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RWTH AACHEN UNIVERSITY

ARPen "in the Wild" – Expansion and Evaluation of an In-Situ 3D Modeling Application

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Abstract

The use of Augmented Reality (AR) has recently seen an increase in various areas of research. Still, 'handheld AR with a mid-air pen' is very much a niche research field. The *ARPen* System belongs to this field. It allows users to perform free-hand three-dimensional (3D) modeling directly in the real world by using a mobile pen. This Bachelor's thesis investigates how usable, functional, and effective the ARPen system is for 3D modeling. For that purpose, we conducted a user study.

After providing each study participant a week-long experimenting phase with the application, we conducted semi-structured interviews. We analyzed the content by adapting *grounded theory* to identify the major themes of the interviews.

Results showcase the system's strengths, such as the freedom it offers to create objects by sketching lines, the creation of primitives, the undo/redo feature, and the concept of the system. Moreover, they describe the system's shortcomings, such as perception problems of the 3D scene through the smartphone, precision problems of pen input, and system ergonomics.

As some of these obstacles tie to the broader category of 'handheld AR with a mid-air pen', we provide design considerations for developing such a system.

Überblick

Der Einsatz von Augmented Reality (AR) hat in letzter Zeit in verschiedenen Forschungsbereichen zugenommen. Dennoch ist “handheld AR with a mid-air pen” ein eher kleines Forschungsfeld. Das *ARPen* System gehört in dieses Feld. Es ermöglicht dem Benutzer, freihändige dreidimensionale (3D) Modellierung direkt in der realen Welt mithilfe eines mobilen Stifts durchzuführen. In dieser Bachelorarbeit soll untersucht werden, wie nutzbar, funktional und effektiv das ARPen System für die 3D-Modellierung ist. Zu diesem Zweck wurde eine Benutzerstudie durchgeführt.

Nachdem jeder Studienteilnehmer eine einwöchige Experimentierphase mit der Anwendung abgeschlossen hatte, wurden die Teilnehmer in halbstrukturierten Interviews zu ihrer Erfahrung mit der Anwendung befragt. Um die Hauptthemen der Interviews zu identifizieren, wurde eine Adaption der Inhaltsanalyse nach *Grounded Theory* durchgeführt.

Die Ergebnisse zeigen die Stärken des Systems auf, wie zum Beispiel die Freiheit, die es bietet, Objekte durch Skizzieren von Linien zu erstellen, die Erstellung geometrischer Primitive, die Undo/Redo-Funktion sowie das Konzept des Systems selbst. Darüber hinaus werden die Schwächen des Systems beschrieben, wie zum Beispiel Wahrnehmungsprobleme durch das Smartphone, Präzisionsprobleme der Stifteingabe und die Ergonomie des Systems.

Da einige dieser Hindernisse nicht nur mit unserem Beispielsystem zusammenhängen, sondern mit der Domäne “handheld AR with a mid-air pen”, werden Design-Aspekte für ein solches System aufgestellt.

Acknowledgements

I would first like to thank Prof. Dr. Jan Borchers and Dr. rer. nat. Simon Völker for examining this thesis.

I would also like to thank my supervisor, Philipp Wacker, for his valuable guidance, assistance, and support throughout this thesis's writing.

Also, I could not have completed this thesis without my friends, parents, and sister. Thank you for your wise counsel and sympathetic ear. You are always there for me.

Conventions

Throughout this thesis, we use the following conventions:

We write out numbers from one to twelve and use digits from the number 13. If a number is in the beginning of a sentence, we write it out.

Moreover, we *emphasize* important technical terms and names the first time they appear in the thesis.

We write source code and implementation symbols in `typewriter-style text`.

We wrote this entire thesis in American English. For the first person, we use the plural form. For unidentified third persons, we use the female form.

We set off download links in colored boxes.

File: myFile[a]

[a]http://hci.rwth-aachen.de/file_number.file

Chapter 1

Introduction

Personal fabrication is the manufacturing of a three-dimensional (3D) model using a personal computer, digital data, and a printer that can produce solid 3D objects [Morris, 2007]. Recent years have shown that the interest in personal fabrication has drastically grown, promising to revolutionize the ways of design and production [Mota, 2011]. Nonetheless, designing 3D shapes that fit into real-world surroundings requires intensive measuring and a sense of spatial awareness. For example, if a user wants to 3D print a coffee cup holder that can be attached next to her car dashboard, it would require her to measure the dashboard's dimensions and then design a 3D model using computer-aided design (CAD) software. Still, the model might not look and fit as well as she intended. Directly using the real-world surroundings in the modeling process could vastly simplify this process.

Modeling in-situ might simplify designing 3D objects that should fit into real-world surroundings.

Augmented Reality (AR) enables the possibility to design objects *in-situ*, as it is the interface between the real and the virtual world. Azuma [1996] defines AR by setting up three characteristics: Firstly, the combination of real and virtual worlds, which AR does by overlaying virtual scenes over the view of the real world. Secondly, real time interaction. And thirdly, accurate 3D registration of virtual and real objects. A virtual effects system, for example, allows for blending virtual objects into a real-world environment and thus fulfills the first criterion. However, it is

AR overlays a virtual scene over the real world view, providing adequate spatial perception for 3D modeling.

neither interactive media nor are the overlays combined with the real world in 3D and thus it would not belong to the category of AR systems. As AR provides an augmented view of the real-world surroundings, employing AR for 3D modeling could provide effective spatial perception and comprehension of designs [Shin et al., 2005].

Handheld AR proves to be the most accessible way of displaying AR.

There are numerous ways to display AR, ranging from head-mounted displays (HMD) (e.g., Microsoft HoloLens 2[1]) to handheld displays. In contrast to other AR systems, handheld AR (HAR) is socially acceptable, readily available, and highly mobile [Zhou et al., 2008]. HAR can be seen in different areas and on different markets, such as medical education (see e.g., Complete Anatomy 2021[2]) and interior design (see e.g., IKEA Place[3]). Furthermore, HAR is the most accessible way of displaying AR, as most modern smartphones can display AR content. Wacker et al. [2019] developed the *ARPen* system, which combines the accessibility of AR-enabled handheld devices with the possibility to design 3D objects in-situ.

The ARPen system combines the accessibility of AR-enabled handheld devices with the use of AR to design 3D objects in-situ.

The ARPen system is bimanual, consisting of a smartphone and a 3D-printed or cardboard pen. Instead of needing extensive measurements beforehand, users can model a shape with the pen directly in its designated surroundings in real-time. Thus, saving the user potential design iterations and accelerating the time to achieve design objectives. ARPen is an open-source iOS application[4] that uses Apple's AR-[5] and SceneKit[6], as well as Open CASCADE Technologies[7]. When using ARPen, the user holds the phone in her non-dominant and the pen in the dominant hand (see Figure 1.1). The pen is tracked in real-time via a marker, using image recognition techniques,

[1] `https://www.microsoft.com/en-us/hololens` Accessed March 13, 2021

[2] `https://3d4medical.com/` Accessed March 13, 2021

[3] `https://www.ikea.com/au/en/customer-service/mobile-apps/say-hej-to-ikea-place-pub1f8af050` Accessed March 13, 2021

[4] `https://github.com/i10/ARPen` Accessed March 13, 2021

[5] `https://developer.apple.com/documentation/arkit/` Accessed March 13, 2021

[6] `https://developer.apple.com/documentation/scenekit/` Accessed March 13, 2021

[7] `https://www.opencascade.com/` Accessed March 13, 2021

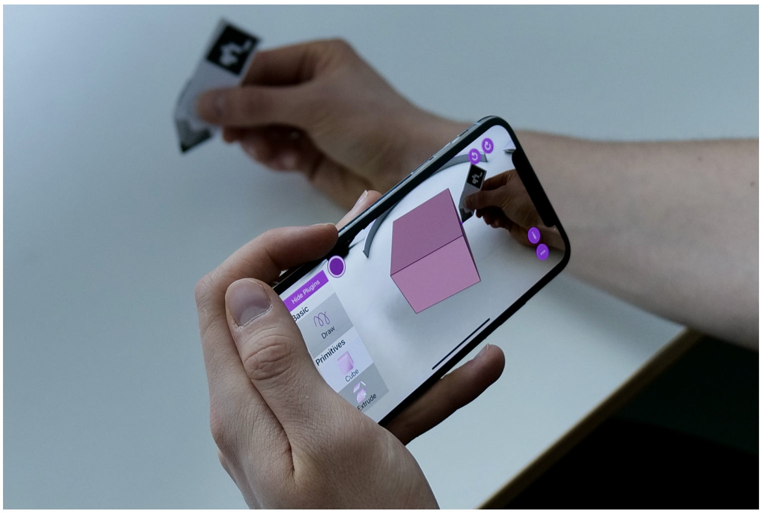


Figure 1.1: The bimanual ARPen system consists of a smartphone and a pen.

which allows the determination of the pen tip's 3D position in the virtual world. Therefore, the pen is a pointing device that enables true 3D input.

Previous work on the ARPen system includes the evaluation of specific parts of the application, such as menu techniques and techniques to move 3D objects [Wacker et al., 2020a, 2019]. We were intrigued to do a system-wide evaluation to assess the usability and effectiveness of our system for 3D modeling, as this had not been done before. As our goal was to gain user insight into qualitative aspects of 3D modeling with our system, we conducted semi-structured interviews with interested individuals using an interview script. For this, we recruited six participants who tested the application in a week-long experimenting phase for which we provided modeling tasks.

We conducted a qualitative user study to assess the usability and effectiveness of ARPen for 3D modeling.

Consequently, we transcribed and then analyzed user comments by doing content analysis. As the data analysis method, we chose to adapt *grounded theory*. The results included 18 major themes that emerged from the interviews. On the one hand, the findings show the system's strengths, such as the concept of the system, the freedom it provides

We implemented multiple scaling and rotation techniques, an undo and redo system, along with the option to edit a shape subsequently.

to create objects by sketching lines, the creation of primitives, and the undo/redo-system. On the other hand, they show weaknesses such as perception problems through the handheld smartphone, precision problems of pen input, and system ergonomics. To gain user insight into our system, we needed to provide a stable implementation of the application with typical CAD software features. Therefore, we added multiple scaling and rotation techniques based on prior work [Mohammed, 2020, Klamma, 2019], the option to edit already created shapes subsequently and an undo/redo system to the application.

This Bachelor's thesis begins with an overview of the related work in Chapter 2. We showcase other existing immersive 3D modeling systems and report on related user experiences with this software type. In Chapter 3, we detail the additional features we added to the system. Chapter 4 gives insight into the reasoning behind the chosen procedure, study design, and data analysis method to ensure our results' validity and reliability. With Chapter 5, we provide the findings of our study, detailing positives as well as negatives of using the system for 3D modeling. In Chapter 6 we interpret the results and describe the limitations of our study. Lastly, we conclude the thesis by summarizing our results and proposing potential ideas for the system's future in Chapter 7.

Chapter 2

Related Work

In the following, we explain similar work to the ARPen System. As the ARPen project includes various significant human-computer interaction (HCI) research topics, we first cover a range of related immersive 3D modeling and sketching systems. As this thesis aims to gain insight into the user experience with ARPen, we then focus on reported user studies of such systems.

2.1 Immersive 3D Modeling and Sketching Systems

The research area of immersive 3D modeling systems includes different interaction techniques to create 3D shapes in mid-air.

One such system is *DesignAR* by Reipschläger and Dachselt [2019]. DesignAR consists of an interactive surface that displays two-dimensional (2D) views and an HMD, creating a combined output space that enables placing 3D objects beyond display borders. The system uses a set of pen and touch techniques for input (see Figure 2.1). The aim was to extend a traditional modeling environment by gaining the ability to place 3D objects beyond the screen.

DesignAR combines the use of an HMD with a 2D interactive surface to create shapes via pen input and touch gestures.

