general.

The Design Space

The Design Space consists of two dimensions (D) which themselves consist of parameters (P). D1 are the input devices. The first parameter (P1) of D1 is the device type, which here is either Pen, tablet or both. Parameter 2 (P2) describes the dimensions of 2D and 3D in which the devices are used. D2 are the sketching operations consisting of three parameters. P3 are the object operations subtracting, selecting, adding, rotating, translating and scaling. P4 is the object type which can be either primitive (e.g strokes) or drawing aids (e.g drawing a surface). P5 is the input type. The input can be direct which means that the output and input are in the same physical space or the input can be indirect which means they are not in the same physical space. Interaction Metaphors are defined by the two dimensions and their parameters. The table representing the Design Space can be seen in figure 13. For example, a 3D mid-air draw would be done with a pen (P1) in 3D space (P2). Drawing adds something to the scene (P3) and creates a primitive object type (P4). Because of the direct interaction with the environment, the input type is di-

		D2: Sketching Operations				
		P3: Object Operation	Select/Add/Subtract/Rotate/Translate/Scale			
		P4: Object Type	Primitive		Drawing Aids	
		P5: Input Type	Direct	Indirect	Direct	Indirect
D1: Input Devices	P1: Device Type	P2: Input Dimensions				
	Pen	3D				
	Tablet	3D				
	Pen+Tablet	2D				
		3D				

Figure 13: Structure of the Design Space represented as a table [4]

rect (P5). The Interaction Metaphors are grouped into 3D mid-air sketching, drawing surfaces, world in miniature, portal into space and primitive extrusion. The implementation of VRSketchIn took one interaction metaphor out of each group to evaluate their system.

3D mid-air sketching
Implemented with the 6Dof-tracked pen in 3D space, the interaction metaphors in this group can have all parameters defined in D2. In the implementation, a primitive could be added to the scene by a stroke in 3D space done with the pen. The size of the stroke can be adjusted and the resulting object moved, by pushing buttons on the pen. Further, the created primitive object could be selected with the pen and moved with the tip of the pen.

Figure 14: A Portal view is shown on the tablet [4]

Drawing Surfaces
Drawing Surfaces can be difficult in mid-air since there are no haptic constraints in a 3D environment. Thus, the interaction metaphors in this group consist of tablet and pen input, where the input is constrained to 2D, but all sketching operations are possible. The implementation lets the user draw the surface on the tablet in 2D, thus keeping the strokes at the same height. Primitives are added to those surfaces by sketching with the pen on the tablet surface. To place a surface in the environment, a button on the tablet is pressed, and the new 3D surface can be placed in the environment by rotating and moving the tablet. Sliding the pen vertically over the tablet changes the distance to the surface and sliding horizontally scales the object. When placing the object a preview on the tablet shows which objects, that are already in the scene, are sliced by the new one.

World in Miniature (WIM)
The true scaled objects in space are manipulated in a miniaturized version of the scene which is linked to the hand-held tablet. This miniature is used for visualization, verification and manipulation of the real sized scene. The miniature scene is placed in 3D space, right above the tablet, and all sketching parameters are supported. Changes in WIM are synchronized with the real scaled scene.

Portal into Space
Through the tablet, multiple views or a different rendering of the scene in 2D space can be visualized and all sketching operations are supported. In VRSketchIn these portals are defined by the user. Figure 14 shows an example of a portal view displayed on the tablet. The red square in the background shows, in which position the user defined this portal. The 3D scene can now be altered and the changes viewed not only from the current position of the user but also from the defined portal view.

Primitive Extrusion
In VRSketchIn a stroke, drawn in the 3D scene with a pen, can be extruded into a solid object, for example, extrude a sale from a curved stroke. The workflow for Extrusion consists of sketching the primitive, selecting it afterward, opening the menu, and at last pressing the extrusion button.

Figure 15: An artist creating 3D curves(red curves) from a 2D picture, as shown in [5]

Figure 16: An artist modeling a 3D fish from a 2D picture, as shown in [5]

Results
The evaluation of VRSketchIn showed that interaction metaphors that required more steps to use, were not as much used as those with few interaction steps. In 3D mid-air sketching the problem of precision remains, but due to the fewer activation steps needed to draw in mid-air, it was used more than precise interaction metaphors. Drawing a surface on the tablet was received very well because it worked similarly to graphic tablets. When placing the surface in the 3D environment, Participants missed automatic alignment or fixed angle rotation, which could be a feature in the future. Drawing surfaces was useful for architectural sketches than for art or illustration. A problem with primitive extrusion is that in order to extrude in different directions the object needs to be rotated first, therefore extrusion in all directions would be a useful feature in later implementations. The biggest issue with the portals was the displacement between interactions with the scene in mid-air and the output on the tablet. A solution would be to introduce interaction metaphors with the portals themselves.