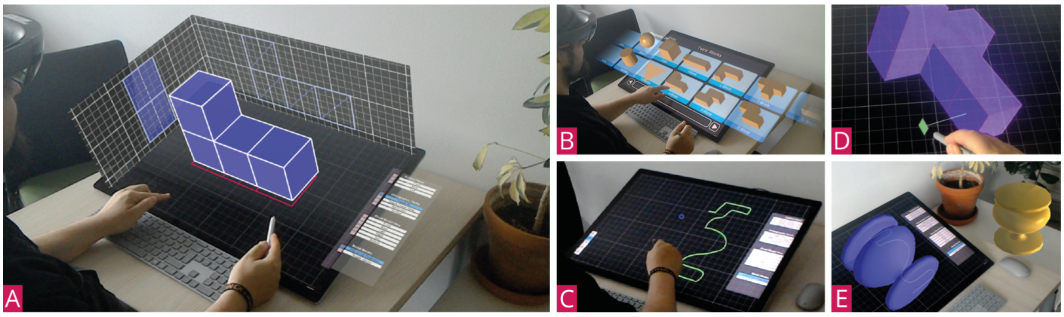


Figure 2.1: Overview of DesignAR: (a) the augmented workstation, (b) an example touch technique, (c) an example pen sketching technique, (d) modeling by extruding faces with the pen, and (e) a 3D object beyond display borders. Images taken from: [Reipschläger and Dachselt, 2019]

RoMA links 3D modeling directly to 3D robotic printing.

Peng et al. [2018] present *RoMA*: a direct combination of 3D modeling with 3D robotic printing. The designer can use partially printed shapes as a reference and, using an HMD and a pair of AR controllers, can add new elements to the design. RoMA allows users to integrate real-world constraints into a design and allows extension of existing objects.

NapkinSketch enables 3D modeling from 2D sketches.

An approach that utilizes HAR is *NapkinSketch* by Xin et al. [2008]. NapkinSketch uses a piece of paper and a tablet, displaying the 3D scene, as input devices. After defining a plane, the user sketches on the tablet. Simultaneously, the drawn sketch is projected onto the previously defined plane, allowing for creating rather complex 3D objects.

SymbiosisSketch combines mid-air modeling with the precision of drawing on a tablet.

SymbiosisSketch by Arora et al. [2018] combines the advantages of drawing in mid-air and drawing on surfaces to model 3D shapes in AR. The system consists of an HMD, a tablet, and a digital pen with six-degrees of freedom (6DoF). Users define a drawing plane using the tablet and the digital pen. Although the shapes appear in the desired surroundings, the tablet and the plane are spatially separate.

Mobi3DSketch by Kwan and Fu [2019] is a HAR 3D sketching system for designers using a single AR-enabled

Figure 2.2: Overview of MagicToon system. The system transforms 2D cartoon sketches into 3D objects. The 3D object has some over-segmented regions. By dragging her finger, the user merges those regions. Image taken from: [Feng et al., 2017]

mobile iOS device. The system uses two input sources to sketch in 3D: the motion tracking of the device and the touch input. The system supports both absolute and relative drawing, enabling the creation of 3D conceptual designs in-situ. Additionally, Kasahara et al. [2012] proposed a system that lets multiple users draw 3D sketches on existing surfaces.

Mobi3DSketch allows sketching 3D conceptual design in-situ by tracking the motion of a handheld device.

Bergig et al. [2009] present a framework for authoring 3D virtual scenes for AR based on hand sketching. Similarly, Feng et al. [2017] introduced *MagicToon* (see Figure 2.2). Using HAR, the tool can project 2D cartoon sketches into the 3D scene. The user interacts with the 3D objects through the touchscreen of the handheld device.

MagicToon projects 2D sketches into the 3D scene.

Furthermore, there are commercial applications for immersive modeling and sketching. Grib3d[1] lets users create 3D shapes out of 2D sketches on paper using an AR-enabled smartphone. Just a Line[2] lets users draw in AR on a smartphone and then share a video of their creation.

Some approaches use Virtual Reality (VR). *(T)ether* by Lakatos et al. [2014] combines touch inputs and mid-air gestures for immersive 3D modeling. The system consists of a handheld display as a window into VR and a tracking system that tracks the user's head, hands, and fingers. (T)ether supports multi-user collaboration on virtual 3D objects . Elsayed et al. [2020] propose *VRSketchPen* as an input device for immersive 3D sketching. A marker-based

(T)ether is a handheld VR system that combines touch input and mid-air gestures for 3D modeling.

[1] `https://grib3d.com/` Accessed March 14, 2021

[2] `https://apps.apple.com/us/app/just-a-line-draw-in-ar/id1367242427` Accessed March 15, 2021

VRSketchPen enables users to draw 3D sketches in VR with a pen that uses haptic feedback.

motion capture system tracks the VRSketchPen in the 3D scene. Via a VR headset, users can draw 3D sketches in the virtual world. The pen uses haptic feedback to help users sketch accurate shapes without constraining their actions. Likewise, the commercial releases Google's Tilt Brush[3] and Gravity Sketch[4] let users paint in 3D space with a virtual reality HMD and handheld controllers.

ARPen solely requires a smartphone and enables true 3D input through the pen.

The ARPen system relies solely on the use of a smartphone instead of requiring additional hardware. Moreover, our system tracks and determines the position of the pen, enabling precise 3D input.

2.2 User Studies on Immersive 3D Modeling and Sketching Systems

Various user studies have been conducted in the field of immersive 3D modeling.

Hürst and Dekker [2013] introduced a virtual grid to deal with precision problems.

Hürst and Dekker [2013] built and evaluated a HAR system for 3D modeling using finger- or pen-based freehand interactions to create and edit 3D models. The system uses an AR-enabled mobile device's camera in order to track specific gestures. The authors conducted a feasibility study of the system with 24 subjects to gain user insight. The study required subjects to do modeling tasks with the system (see Figure 2.3). The results showed that free-hand drawing is too difficult for most users without solutions such as their proposed virtual grid design, enabling participants to draw simple geometric shapes reliably. Additionally, ergonomic discomfort and depth perception also were an issue. The findings, however, showed a high usability and entertainment value, suggesting massive potential for this type of system but limited utility for serious applications.

Huo et al. [2017] presented *Window-Shaping*, a HAR system that allows the direct creation of 3D shapes on and

[3] `https://www.tiltbrush.com/` Accessed March 14, 2021
[4] `https://www.gravitysketch.com/` Accessed March 14, 2021

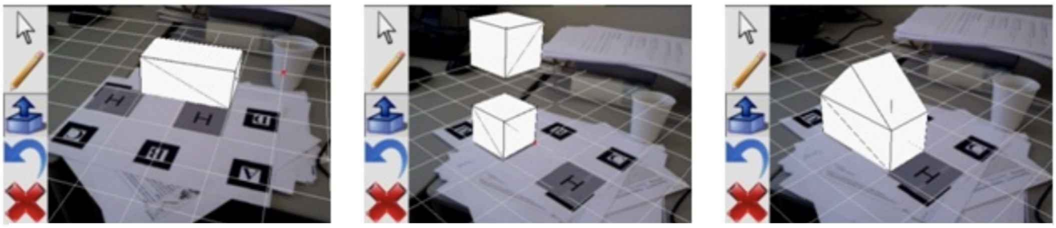


Figure 2.3: Example tasks from the feasibility study of a HAR immersive 3D modeling system. Image taken from [Hürst and Dekker, 2013]

around physical objects. Using a Google Tango device, users define a plane on any physical surface by drawing in the physical scene. Touch gestures on the device screen are 'unprojected' in the physical environment to obtain a 3D point and its normal vector in the world coordinate system. The authors conducted a user study to evaluate their prototype. They collected user feedback regarding the utility, experience, potential, and limitations from eight participants. After completing design tasks, participants filled out a questionnaire and answered open-ended questions. Findings show users having generally positive reactions while also exposing limitations, including problems with accuracy and user fatigue.

The results of the user study on Window-Shaping showcased limitations in accuracy and user fatigue.

Israel et al. [2009] investigated 3D sketching using a hybrid pen in a VR-cave system. The developed prototype for the study used line-based sketching and an undo system. The user study aimed to compare 3D to 2D sketching to find the advantages and disadvantages of 3D sketching. The authors conducted two focus group interviews. Following that, they created a questionnaire for validation of the results. Results showed that users are interested in using the 3D space as a medium for design, especially regarding spatial thinking.

Israel et al. [2009] found that users are interested in using the VR 3D space as a medium for spatial thinking.

In contrast to these studies, we gave participants a week long experimenting phase with the application before conducting semi-structured interviews. Additionally, we designed modeling tasks for the long-term experimenting phase. These tasks ranged from strict to loosely defined to ensure freedom in the usage of the system.

As in none of these studies, we designed modeling tasks for a week-long experimenting phase with ARPen.

Chapter 3

Adding New Features to ARPen

We added several features to improve the usability of ARPen for 3D modeling. For some features, rough implementations already existed from previous studies. We modified and expanded these implementations for them to be useable in the context of the whole system. The following sections describe the new features added to ARPen.

3.1 Scaling

Previous work on ARPen included a user study that identified the most effective and user-friendly scaling techniques for the ARPen system [Mohammed, 2020]. As scaling is fundamental to the 3D modeling process, we implemented the two recommended scaling interactions. While the study mainly focused on scaling relative to a corner, we also decided to implement scaling relative to the object's center. All of the implemented scaling techniques perform uniform scaling.

We implemented two scaling techniques: Pen Ray Scaling and Pinch Scaling.

Pen Ray Scaling Figure 3.1 shows *Pen Ray Scaling*. Using ray-casting to determine whether or not the pencil point

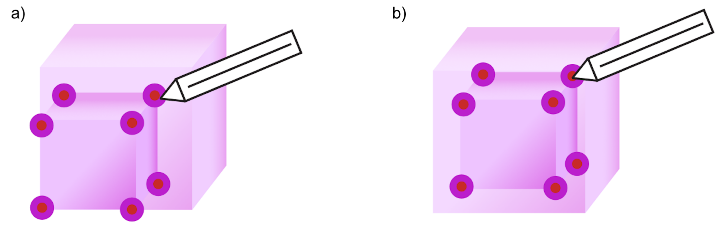


Figure 3.1: Pen Ray Scaling: relative to (a) a corner or (b) the center

Pen Ray Scaling uses ray-casting to select a shape's corner and mirrors the pen's movement to scale the object.

hovers behind or in front of one of the object's corners, Pen Ray Scaling lets the user select a corner and then mirrors the pen's movement, thereby scaling the entire object. In contrast to other pen-based scaling interactions, users felt relaxed and enjoyed when using Pen Ray Scaling.

Pinch scaling allows users to scale an object by using a pinch gesture.

Scaling Using a Pinch Gesture After tapping one of the object's corners on the touchscreen, users can perform a two-finger pinch gesture to scale the object. Users claimed that *Pinch Scaling* felt very intuitive, as they knew the pinch gesture for scaling from other applications.

3.2 Rotation

We implemented three rotation techniques.

Additionally, work on ARPen included a user study that evaluated different rotation techniques for the ARPen system [Klamma, 2019]. We implemented three rotation techniques that showed promising results in the study. Since the proposed interactions from the user study focused on rotating relative to the object's center, we chose to implement this as well.

Direct Device Rotation mirrors the device's orientation onto the object.

Direct Device Rotation *Direct Device Rotation* requires the user to press and hold an on-screen button. While holding the button, the device's orientation is mirrored onto the object, allowing it to rotate by rotating the device. Direct

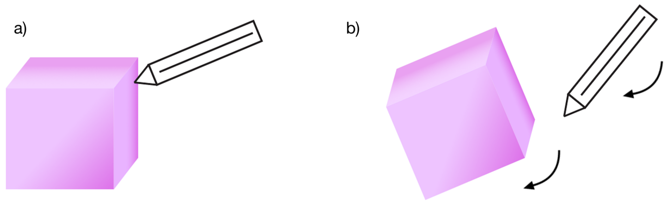


Figure 3.2: Direct Pen Rotation: (a) selecting an object, (b) the object mirroring the pen's orientation

Device Rotation received positive feedback overall in the study and excelled in the categories of speed and precision.

Touchscreen Rotation *Touchscreen Rotation* allows the user to rotate the object by swiping across the touchscreen after tapping an object to select it. Users achieved good results in the user study using Touchscreen Rotation.

Touchscreen Rotation allows the rotation of an object by swiping across the screen.

Direct Pen Rotation *Direct Pen Rotation* (see Figure 3.2) works similarly to Direct Device Rotation. After selecting an object, the user must press and hold an on-screen button. In contrast to Direct Device Rotation, the orientation of the ARPen now is mirrored onto the object. By rotating the pen, the user rotates the selected object. Direct Pen Rotation achieved good results in the user study.

Direct Pen Rotation mirrors the orientation of the ARPen onto the object.

3.3 Undo and Redo System

To allow users of ARPen to reverse unwanted actions, the development of an undo and redo system was vital. We chose to implement linear undo. Linear undo utilizes a stack to store significant actions that the user did. When the user performs an action, it is added to the top of the undo-stack. A stack works according to the Last In - First Out (LIFO) principle; hence, when the user taps the undo-

We implemented a linear undo and redo system.

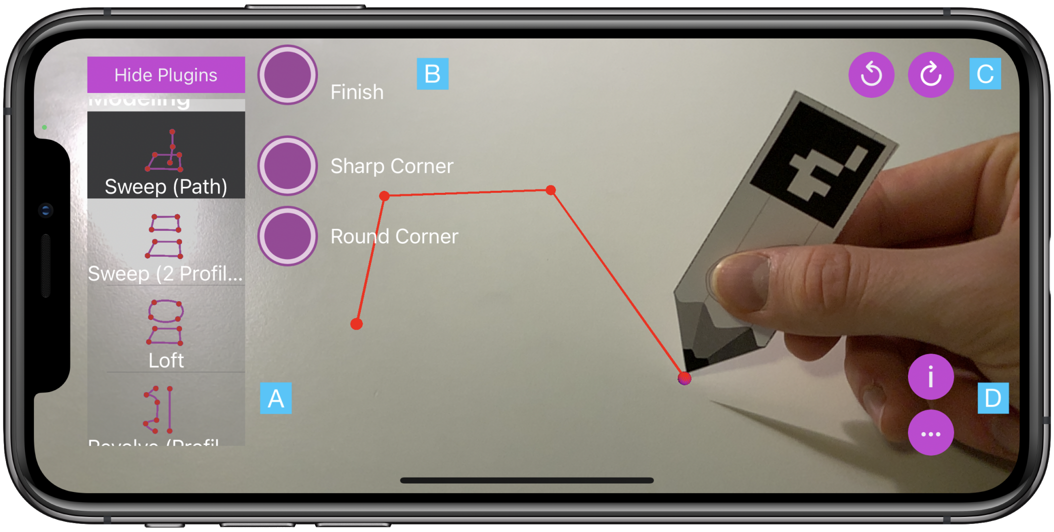


Figure 3.3: Screenshot of the ARPen application used with a cardboard pen. The user interface: (a) scrollable plugin list, (b) software buttons, (c) undo/redo buttons, (d) instructions, and settings button. The selected plugin is a node-based modeling technique used to create a path by setting nodes.

button, the last action is undone. Undoing an action results in it being added to the top of the redo-stack. Redoing an action causes it to be pushed onto the undo-stack again. A detailed description of our implementation can be found in Appendix A. An undo- and redo-button was added to the user interface (UI) in the screen's top right corner. The UI can be seen in Figure 3.3. The user has the possibility to undo and redo in these possible scenarios: translation, rotation, scaling, object creation, path creation, object manipulation, merging, and cutting.

3.4 Subsequent Object Manipulation

In node-based modeling techniques, the user creates 3D shapes by drawing open and closed paths. Paths are created by placing nodes in the scene (see Figure 3.3). The techniques (see Figure 3.4) include *Revolve(Profile + Axis)*, *Revolve(Profile + Circle)*, *Revolve(Two Profiles)*, *Loft*, *Sweep(Two Profiles)*, and *Sweep(Path)*. As the undo/redo history works according to the LIFO principle, we wanted to

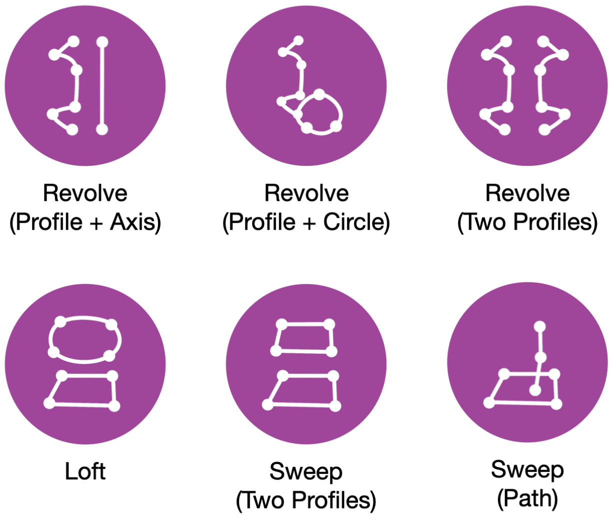


Figure 3.4: Overview of the node-based modeling techniques. The icons showcase the path patterns the user needs to draw to create an object.

enable users to edit specific nodes of the paths of 3D objects subsequently. Upon selecting an object, the paths out of which it consists are displayed to the user. Then, the user gets multiple choices of what to do. Node-style can be switched from sharp to round, which changes the style of the corresponding edge. Single nodes can be moved around, and furthermore, new nodes can be inserted on the existing path. A new one is inserted in the middle of a part of the path after selecting two neighboring nodes.

We added the option to edit 3D models created by node-based modeling techniques subsequently.

Chapter 4

User Study Method

In the following, we describe the used methods and study procedure. Additionally, we give insight into the reasoning behind the chosen study design and data analysis method.

4.1 Restatement of Purpose

As previously stated, the purpose of this study was to gather user impressions of the ARPen system to answer our central research question: ”How usable, functional and effective is the ARPen system for 3D modeling?”. Previous work dealt with the independent assessment of features like menu techniques [Wacker et al., 2020a]. We were intrigued to assess the usability and effectiveness of the complete ARPen system for 3D modeling. Hence, our central research question. By collecting feedback from interested individuals, we hope to answer our research question, understand the intricacies of 3D modeling with ARPen and gain insight into the advantages and disadvantages of the ARPen system. While the results of this study are to be utilized for future design decisions of the project itself, this study aims to provide design considerations for other ‘handheld AR with a mid-air pen’ systems for 3D modeling.

To understand the intricacies of 3D modeling with ARPen, we conducted a qualitative user study.

We wanted to gain insight into ‘handheld AR with a mid-air pen’ systems for 3D modeling.

4.2 Methods

We chose do conduct qualitative research.

We deduced the study design from the research question. Quantitative research, on the one hand, is an appealing choice for numerical data studies. On the other hand, qualitative research offers insight from data based on interviews, focus groups, questionnaires, or recordings. Qualitative research is interested in non-numerical, textual data and is therefore well suited for understanding users' views and perceptions and for gaining unique user insights. Given the nature of our research question, choosing a qualitative research approach was vital. The data collection approach selected was conducting interviews.

We asked participants about their experience in semi-structured interviews.

In contrast to questionnaires, interviews allow the respondents to go on at great length, generating ideas and sharing insights that would have been lost to surveys [Lazar et al., 2017, p. 188]. Hence, they are beneficial for increasing our understanding of the ARPen system. Additionally, interviews allow the most freedom to receive detailed responses, which questionnaire-based studies generally do not. As for the interview structure, we selected semi-structured interviews. In semi-structured interviews, the interviewer can pursue inquiries within the interview to follow up on exciting and unexpected avenues [Soegaard and Dam, 2012]. They open up the possibility of exploring topics in-depth. That may be harder to achieve with fully structured interviews [Lazar et al., 2017, p. 199]. We created an interview script to ensure that relevant issues get discussed. The final script is included in Appendix B.2. Because of the global COVID-19 pandemic[1], we chose to conduct the interviews online via Zoom[2] video calls. Online interviews are close in spirit to traditional face-to-face interviews, with questions and responses coming in near real-time [Lazar et al., 2017, p. 217].

[1] `https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/nCoV_node.html` Accessed March 2, 2021

[2] `https://zoom.us` Accessed March 2, 2021

4.3 Sampling

Respondent	Gender	Age	Highest Academic Level	CAD Experience
R1	m	25	High School Diploma	4
R2	f	29	High School Diploma	4
R3	f	29	M.Sc.	4
R4	m	28	Diplom	4
R5	m	22	B.Sc.	2
R6	m	20	High School Diploma	3

Table 4.1: Overview of the respondents (1 = not very experienced, 3 = about average, 5 = very well experienced)

Since our research question aims to gain valuable insight into the effectiveness of ARPen for 3D modeling, the sample must consist of users who are experienced with CAD 3D modeling software. Furthermore, since ARPen is an iOS-exclusive application, participants must own an iPhone. We recruited participants by doing snowball sampling. In snowball sampling, an already recruited subject recruits further subjects from her personal contacts. Using snowball sampling proved to be a fast and easy recruitment strategy for finding participants who matched our criteria in the academic environment.

We recruited six participants using snowball sampling.

We recruited six participants, of which four were women, and two were men (see Table 4.1). Five out of the six participants' (R2-R6) first language was German. One participant's (R1) first language was English. All participants fell in the age group of 20-30 years old. When asked about how much experience respondents had with HAR, R1 and R6 expressed that they had none. R2 and R3 said they had little experience, while R4 and R5 were very well experienced with HAR due to their research work. Every respondent said they had experience with pen-based systems from their work environment. An additional participant was recruited for pilot testing the user study. The data collected in the pilot test was neither included nor analyzed.

4.4 Apparatus

Because we asked participants to use ARPen on their personal smartphones, different devices were used to conduct the study. The following table provides an overview of the key data of the used iPhone models. All iPhone cameras had a resolution of 12-megapixels. However, the camera system differed between single, dual, and triple systems. Apple[3] provided all data.

Respondent	iPhone	Size	Weight	Chip
R1	12 Pro	146,7mm × 71,5mm × 7,4mm	187g	A14 Bionic
R2	6S	138,3mm × 67,1mm × 7,1mm	143g	A9
R3	11	150,9mm × 75,7mm × 8,3mm	194g	A13 Bionic
R4	12 mini	131,5mm × 64,2mm × 7,4mm	133g	A14 Bionic
R5	XR	150,9mm × 75,7mm × 8,3mm	194g	A12 Bionic
R6	8 Plus	158,4mm × 78,1mm × 7,5mm	202g	A11 Bionic

Table 4.2: Overview of the used devices (Size in mm: Height × Width × Depth)

4.5 Procedure

The user study started with a long-term experimenting phase with ARPen followed by post-interviews.