Lift-Off

Lift-Off [5] is an immersive 3D modeling system using VR and a bimanual 3D user Interface. The system is inspired by traditional sheet metal sculpture and therefore made for artists and designed to have a familiar approach to handcrafting. The general steps are to first sketch a 2D image outside of VR using pen and paper or digital software. Afterwards transfer the 2D image to the VR environment. By projecting the 2D image in 3D space and tracing, modifying and scaling the lines and curves of the sketch a 3D model can be created.

Setup
To create a 3D model out of a 2D sketch they use a specific setup of applications and hardware. The VR environment is given by a four-wall CAVE™ environment as well as two custom-made styluses with two push buttons each, to support bimanual inputs. The buttons enable create, confirm and delete operations.

Approach
After transferring the 2D slide to the VR environment, 3D rails are created. This is accomplished by either freehand drawing, which generally results in inaccurate modeling or by lifting rails of the slides. When the hand gets close enough to the slide, a curve between the two styluses is created. By rotating the hands the curve can be modified to fit the line on the slide better. To confirm the selection the button on the stylus is used. The rail can now be modified even further to determine the depth of the curve. For this a 3D guide perpendicular to the slide is created, to allow precise actions. Continuing these steps will provide the artist with an outline of the model, which is then used to form a surface sheet. To bend a rail into a surface sheet the user sweeps a profile rail along the guide rails, creating a surface mesh. Their implementation allows sweeps on one, two, three or four rails, to create complex shapes. For this to properly work, it is important to have connecting rails. For even more detailed work it is possible to combine connected rails on the connection point or to divide a rail on a specific point of the rail, splitting it into two connected rails. Deleting rails is also an option. Using only the stylus in the non-dominant hand, reorientation can also be accomplished, by using the primary button and scaling by using the secondary button. For rendering, they provide three different surface materials to choose from, as well as different surface thicknesses, which can be configured before starting the modeling.

Results

Lift-Off provides an immersive 3D environment for modeling making use of 2D sketches to overcome the lack of control in freehand drawing and the difficulty of drawing from scratch in 3-dimensional space. It also allows the user to inspect the model from every possible angle, by moving around. However, Lift-Off has its own challenges. First of all, even though the styluses are custom-made to be as light as possible, sculpting in mid-air can be physically tiring after a while. Another important challenge to mention is that since the inputs are 2D sketches, the resulting models are relatively simple from a geometric standpoint. The last problem is that once the artist is in the VR environment, he can not modify the 2D sketch anymore.

Discussion

We have now shown different approaches to combine 2D and 3D modeling, using VR and AR. However, there are challenges to consider. Approaches like Mockup Builder or Symbiosis Sketch are hard to use for the first time and need time to get used to the applications, while others like DesignAR or VRSketchIn are intuitive and easy to use for the first time. Others, like Lift-Off, are made for artists specifically, making the approach not usable for engineers for example. Low precision and fatigue of drawing in mid-air are common problems, that some papers address, but do not provide a full solution. Also tracking accuracy differs in every approach. Sketching in mid-air was adressed in every paper and besides using 2D operations that are then transformed into 3D, no other solution was presented. In terms of affordability, Mockup Builder has provided a good example of creating a suitable AR environment using low-price equipment. We have seen papers with a static workspace, in which you are not allowed to move around freely, as well as dynamic workspaces. Although dynamic workspaces allow the user to move around freely and observe the models from different perspectives, it might also increase tracking discrepancy. During the developement of interaction techniques, their complexity should be considered. If techniques that combine the 2D and 3D modeling aspects are too complex, they get used less, and the advantage of combined 2D and 3D modeling, cannot be utilized fully. Occlusion is a problem that occurred in some papers. However, the problem is easily avoidable as shown by DesignAR, using the 2D surface as the only input or by DualCAD using the phone as an extra tracking device.

Conclusion and Future Work

Depending on the target group, the systems focus on different topics. Since Lift-Off is designed for artists, the approach stays close to traditional and familiar approaches, creating an intuitive workflow for artists. Nonetheless, some approaches can be improved for future work, for example the tracking accuracy of DualCAD can be increased by implementing modern tracking algorithms or using more tracking devices as Mockup Builder does. In terms of affordability, Mockup Builder also shows that even low-price gaming equipment can be utilized for creating 3D models. In the future to allow collaborative modeling, DesignAR configured dedicated server which will allow to connect a series of devices with real time modeling feature. The results show that imprecise 3D sketching still is an issue in combined 2D and 3D modeling and that all papers provide a good basis for applications that combine 2D and 3D modeling, but there needs to be much more research on this topic to develop fully fledged applications. DesingAR shows promising results for example on providing precise actions on the models using the 2D tablet with accurate pen and touch inputs but not tested for complicated modeling. All in all, every approach has its own up- and downsides, depending on the target group.

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