Participation in the study consisted of two steps: an experimenting phase with the system and post-interviews. Before conducting the interviews to measure the user experience with ARPen, the study began with an experimenting phase. We wanted participants to go through a long-term experimenting phase with the system, in contrast to other studies with a shorter experimenting phase [Hürst and Dekker, 2013, Hsu et al., 2020, Zhang and Oney, 2020]. We asked participants to use the ARPen application for approximately five days at home. Instead of the usual setting, where participants use the software of interest in a controlled environment for a short time, our idea was to let participants freely use the application over a more extended period in a somewhat more ‘natural’ environment. The aim was to let users get accustomed to the application in order

[3] `https://support.apple.com/de_DE/specs` Accessed March 3, 2021

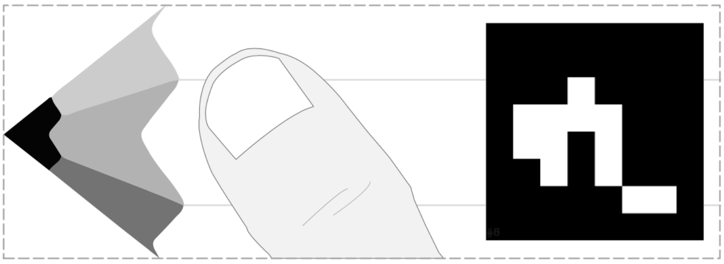


Figure 4.1: The cardboard version of the ARPen. Participants used this pen in our user study.

to receive more detailed impressions. Along with the cardboard version of the actual ARPen (see 4.1), participants received instructions by mail. Besides, we also made sure to send participants snacks during the study. The instructions contained a URL to download the expanded version of ARPen and a document containing 3D modeling tasks. We wrote the tasks to introduce users to the application and instruct them to use specific features. Finishing one task approximately took 15 minutes, depending on the speed of the user. We provided tasks for five days, increasing the difficulty of the tasks every day. The tasks ranged from very strict to loosely defined, ensuring that users sought their way around the application and used features they did not need to use before. On the last two days, the task requested incorporating real-world objects into the modeling process. The 3D modeling tasks are provided in Appendix B.3. We asked participants to share their results each day to ensure they used the application and completed the tasks.

We provided 3D modeling tasks for the experimenting phase to ensure that participants use specific features.

Along with the documents, participants received a consent form (see Appendix B.1) which emphasized that the interview data would be used only for the stated scientific purpose. The respondent's right to decline participation or later withdraw from the study was stressed multiple times. The written consent was received prior to starting each interview. Participants themselves could book a date for the interview via a Doodle[4] poll. After the participants finished the experimenting phase, the interviews were conducted by the author. Participants had the choice of conducting

[4] `https://doodle.com/en/` Accessed March 7, 2021

To pilot test the study procedure, we recruited a seventh participant.

the interview in either German or in English. Each participant chose her native language. All interviews took place in February of 2021 and had a duration of approximately 60 minutes. To reflect and review the procedure, we conducted a pilot test of the procedure with a seventh participant, which resulted in no changes.

4.6 Developing the Instruments

To ensure that we discuss relevant topics, we used an interview script for the semi-structured interviews.

The development of the interview script was an iterative process. The first draft was loosely inspired by the questions for "evaluation during the development process" proposed by Lazar et al. [2017, p. 195-196]. Since these proposed questions focused on designing a different system, we coherently adapted them to fit our research question. Furthermore, we added more questions that went into specifics of the ARPen system. We designed all questions to be open-ended because the interview aimed to animate the respondent to voice her thoughts and subjective opinions on the application. To determine whether the proposed draft of the interview script was suited for our study and research question, we conducted a pretest with a seventh participant. Results of the pretest showcased that we needed to make some changes to the draft. The participant felt compelled to talk about the 3D modeling tasks themselves rather than the experience with the application. For that reason, we slightly changed the briefing as well as rephrased some of the questions in order for participants to interpret them correctly. Since we noticed that the participant's answers tended to be shorter, some questions were slightly modified. Yes-no questions intended for participant data collection were pushed from the start to the end of the interview to unloosen the participants' way of responding. We added a collection of differently phrased questions for each question in case a participant was very short-spoken. The final interview script can be found in Appendix B.2.

We pretested the interview script with a seventh participant.

4.7 Data Analysis

We conducted a content analysis by following the *constant comparative method* based on the notion of grounded theory [Strauss, 1987]. We chose to conduct a content analysis because it is specifically suited for making inferences by objectively identifying specified characteristics of messages, which aligned best with our research goal [Holsti, 1969, p. 14]. Grounded theory, presented by Glaser and Strauss [1967], is an inductive methodology. It starts from a set of empirical observations and aims to develop a well-grounded theory from the data. Analyzing data with grounded theory usually consists of four stages [Lazar et al., 2017, p. 305-306]:

We chose to do a content analysis following grounded theory.

1. Open coding
2. Development of concepts
3. Grouping concepts into categories
4. Formation of a theory

Open coding is the process of identifying phenomena in the collected data and creating distinct codes to label them. Since the codes emerge from the data, this process can be categorized as *emergent coding*. Stages 2 and 3 often are referred to as *axial coding*. Axial coding is the process of drawing connections between the codes assigned in open coding and grouping them into higher-level concepts, which then can be grouped into categories [Lazar et al., 2017, p. 306]. Stage 4 is sometimes referred to as *selective coding*, the process of grouping categories together to form one core category, the theory. Part of selective coding also is to revisit the collected data and relabeling it with that core category. This process may be iterated by collecting and analyzing data multiple times [Myers, 1997].

We chose the grounded theory approach to data analysis because it puts very few constraints on the researcher. Itss inductive nature and emergent coding approach supported identifying relevant points about ARPen. Nevertheless, As generating a theory was not our goal, we adapted grounded theory to identify major themes from the interviews.

to cater to the study design, we made adjustments to the approach. We disregarded theory generation or selective coding. The generation of categories to discover the conducted interviews' major themes seemed to be a more feasible goal for our research.
Additionally, we only analyzed already collected data since the number of participants was predetermined and relatively small. Making sense of data that already has been collected by doing grounded theory, is a common approach in HCI and computer-supported cooperative work (CSCW) research [Muller and Kogan, 2010]. We analyzed the data computer-aided by using MAXQDA2020[5] since computer-aided qualitative data analysis software (CAQDAS) helps organize, manage and analyze information [Kelle and Bird, 1995]. The data source for the analysis was the transcripts of the six hours of interviews with six participants. We created the transcripts with the software Sonix[6] because of its multilingual support for auto-generation. All of the conducted interviews were transcribed and analyzed by the author. The transcripts are available for download below.

File: Transcripts from the Interviews[a]

[a]http://hci.rwth-aachen.de/arpen-ios-app

In the following subsections, we describe the single steps of the analysis.

4.7.1 Open Coding

As stated above, open coding is the process of breaking down the data into phenomena and labeling them with distinct codes [Lazar et al., 2017, p. 306]. While working through every transcript, we closely examined the partici-

[5]https://www.maxqda.de/software-inhaltsanalyse?gclid=Cj0KCQiAhP2BBhDdARIsAJEzXlFep5UsMtrHqsbm3f79Q3Fn_peH3i8kH0JpjWGl11xOTaOgbSIyvMQaArc8EALw_wcB Accessed March 3, 2021
[6]https://sonix.ai Accessed March 3, 2021

pants' statements and observations about their experience with the ARPen system. To describe these instances of the data, we decided that the labeling should stay as close to the original wording as possible. To give an example of the labeling, one of the labels assigned to the following quote was 'Precision is difficult':

In open coding, we coded 686 pieces of data.

> "The precision, in general, is just difficult - to create anything exactly the way you want it." (R4, 00:06:13)

The coding rule for that label was: "User expressed that they think precise input is difficult with the pen." We worked through every transcript twice in order to not miss anything. In the end, we coded 686 pieces of data.

4.7.2 Writing Memos

When doing grounded theory, a core part is to interrupt, reflect, and analyze the progress by writing memos [Lempert, 2007]. Some ideas for later concepts were based on memos that we wrote in the open coding phase. When coding pieces of data about the fact that users did not understand some modeling techniques of ARPen, we wrote the following memo about a possible correlation with problems with the instructions feature:

To reflect on the progress of the analysis, we wrote memos.

> "Several users stated that they did not understand all the modeling techniques of ARPen. Especially the node-based modeling techniques. Some of the same participants had mixed responses to the instructions feature. There might be more data that supports grouping this into a concept."

4.7.3 Discovering Major Themes

Axial coding is the process of drawing connections between the codes assigned in open coding and grouping them. As

As a result, we discovered 18 major themes that emerged from the interviews.

the first step, we grouped the codes generated in the open coding phase (Subsection 4.7.1 “Open Coding”) into concepts. Groups were generated by comparing user thoughts for similarity and critically questioning the reasons behind them. After reviewing the first draft of concepts, we decided to refine some of them. The second step was to group the concepts into categories by again thinking about similarity and correlation between concepts. We chose not to discard results dependent on the number of coded segments because of our relatively small sample size of six. After this process, we discovered 18 major themes that emerged from the interviews. A complete list of all concepts and themes that emerged during the analysis can be found in Appendix B.4.

Chapter 5

Results

5.1 Overview

By analyzing our collected data with grounded theory, 18 major themes emerged. Tables 5.1 and 5.2 showcase the themes, ordered by the number of coded segments.

Resulting Theme	Includes Observations from Respondents	Total Number of Coded Segments
Perception Problems Affect Modeling Experience	R1, R2, R3, R4, R5, R6	92
Usability Problems with Node-based Modeling Techniques	R1, R2, R3, R4, R5, R6	76
Problems with Understanding Node-based Modeling Techniques	R1, R2, R3, R4, R5, R6	69
Positive Feedback for Primitives	R1, R2, R3, R4, R5, R6	68

Table 5.1: Part 1/2 - Overview of the resulting themes. Ordered by the number of coded segments.

Resulting Theme	Includes Observations from Respondents	Total Number of Coded Segments
System Ergonomics	R2, R3, R4, R5, R6	62
No User Confidence in Precision	R1, R2, R3, R4, R5	52
User Interface Usability and Effectiveness Problems	R1, R2, R3, R4, R5, R6	48
ARPen's Difficulty Level	R1, R2, R3, R4, R5, R6	31
Tracking Problems	R1, R2, R3, R4, R6	28
General Impressions of the Application	R1, R2, R3, R4, R5, R6	27
User Trust in and Suggestions for Undo/Redo	R1, R2, R3, R5, R6	25
Mixed User Feelings about all Interaction Types of Rotation	R1, R2, R3, R4, R5, R6	22
Multiple-select-based-plugins Usability Problems	R1, R3, R4, R5, R6	20
Positive Feedback for Node-based Modeling Techniques	R1, R3, R4, R5, R6	18
User Feedback and Suggestions for Features for Working with Existing 3D Models	R1, R2, R3, R5	17
Application Performance	R1, R2, R3, R4, R5, R6	14
Additional Manipulation Features	R3, R5	11
Preference for Pen-based Interactions	R1, R4, R5	6

Table 5.2: Part 2/2 - Overview of the resulting themes. Ordered by the number of coded segments.

5.2 Major Themes of the Interviews

In the following, we will discuss the resulting themes one by one. The author translated quotes from participants R2-R6.

Perception Problems Affect Modeling Experience The most coded theme deals with perception problems. As a 3D scene is projected onto the 2D phone screen, it is not easy to correctly judge the distances between virtual objects. Respondents expressed that after completing shapes and then later changing their perspective, they found themselves surprised by what they had designed. From the initial perspective, it seemed like they created the shape as they had intended. Upon changing the perspective, they could now see that the shape was "not what [the users] thought it was" [R1, 00:41:56]. R3 expressed:

The estimate of one's 3D design was difficult due to the perception of the scene.

> "It depended a bit on the perspective from which I was looking [onto the scene]. So I thought from one perspective, 'Ah, that looks good!' and then I turned a bit to the other side and saw, 'Ah, no. It's not the same [as I wanted it to be].'" [R3, 00:09:12]

For a user to check whether or not the model came out to their liking, "[the user] would have to stand up again, look at it from one side and then look at it again from another side" [R5, 00:06:07]. R4 described working with the perspective as "difficult and then also exhausting." [R4, 00:13:22]. When asked whether or not users felt like there was a direction in which they had the most perception problems, the respondents expressed that depth perception was the most problematic. R4 said:

Participants described they needed to check their 3D model from all sides.

> "[...] but [the direction] away from me, or towards me - I sometimes found that hard to estimate: 'How far away is that now? How close is that still?' And again, especially in relation

to other objects. It's not easy to see how they are positioned in relation to each other." [R4, 00:11:31]

Participants struggled with depth perception.

To solve these problems, the respondents recommended multiple solutions. Notable concepts included: the idea to empower the user to rotate the whole scene, enable the user to choose a layer to model on, for example, like in SolidWorks[1], and to include constant size indicators for objects [R4, 00:38:42, R2, 00:11:07, R1, 00:14:41]. The most popular concept was to provide a grid with which the user could work to avoid perception problems. Respondents expressed that a grid would help them. As R6 put it:

To solve perception problems, participants wished for a virtual grid.

> "My wish would be that you could set up some sort of grid with which you could work. [...] like a spatial grid that defines the depth where you can clearly see: lines lead away from you to the back and run narrower. As a way to also recognize the depth. [...] It would perhaps also be quite pleasant if you could turn it on and off." [R6, 00:09:02]

Perception problems also included the process of working with real-world objects. R5 said that she found it very difficult to model with real-world objects because of the occluding behavior: "It's just not possible with the perspective - even when I start modeling there, it just doesn't look like it is behind [the object]." [R5, 00:52:41]

Usability Problems with Node-based Modeling Techniques The second most coded theme concerned usability problems with node-based modeling techniques (see Figures 3.3 and 3.4). Users often described the different types of Revolve and Sweep as hard to work with: R4 expressed that he thought Revolve(Profile+Circle) and Revolve(Two Profiles), were "not working so well" [R4, 00:30:09]. When R3 talked about the experienced problems

[1] `https://www.solidworks.com` Accessed March 2, 2021

with Revolve(Profile+Path) she made a connection to the previously talked about perception problems:

> "With [Revolve(Profile+Path)], I somehow had problems with that. I modeled funny things with it that I did not want to model. However, I think that was mainly because I could hardly estimate the dimensions [...]. I thought I had just drawn a line, but then it was somehow a bit curvy. And there are just no nice, straight results. So, not the [intended model] is the output, but something crazy, which I did not want to paint." [R3, 00:31:24]

Commenting on that same note, that the output sometimes was not as intended, R2 said that it "took [her] long to get the shape the way [she] wanted it to be" with Revolve(Profile+Path) [R2, 00:17:20]. R5 and R6 described the same problem with Sweep(Two Profiles). R6 said that the output was "very different from what [she] wanted." and R5 said that she found it "freally difficult to achieve nice [output]." [R6, 00:06:50, R5, 00:10:51]. The general concept of the existing mismatch between the users' intended model and the actual output arose a lot during the interviews. User R5 described her broad experience with the node-based modeling techniques by saying:

Respondents described a mismatch between the intended output and actual output with some node-based modeling techniques.

> "But in the end, it just doesn't look exactly how I imagined it would, because it just didn't work out the way I wanted it to." [R5, 00:37:47]

When asked about a solution to prevent that mismatch, respondent R1 thought a fitting idea might be to visualize the object instead of just it's skeleton:

> "If there was just a little automatically generated preview of what it looks like, then I could probably more easily make adjustments, rather than having to build the shape and then press the undo button a few times." [R1, 00:31:12]

As R4 described "seeing the output beforehand was very useful", we thought this idea was noteworthy [R4, 00:48:34].

To reduce that mismatch, respondents suggested showing preview of the resulting 3D model for the node-based modeling techniques.

Because of the discussed problems, the respondents expressed that they had little to no trust in these modeling techniques and instead used the ones they deemed easier to use. R4 said that he "specifically wanted to use the [node-based techniques] that promised to be a bit more complex", but after failing to model something he intended, he "withdrew and chose to work with [primitives]" [R4, 00:40:51]. Adding to that narrative, R1 described some of the node-based techniques as "tricky" [R1, 00:09:14].

Problems with Understanding Node-based Modeling Techniques What became clear from the interviews is that there are issues with understanding some of the node-based modeling techniques. While the respondents generally stated that they did not understand all modeling techniques, some were often mentioned. Mostly affected by this were Revolve(Profile+Circle) and Revolve(Two Profiles). R4 detailed his problems with the techniques:

Not all node-based modeling techniques were easy to understand.

> "It was not obvious to me what *revolved* around what. With Revolve(Profile+Path), it was quite clear to me. I thought: 'Okay, in the middle, I have the axis of rotation, and on the outside, I have the profile. Well, that will probably be rotated around the axis of rotation.' You know that from classic CAD software, and that was, so to speak, known to me and I learned that during my studies. With Revolve(Profile+Circle), I could somehow not really transfer that or imagine that concept. And the same with Revolve(Two Profiles). These are the two that I did not really understand. And that has to do in particular with the idea of what rotates around what with what result, I would say." [R4, 00:26:54]

The modeling technique Loft also confused the participants. R6 asked during the interview: "So between Loft and Sweep(Two Profiles) - is there actually a difference?" [R6, 00:17:40]. R3 asked the same question in her interview [R3, 00:24:37]. The application provides an instructions feature for each technique to prevent that very user confusion. When asked what users did to understand the techniques, participants described that they at first tried a 'trial and error' approach and modeled the technique's icon (see Figure 3.4), only later checking the instructions. R3 described:

> "I mostly at first just drew what was on the techniques icon to understand how these modeling techniques work. I simply traced the profile and then understood what it was doing for almost all of them. And if it did not work directly, I then turned to the instructions [...]" [R3, 00:28:36]

When asked about the usefulness of the instructions, the respondents reacted differently. While R6 found it "helpful" and R2 said that the instructions "actually explained everything", others were not entirely satisfied [R6, 00:21:11, R2, 00:23:06]. R4 wished for video explanations instead of text explanations and said:

> "[...] it would have been cool to see some kind of preview: 'What exactly does this do?'. So some kind of [animation] so that I can see: 'Okay, now if I would have drawn this and then if I would have drawn this, then this would be the output'. I think that would make it almost self-explanatory for how to deal with most of the techniques." [R4, 00:18:03]

As respondents found the text instructions feature to be unsatisfactory, they wished for video instructions.

As R3 called for the same feature, we perceived this as significant [R3, 00:00:28].

Positive Feedback for Primitives We received positive feedback for the primitives feature. ARPen lets users create predetermined primitives by tapping and holding a software button and then dragging the pen through the scene to determine the scale. Possible creations include cylinders, cubes, spheres, and pyramids. Participants expressed that they felt drawn to the primitives feature and wanted to work with them. When asked to elaborate on that, R3 stated:

> "I simply prefer to work with [the primitives]. Because that's just the fastest for me and as I said before, if I want to build all these [complex] objects, then I just prefer to work with primitives and merge/combine them to realize the final form!" [R3, 00:34:42]

We got very positive feedback for the primitive creation.

The respondents described the primitives as "easy", "fun to use", "intuitive", and "fast" [R2, 00:16:31, R4, 00:13:22, R1, 00:09:14 R5, 00:27:52]. R6 voiced that the primitives were simple because "you could see right away how it would be modeled in the modeling process." [R6, 00:15:53]. Additionally, users liked the extrude feature, which is another way to create a cube [R5, 00:44:10].

The pinkie grasp did not work for every respondent.

System Ergonomics As the ARPen system is a bimanual AR system with a pen and smartphone, users must hold the phone horizontally in one hand, using the other hand to hold the pen. Previous studies have shown that participants preferred to hold the phone according to the *pinkie grasp* (see Figure 5.1) when using ARPen [Wacker et al., 2019]. Because of this, we asked our participants to do so as well. Moreover, we asked participants to charge their phones while using the application. We specify the used iPhone models in section 4.4. Respondents said that the bimanual use resulted in some difficulties. R4, for example, stated that "the coordination of everything at the same time" made using the application difficult, but later on described that over the usage time, he found it to be "easier" [R4, 00:24:13, 00:32:08]. R3 and R2 described the same experience [R3, 00:00:28, R2, 00:21:53]. Holding the phone with the pinkie grasp seemed to be the bigger problem for the users. R6 described that her iPhone 8 Plus "kept falling out of [her] hand" when using the pinkie grasp

Figure 5.1: A user holds the phone with the pinkie grasp. The phone rests on the pinkie finger, with the index finger holding the top.

[R6, 00:25:12]. When asked what she did as an alternative, she said she needed to find a different way of holding the phone [R6, 00:25:12]. R4, who used the iPhone 12 mini, also described that he needed to find an alternative way to hold the phone because his hand hurt and "cramped" [R4, 00:32:08]. Furthermore, R3 said that holding her iPhone 11 was "exhausting" after ten minutes and that she also needed to change the way she held the phone [R3, 00:19:35]. Additionally, users described that their pinkie hurt because of the phone's weight [R5, 00:24:01]. R5 described that with the growing pain, the "frustration" also grew with the application [R5, 00:42:19]. When asked how users dealt with the pain, multiple users said they had to lay the phone down. R4 expressed:

Respondents came up with alternative ways to hold the phone because their hands hurt.

> "Then I had the feeling: 'Ah, now I have to rest my hand here for a moment, take [the phone] in my hand normally or put [the phone] aside for a moment and then shake my hand and continue.'" [R4, 00:35:24]

R5 went on to say: "I wouldn't use [ARPen] for long acts.

In fact, because it's just... yes, unpleasant." [R5, 01:03:10].

No User Confidence in Precision Another theme that emerged from the interviews was missing confidence in the precision of pen input. Respondents expressed drawing precisely with the pen was hard. R4 stated:

Participants felt like the input was too imprecise to achieve what they wanted.

> "The precision is generally difficult, creating something exactly the way you want it. And that's especially true if I wanted to create several identical objects, for example. I probably would have had to copy them somehow. But if I kept redrawing them, then of course they rarely turned out the way I intended." [R4, 00:06:13]

Similar to R4, R5 also suggested the concept of duplicating objects because they would not turn out identical [R5, 00:13:52]. R1 remarked that he preferred using the primitives over the node-based modeling techniques since they allowed for "nice clean lines", while drawing an axis-aligned line would "take [the user] quite a while"[R1, 00:28:42]. Respondents also noted the trembling of the pencil point as an issue for precision. R1 observed: "[...] even though you're holding the pen steady [...] the [pencil point] trembles." [R1, 00:06:18]. Regarding being able to model on the same level, R2 said that she was not sure "how well it works or whether it works at all."[R2, 00:04:41]. When trying to draw in mid-air, users especially found it hard to be precise, and it was easier "to [use ARPen against a surface] to model more accurately. I actually found that quite helpful." [R3, 00:07:31].

Respondents struggled with drawing axis-aligned lines.

User Interface Usability and Effectiveness Problems During the interviews, the respondents gave some general remarks on the user interface. As changing the plugin requires users to scroll through a list on the left side (see Figure 3.3) of the screen, some users expressed that changing the plugin "slowed down" the modeling process [R5, 00:43:11]. R6 recommended including a dedicated translation-button in the UI as it is one of the most used plugins [R6, 00:34:08]. Another wish of R6, which R3 echoed, was to include the possibility of choosing the direction in which the primitives are built so the user would not need to rotate it immediately [R6, 00:11:27, R3, 00:05:21]. The respondents also commented on irregularities in the interface, which seemed to cause confuse users. R4 stated:

> "The extrude plugin, I did not get [the user interface] at all, because [the buttons] had different sizes and were not labeled." [R4, 00:20:36]

R3 noted that she had difficulties reading some of the labels on dark backgrounds as their font color is black [R3, 00:43:39]. R4 also said that it was "really annoying" that she could not read some of the plugin's names due to the length constraints [R4, 00:46:47]. Some of the respondents also complained about the software buttons' reachability because of the plugin list on the left. R5 remarked:

Few participants could reach all elements of the user interface.

> "The software button is way too far to the right for me. I can barely reach it with my thumb. It was just completely unpleasant to tap it. I would have liked for the menu to be much narrower and much closer." [R5, 00:08:20]

This problem resulted in R6 expressed the wish to be able to "personalize the position of [the button], for example. Also if you're left-handed, I thought it would be quite cool, if you can then also bring [the button] to the other side." [R6, 00:04:26]. As the undo-button required users to take their hand that holds the pen out of the scene and interact with the screen, R2 and R3 stated that it broke their modeling experience [R2, 00:18:37, R3, 00:21:04].

To account for different hand sizes, participants wished for a customizable UI.

ARPen's Difficulty Level When asked about the difficulty level of ARPen, respondents' reactions were assorted. R6 found the application's difficulty level to be mixed and expressed that it really was "dependent on the currently used [modeling technique]." [R6, 00:14:54]. R5 found

The participants found ARPen's difficulty level to be dependent on the currently used modeling technique.

the application "generally easy" to use and R2 found the concept of the application to be "self-explanatory" [R5, 00:32:24, R2, 00:14:26]. While R4 did not feel "over-challenged" by the application, he stated that he found the application "rather difficult" to use [R4, 00:13:22, 00:23:46]. R3 did not share that sentiment and expressed that she felt "over-challenged in the beginning" [R3, 00:40:01]. Furthermore, R2 described having initial difficulties and stated that "[in the beginning] I did not know what to do at all" [R2, 00:22:40]. R1 described the need for an "initial break-in period" with the application [R1, 00:08:38].

Tracking Problems Respondents further experienced problems with the tracking of ARPen. General remarks about the tracking systems included R2's description of how sometimes "the [pencil] point did not appear, no matter whether I held [the pen] far away or close, nothing appeared. And then it sometimes took forever for me to continue." [R2, 00:04:41]. Respondents also linked the lighting situation in their homes to some tracking problems. R6 described "that the artificial light reflected very easily [on the pen] and then [the tracking] did not work" [R6, 00:23:53] and R2 said that maybe it was "because it was dark in some parts, or because it wasn't bright enough" [R2, 00:04:41]. Furthermore, respondents expressed that accidentally occluding the marker was a frustrating part of the experience. R1 said:

> "[...] and would be nice, also, if you can hold the pen however you want to hold the pen and not have to make sure that it can read [the marker] code [...]. Just because you're very focused on the task right now, but then sometimes if your finger is covering a little portion of that [marker], then all of a sudden the thing disappears, and you're like, gosh, dang. So that would be nice." [R1, 00:20:08].

Respondents also expressed that tracking problems included the coordinate system moving uncontrollably through the scene sometimes, resulting in objects "flying or just slipping away" [R2, 00:11:46].

General Impressions of the Application The concept of the application got positive feedback from some respondents. R1 said:

> "I think the concept in general [is beneficial]. Like, the concept making shapes [...] while looking at all of the objects around your room. I think [...] that inherent idea behind the app is incredibly useful in modeling because just [...] modeling something on the [computer], even though you have the dimensions, it's hard to [imagine it being in] your space. I feel like that's just kind of inherently difficult for [users] to do. Some people can do it better than others, but I feel like, with something like [ARPen], anybody can do it." [R1, 00:43:09]

The concept of the application got positive feedback.

Respondents also described that the initial excitement got lost with the usage problems. R5 said: "[...] at the beginning there was still such an excitement to use [ARPen]. And then it just became less exciting, because it somehow got more frustrating." [R5, 00:42:19].

User Trust in and Suggestions for Undo/Redo It emerged that respondents frequently used the newly added undo and redo feature (see Chapter 3). R1 noted: "The undo button - fantastic feature. Used it all the time." [R1, 00:31:12] and R2 stated: "I've often drawn things that didn't fit. Then I used undo again, and the previous node was still there and I could continue to draw." [R2, 00:18:37]. Still, the undo/redo history's LIFO principle turned out to be problematic to the respondents. R6 explained the need for a delete feature:

Users needed the undo and redo feature.

> "[...] I also thought, maybe it would be useful to have a delete button, because if you... I don't

> know, five steps before you've done something that you want to delete, then it's just stupid if you have to delete everything else as well." [R6, 00:05:15]

Furthermore, users suggested features to bypass the LIFO principle of undo.

R5 echoed that wish and said: "Then I have to either delete everything or undo until [everything else] also got deleted again, and that sucked." [R5, 00:13:52]. R3 wished for a feature that would allow undoing specific actions independent from the position in the history [R3, 00:37:52].

Mixed User Feelings about all Interaction Types of Rotation Another theme that came up was the respondents' dissatisfaction with all types of rotation. Respondents mostly reacted negatively to Direct Device Rotation. To quote R4:

> "Actually, it's [inconvenient] because of the perspective change or rather using the device's orientation to rotate the object while at the same time changing your position to the object - I found that to be extremely unintuitive. I think [...] that's exactly why that would be a function I would not touch again. I would always use the other [rotation techniques]." [R4, 00:31:26]

R1 felt using Direct Device Rotation to rotate the shape was "unnatural" [R1, 00:34:40]. R6 said Direct Device Rotation not really allowed to rotate a shape in all directions [R6, 00:44:23].
The participants generally preferred using Touchscreen Rotation over Direct Device Rotation. For example, to quote R4:

> "I found it way easier just swipe with your fingers across screen and turn [the object]. So, really I found that ten times easier I would say. If I had to put a number on it!" [R4, 00:30:58]

Additionally, respondents expressed dislike for Pen Rotation. Pen Rotation only allows "rotating the object in little increments because it stops reading the marker", and thus, it is "hard to rotate precisely" while using it [R1, 00:45:41].

All types of rotation got mixed reactions from users.

Multiple-select-based-Plugins Usability Problems
Some modeling techniques require the user to select the desired shape, perform the intended action and then deselect the shape. Respondents found that to be irritating with the translation feature as it allowed for selecting multiple objects. R4 said:

> "And what I often experienced was [...] when I wanted to move an object, I moved it and then went on to move the next one, but I didn't deselect the first one again and then I quite often started to move both objects and only then realized: 'Ah now I have moved the object that I already moved!' And then I had to move it back again and then deselect it and select it again. And that was always very tedious." [R4, 00:15:06]

R4 also stated that he "never wanted" to move multiple objects at once [R4, 00:17:21]. R5 expressed that the problem was "a bit annoying" [R5, 00:05:22]. A sentiment which R3 repeated [R3, 00:45:31]. Additional selecting problems also occurred while using boolean cut. Respondents expressed that it was not clear "which object had to be selected first" or that they "selected in the wrong order together" [R4, 00:28:09, R5, 00:05:22]. R6 expressed the wish to select more than two objects when merging [R6, 00:21:38].

Users never wanted to translate multiple objects.

Order of selection for boolean cut seemed to confuse users.

Positive Feedback for Node-based Modeling Techniques
In addition to the usability problems, respondents also shared what succeeded from the node-based modeling techniques. R6 found Revolve(Profile+Path) to work "very well" [R6, 00:21:38]. Moreover, R1 described Sweep(Two Profiles) as "super easy to use" and said it "allowed [the user] a lot of freedom to make some pretty eccentric

Sweep(Path) was the most popular node-based technique among the users.

shapes." [R1, 00:27:59]. By far, the most popular node-based modeling technique was Sweep(Path). R3 and R5 stated that they used it the most of all the node-based modeling techniques [R3, 00:33:10, R5, 00:44:10]. Moreover, R6 said:

> "I find Sweep(Path) very good. With that, you can work pretty fast and well. Yeah, work with the height and stuff like that. It does that quickly and the way I wanted it to." [R6, 00:21:38]

Respondents described difficulties with using existing 3D models in the modeling process.

User Feedback and Suggestions for Features for Working with Existing 3D Models Alongside the primitives feature, merging and cutting got positive feedback. Respondents said it was "really good", "relatively quick [and] useful"and "easy" [R1, 00:27:59, R2, 00:25:19, R3, 00:00:28]. However, the respondents expressed that difficulties arose when working with existing 3D models in the modeling process. R5 declared:

> "[...] I also found it difficult to interact with existing models or to build on top of them. [...] Firstly, because you don't have real physical feedback, where models touch, to estimate that somehow. And also [...] to edit [one surface] exactly so that the [size is identical to the other] surface. [...] I couldn't get it to look perfect somehow." [R5, 00:17:14].

R2 also described difficulties with getting two objects to fit precisely on top of each other [R2, 00:36:32].

Application Performance Concerning the application's performance, respondents R3 and R5 said the performance application was "smoothly" on their iPhone 11 and iPhone XR respectively [R3, 00:21:04, R5, 00:02:54]. R2, which used an iPhone 6S said that "[the phone] got very hot and then also [the application] crashed at some point." [R2, 00:07:20].

Additional Manipulation Features When talking about the manipulation of objects, in addition to the path editor R3 wanted to be able to grab individual vertex points of objects and move them, thus manipulating the shape [R3, 00:12:05]. R5 expressed that scaling "works without problems and also very smoothly" but that she would have liked to be able to use non-uniform scaling [R5, 00:08:20, R5, 00:10:30].

Preference for Pen-based Interactions A further theme that emerged was the general preference for pen-based interactions. As described in Chapter 3, we implemented several interaction types for the rotation and scaling of objects. Regarding the interaction types, R5 shared:

Users preferred using the pen-based interactions over the other implementations.

> "[...] for me it was the most comfortable, because I use the pen all the time anyway, to do that with the pen and not with the touchscreen or with the device itself." [R5, 00:34:48]

Adding to that, R1 said that he "mostly wanted to use the pen" primarily for scaling [R1, 00:12:50].

Chapter 6

Discussion

In the following, we summarize and classify the obtained results to answer the research question. Furthermore, we discuss the limitations of the study.

6.1 Findings

The 18 themes described in Chapter 5 give a real insight into difficulties users experienced with ARPen.

The most coded resulting theme was about the perception problems user experienced. This theme's emergence shows that our results have merit, as users experiencing problems with perception are not uncommon in handheld AR [Dey et al., 2012]. The problems heavily impacted the estimation of distances between objects and the assessment of built shapes. The respondents could not correctly estimate what shape they had created and struggled with the depth perception. In the user study conducted by Hürst and Dekker [2013], users similarly struggled with depth perception (see Chapter 2). These perception problems had an impact on the effectiveness of ARPen for 3D modeling. The constant shifting of the perspective to resolve perception problems required a lot of movement. As this demands lots of effort, we propose developing a solution that accommodates the

Our results have merit, as perception problems are not uncommon in handheld AR.

users' perception problems. The most suggested proposal was to incorporate a grid that would make the perception more palpable for the user. Wacker et al. [2020b] already researched approaches for solving perception problems and recommended integrating a 'heatmap', which colors shapes in the scene based on their distance to the pen. We propose following that concept, expanding it to include path creation, and integrating it into the application. The participants' main wish was to include a grid that would help with perception.

We suggest including and expanding the heatmap approach by Wacker et al. [2020b] to reduce perception problems.

Moreover, participants made many remarks about the precision of pen input. They felt like they could not achieve what they wanted to and could not draw axis-aligned lines. Furthermore, participants also noted that the pencil point's trembling and the moving of the coordinate system affected their accuracy. Previous studies had already shown that without assistance, accuracy is hard to achieve [Wacker et al., 2018]. As precision is vital for 3D modeling, we strongly advise integrating features that assist the user. Introducing a virtual grid to the system of Hürst and Dekker [2013] helped users to draw reliably. Hence, we suggest that introducing a virtual grid concept might improve input accuracy with the ARPen as well. A potential grid concept should have the option to be turned on or off. Also, it should allow snapping the pen point to grid lines, thus allowing for higher precision.

A virtual grid might solve both precision and perception problems.

Moreover, the participants of our user study wished for a grid for solving perception problems. We suspect a correlation between some of the precision and perception problems. Helping the user see where in the scene she is modeling might lessen the extent of precision errors. Thus, introducing a grid may enable more precise input and help solve perception problems. Nevertheless, we want to note that Wacker et al. [2020b] proposed a grid prototype to solve perception problems, but it did not turn out to be the most intuitive technique in the study. Still, as the grid was the most mentioned proposal to solve participants' perception problems, we found it a noteworthy suggestion. Other demanded solutions for precision problems included a duplication feature. Besides that, the results showed that users had difficulties precisely modeling two objects that fit together. We propose to integrate features that make working with already created 3D models easier.

Participants frequently remarked usability problems with the node-based modeling techniques. As users described the difficulty level of ARPen to be dependent on the currently used technique, resolving these issues could lead to an overall more leisurely experience. Users shied away from conducting rather complex modeling tasks with the system but enjoyed using the primitive features to model an object quickly. Respondents expressed that their intended output did not match the actual output. This may partly be related to the problems with perception and precision. In finding a solution for these problems, usability problems with the node-based modeling techniques may exist to a lesser extent. To allow users to get rid of the wrong output in different ways, we encourage integrating a deletion feature in addition to undo.

Solving perception and precision problems might increase the usability of node-based techniques.

We suggest implementing a deletion feature.

Moreover, we advise integrating previews of objects built with node-based modeling techniques. As respondents described, using the primitives was easy because of the generated preview, this could enhance, simplify, and clarify the modeling process. Furthermore, including previews for subsequent manipulations would answer the demand for additional manipulation features. The usability problems may also be linked to remarked understanding issues with some of the node-based modeling techniques. Respondents expressed that they did not understand all modeling techniques and that using the instructions feature did not always help. Participants mentioned including video demonstrations instead of text-based instructions quite often. We suggest implementing video-based instructions, as this could also address the confusion with the multiple-select-based-system of boolean cut. Additionally, we advise getting rid of the multiple-select-based-system for translation as it simply seemed to confuse users and did not want to move more than one object at a time.

We suggest implementing previews for node-based techniques.

Respondents also gave vital feedback on the pinkie grasp. Using ARPen with the pinkie grasp resulted in hand cramps and pains. Respondents did not want to use ARPen for more extended periods and tried to find new ways to hold the phone as an alternative to the pinkie grasp. Each participants came up with individual grasps.

Since one could argue that small hands or heavy phones are the reason for the resulting pain, we want to note that not only the user with the biggest (iPhone 8 Plus) and a rather big phone (iPhone 11) had problems with the pinkie grasp, but also the user with the smallest phone (iPhone 12 mini). This theme surprisingly contrasts results of previous work which showed that participants preferred to hold the phone according to the pinkie grasp [Wacker et al., 2019]. As we set up the experimenting phase of our study to be long-term, consisting of five use days, we propose that the gathered user insight unveiled not contradicting but rather additional information relevant to choosing a grasp for the phone. Since our results showcase that requesting the use of the pinkie grasp could potentially disregard a substantial part of the user audience for ARPen, we advise looking into more flexible possibilities. As we asked users to charge the phone while using it and the phones became increasingly hot, this might have played an additional role in not wanting to hold the phone for long.

To account for different hand and phone sizes, we suggest looking into more flexible possibilities than the pinkie grasp.

Furthermore, due to the COVID-19 pandemic[1] participants used the application on their own and without external guidance. Thus, we could not guarantee that the participants followed all our recommendations like charging the phone during the use of ARPen. Simple nuances like these could have influenced the results about system ergonomics.

Concerning the UI (see Figure 3.3) itself, it became apparent that a customizable UI is needed to account for different hand and phone sizes. Customization could be realized by, for example, changeable button positions as respondents expressed that some elements of the user interface were hard to reach. Since the pinkie grasp mainly allows to reach the left side of the screen with the hand that holds the phone, we suspect that the pinkie grasp's insufficient adaptability for different hand and phone sizes is partly the reason for that. Since the user interface and the way the user holds the phone are dependent on each other, we advise developing an interface that is customizable to the extent that it also accounts for people not using the pinkie grasp. As of now, the user interface is built for holding the phone in the left hand. The results point out that a version

We propose developing an utterly customizable interface to support individual grasps.

[1] `https://www.rki.de/DE/Content/InfAZ/N/Neuartiges_Coronavirus/nCoV_node.html` Accessed March 2, 2021

for holding the phone in the right hand needs to be added. A new interface should also address the irregularities that confused respondents and change the plugin list on the left side as it slowed users down. Based on the fact that users thought pressing the undo button interrupted their modeling flow, efforts should be made to make the user interface usable with the one hand that holds the phone.

Regarding interacting techniques, results showcased that out of the provided techniques, pen-based interactions were preferred. Users found it more comfortable to keep using the pen instead of switching over to the touchscreen. Since users mentioned that extracting the pen from the scene by pressing the undo-button seemed to interrupt the modeling experience, we suspect the same here. Our advice is to focus solely on pen-based interaction techniques in the future. It became apparent that the implemented rotation techniques were received primarily negative. Direct Device Rotation was mainly perceived negatively. As Pen Rotation was received rather poorly, combined with the fact that touch screen interactions break the modeling experience, we suggest including new rotation techniques.

We suggest researching new rotation techniques.

Technical aspects of the ARPen system also had an impact on the usability of 3D modeling. Some respondents experienced crashes and minor bugs in the application, which may have caused additional frustration. ARPen uses an image recognition approach to pinpoint the position of the input pen. This comes with some disadvantages, as the tracking was dependent on the lighting situation at their homes to read the marker. We suggest looking into possibilities for enhancing the tracking performance in low light situations. As the study used the cardboard ARPen instead of the 3D printed one, the suggestion has to be interpreted to this fact.

Generally, users liked and gave positive feedback for the application's concept and the possibility to model in-situ. Users enjoyed the freedom our system offers when creating objects by sketching lines. Despite usability problems, users still enjoyed using specific node-based modeling techniques and found some of them easy to use, most prominently Sweep(Path). As they were fast and intuitive, users felt drawn to use the primitives feature, which got positive feedback. Users also noted that the undo/redo-system worked very well and provided needed support during the modeling process.

Applying the suggestions made could improve the effectiveness and usability of ARPen.

These findings point out the strengths as well as the weaknesses of the ARPen system. We learned that the described difficulties impact the user experience with ARPen for 3D modeling and determined ways to improve our system's effectiveness and usability. To answer our research question, we conclude that while the system has great potential, the above actively demonstrates that there is further room for improving the ARPen system and adapting it to user needs. We suggest that moving forward, implementing the discussed proposals could enhance the effectiveness and usability of the ARPen system for 3D modeling.

Besides, for 'handheld AR with a mid-air pen' systems, we propose to add features that reduce the overall perceptual difficulties due to the handheld smartphone, pen input inaccuracy, as well as system ergonomics since these shortcomings are not only related to our example implementation but are more domain specific.

6.2 Limitations

The presented study has some limitations that need to be considered. Most notably, we worked with a very small sample size of six participants. We recruited participants by doing snowball sampling. Inherently to snowball sampling, the sample consists of people of similar demographics. Snowball sampling is also a non-probability sampling technique, which researchers generally should not use to infer from the given sample to the general population in statistical terms [Vehovar et al., 2016].

We worked with a small sample size and only one data source.

Additionally, the transcripts of the interviews are the only data source used for this analysis. The initial aim was to include multiple data sources, such as the respondents' scene files, to achieve data source triangulation. However, this was not possible due to time constraints. The collected data were analyzed only by the author. Concerning reliability, the author designed the study and thus is a subjective coder. Such a coder may be constrained in her abilities to think beyond the already established concepts in their mind. [Lazar et al., 2017, p. 320]. Since the author developed parts of the application, there is a certain bias to want to see the application succeed. To address these potential issues, we always followed the planned procedure, reported every detail of the study and analysis, and reflected on the process through memo writing. To maximize the results' validity, we followed established procedures, conducted a pilot study, pretested the interview script, and made sure to report on the procedure and analysis in this thesis.

All the results must be interpreted in relation to these facts.

Chapter 7

Conclusion

Finishing with this last chapter, we summarize our work and give a short outlook on potential concepts for the ARPen project's future.

7.1 Summary and Contributions

In this Bachelor's thesis, we assessed the usability and effectiveness of our system for 3D modeling. To gain user insight into qualitative aspects of 3D modeling with our system, we conducted a qualitative user study. Our sample consisted of six participants, recruited by snowball sampling. The participants used the application over five days in a long-term experimenting phase. To guarantee the usage of certain features, we provided modeling tasks for the experimenting phase. The tasks ranged from predefined to free and regarding difficulty from easy to hard. After the experimenting phase, we conducted semi-structured interviews with the participants about their experience with the application. We used a pre-tested interview script to ensure that specific questions got asked. Following, we transcribed and analyzed the interviews. For the data analysis method, we chose to do a content analysis, loosely following grounded theory. To gain user insight into our system, we needed to provide a stable implementation of the application with standard CAD software features. We expanded the ARPen system with additional features such as multiple interaction types to scale and rotate an object based on previous work by [Mohammed, 2020] and [Klamma, 2019], a complete undo/redo system, and the possibility to subsequently manipulate created objects.

Eighteen majors themes that deal with the user experience with ARPen emerged from the interviews. The findings of our study showcased the system's strengths, as well as its shortcomings. Users generally enjoyed the concept of the system, the possibility to model in-situ, the freedom our system offers when creating objects by sketching lines, the primitive creation, as well as the undo/redo-system. Still, there is further room for improving the ARPen system and adapting it to user needs. Issues such as the perception through the handheld smartphone, the precision of pen input, and system ergonomics impact the user experience with ARPen for 3D modeling. We discussed possible connections between problems and determined ways to improve the effectiveness and usability for 3D modeling.

We conclude that while the system has great potential, the findings demonstrate that there is further room for improving the ARPen system and adapting it to user needs. Moving forward, implementing the discussed proposals could enhance the effectiveness and usability of our system for 3D modeling. Furthermore, we suggest that overall perceptual difficulties due to the handheld smartphone, pen input inaccuracy, and system ergonomics are not only related to our example implementation but are more domain-specific. When developing a new 'HAR with a mid-air pen' system, features that reduce these problems should be considered.

7.2 Future Work

During the development and the writing of this thesis, we outlined potential future endeavors for the ARPen project. These suggestions are additional to the ones outlined in Chapter 6.

Given that ARPen is developed for iPhone and that Apple has now added a LiDAR scanner to their current lineup (iPhone 12 Pro[1]) of handheld devices, research into using the LiDAR technology for enhanced depth perception in ARPen could be conducted. Additionally, the LiDAR scanner could be employed similarly to AreaTargets[2]. Since using ARPen against a surface improves precision [Wacker et al., 2018], the LiDAR scanner could be used to create a 3D scan of a surface, thus enabling the delivery of augmentations to scanned real-world objects. A virtual grid could potentially be realized like this.

The possibility to scan surfaces with LiDAR to deliver augmentations might be an exciting endeavor.

Given that it is a standard CAD feature, allowing the user to view and manipulate faces and vertices of 3D objects may prove useful for ARPen. This could help mitigate some of the issues with accuracy and might prove to be useful to resolve issues of working with an already created 3D object.

ARPen could include the concept of faces and vertices of 3D objects.

As participants found the included rotation techniques to neither be intuitive nor effective, we propose the creation of new rotation techniques to be considered. As non-isomorphic rotation techniques are relatively popular in commonly used CAD software, the same may hold for the ARPen system.

Non-isomorphic rotation techniques should be included.

[1] `https://support.apple.com/de_DE/specs` Accessed March 15, 2021

[2] `https://library.vuforia.com/features/environments/area-targets.html` Accessed March 15, 2021

Appendix A

Implementation of the Undo/Redo System

In the following we describe how we implemented the undo/redo system for ARPen. Besides standard UML conventions, in Figures A.1 and A.2 we use the following conventions regarding access control: $\sim$ stands for *implicitly internal* and $-$ for *implicitly private*.

The class `Action` is the base class for all types of steps that the user can do in the application. It stores the current scene, as well as the reference to the used 3D shape. Additionally, it implements two methods `undo()` and `redo()`.

For each specific action that a user can do, there is a subclass of `Action`. All subclasses override the existing `undo()` and `redo()` methods with implementations specific to that action type. Moreover, they store the needed attributes for that implementation.

To give an example: For when a single or multiple 3D model get translated, there is the subclass `TranslationAction` (see Figure A.1). It stores the objects' positions before the translation in `initialPositions` and the positions after the translation in `updatedPositions`. Calling `undo()` sets the objects' current position to the ones stored in `initialPositions`. Calling `redo()` to the ones stored

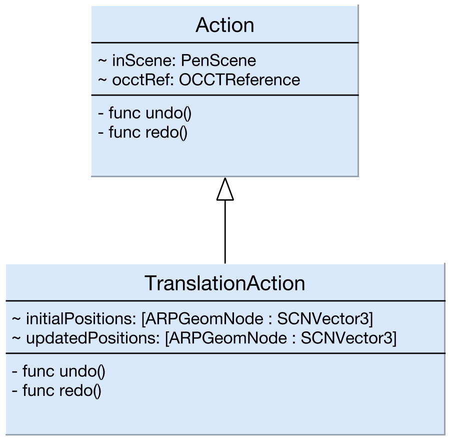


Figure A.1: The base class `Action` and one of its subclasses `TranslationAction`.

in `updatedPositions`.

The `UndoRedoManager` (see Figure A.2) maintains actions. It manages two stacks: one for actions that are to be undone and one for actions that are to be redone. Whenever an action is completed, the `UndoRedoManager` has to push an instance of the according `Action` subclass onto the `undoStack` by calling the function `actionDone(action: Action)`.

Whenever the user requires to undo an action, the `undo()` function of the `UndoRedoManager` is called. The most recent action then gets taken from the `undoStack`, the action's own `undo()` function gets called, and then it is pushed onto the `redoStack`. Whenever the user presses the redo button (see Figure 3.3), the `redo()` function of the `UndoRedoManager` is called. The most recent action then gets taken from the `redoStack`, and the action's `redo()` function gets called. Then it is pushed onto the `undoStack`.

As some classes may need to be notified and react when an action is undone or redone, the `UndoRedoManager` employs the `UndoRedoManagerNotifier`.

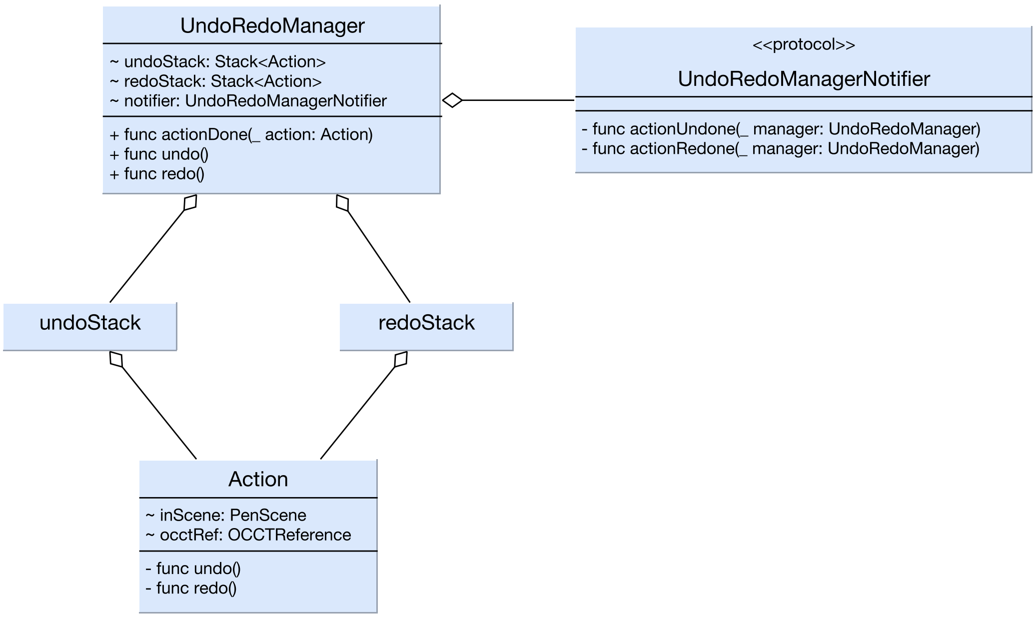


Figure A.2: The `UndoRedoManager` and `UndoRedoManagerNotifier`.

Whenever an action is undone, the notifier's `actionUndone(manger: UndoRedoManager)` function gets called. The same holds for when an action is redone. Any class that extends the `UndoRedoManagerNotifier` protocol can react accordingly by overwriting `actionUndone(manager: UndoRedoManager)` and `actionRedone(manager: UndoRedoManager)`.

Appendix B

Study Material

B.1 Consent Form

The following page contains the consent form we handed to participants before conducting the user study. We removed all emails, and phone numbers have for publication.

Informed Consent Form

ARPen “in the Wild” - Expansion and Evaluation of an In-Situ 3D-Modeling Application

PRINCIPAL INVESTIGATOR Andreas Dymek
Media Computing Group
RWTH Aachen University
Phone: [redacted]
Email: [redacted]

Purpose of the study: The goal of this study is to determine the effectiveness of ARPen. Is the goal of "3d modeling is now as simple as doodling!" achieved? Participants will be asked to complete Modeling Tasks using the ARPen System. After that an interview is conducted. The interview and data from the modeling tasks will be used in the analysis.

Procedure: Participation in this study is set up like this: You will be asked to complete Modeling Tasks using the ARPen application, which should approximately take 15 minutes per day, for 5 days.

After the study, we will conduct an interview with you about the tested system. In this interview, we will ask some questions about your experience, positives, negatives and your general impressions.

Risks/Discomfort: You may become fatigued during the course of your participation in the study. Because of the COVID-19 pandemic, we will not be able to join you in person for the modeling tasks. Please make sure to give yourself several opportunities to rest, additional breaks are also possible. There are no other risks associated with participation in the study. Should completion of the tasks become distressing to you, please terminate it immediately. In the interview you will be given several opportunities to rest, and additional breaks are also possible. Should completion of the interview become distressing to you, it will be terminated immediately.

Benefits: The results of this study will be useful for future design decision for ARPen itself, but may yield information for handheld AR- and pen-based systems in general.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue the participation.

Cost and Compensation: Participation in this study will involve no cost to you. There will be a little snack inside this envelope.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.
_____ I have had the information on this form explained to me.

Participant’s Name	Participant’s Signature	Date
	Principal Investigator	Date

If you have any questions regarding this study, please contact Andreas Dymek at [redacted] email: [redacted]

B.2 Interview Script

This is the final interview script.

Interview Script

User Study by Andreas Dymek
ARPen "in the Wild" – Expansion and Evaluation of an In-Situ 3D-Modeling Application

Interviewee (ID):
Gender:
Age:

Briefing

- Go through the given consent form
- Brief introduction to the research question (little to no details)
  General Impressions of the Application
- This interview is ***not*** about the tasks, but about the application and your experience
- Preferred language for the interview – German/English?
- There are no wrong answers!
- Please feel free to take out your iPhone and open the application

ARPen

1. You have now used the app for five days. For the start, I would like to ask you about your general experience during the modeling.
   What was your experience during modeling like (frustrations/positives)?

   a. How did you feel during the use of the modeling techniques?
   b. How would you describe your experience with the modelling techniques?

2. What does ARPen not do that you would like to be able to do (is there missing functionality)?
   If there is an answer, where did you have trouble (did this missing element complicate the use)?

3. What (if anything) would you like to change about ARPen?

   a. Why?

4. Did you find this application easy/hard to use?

   a. Why?
   b. Why did that cause you trouble?
   c. How did you deal with this problem?
   d. What made the app easy to use for you?

5. Do you understand the modeling techniques?

   a. How would you describe your understanding of the modeling techniques?
   b. Which aspect of the modeling techniques did you not get?
   c. How long did you take to get the modelling techniques? What helped you understand them?

6. Was there any technique that you found particularly useful? Was there any you found particularly not useful?

7. You used the app for five days now. Did anything change in your way of using the application?

    a. Did your feeling/thoughts towards the app change?

8. When you were using the app…
   Did you find yourself drawn to the same plugins over and over again?
   Did you just switch randomly? In both cases: Why?

    a. Which would you call your favorite plug-in? Which would you call your least favorite?

9. Was there anything you found particulary useful/helpful?

10. For this question. Please take your iPhone and open the application and do something you want to do. Are there any additional thoughts that come to mind that you want to share?

Data Questions

1. Profession:

2. Highest educational level:

3. How much experience do you have with CAD software on a scale from 1 to 5?
   [1 = not very experienced, 3 = about average, and 5 = very well experienced]

4. What software did you use?

5. How much experience do you have with handheld AR?

6. How much experience do you have with pen-based systems?

7. What iPhone model did you use for this user study?

Debriefing

- Thank you so much for participating.
- Anything else you want to add?
- Would you be available for questions later?
- Do you have any questions?
- More detailed information on research
- *To what extent is our system usable, useful and effective to use in 3D Modeling?*
  The question here seeks to determine the effectiveness of ARPen. User study to assess the qualitative aspects of the 3D modeling methods measures aspects of the user experience and will facilitate future designs directions.

B.3 Study Tasks

These are the modeling tasks. We removed all URLs, emails, and phone numbers for publication.

Modeling Tasks for User Study Participants

E-Mail: | Mobile phone:

Dear [reader],

Welcome to this little adventure.
In this file you should find for one the actual “ARPen” and also a little snack as my way of saying thank you.

How to Download:
To download the actual app, please open the following link on your iPhone or scan the QR Code:

Hit the download button, and allow the website to install the app. When you want to start the app, you should see a message as shown on the left.

To be able to open the app, open the Settings app. Go to General -> Device Management. There you should see the “RWTH Aachen University” developer profile. Tap on that profile and select “Trust RWTH Aachen University”. Once you have done that, the app should open without any problems. If you experience any troubles during the process, feel free to contact me.

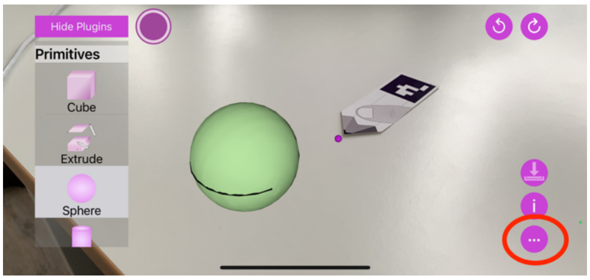
ARPen:
The ARPen system is a bimanual AR System with a pen & smartphone used for in-situ 3D modeling.
Previous studies have shown that the best way to hold your phone when using ARPen is the pinkie grasp: the phone is placed horizontally on the non-dominant hand’s pinkie so that the camera is not occluded. The user holds the pen in the dominant hand.
Please connect your phone to a power outlet while using ARPen. Thank you!

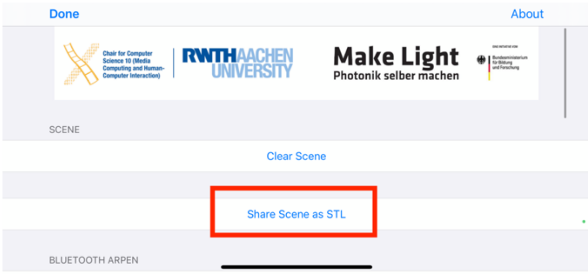
Study Information:
This study's general goal is to collect user impressions of the complete ARPen system in the final interview.

Of course, to be able to do that, the interviewee needs to know the application and some of its possibilities.
For that reason, I designed multiple tasks for you to do each day of this 5-day testing period.

After completing the tasks for the day, please send the resulting scene to my email.

Sharing Instructions:





The following task instructions are just recommendations!
If you at any point want to use another technique, please feel free to do so!

ARPen is split up into “plugins”, each being responsible for a specific interaction. If you find yourself lost at any time while using a plugin, press the “i” button for further instructions.

<u>*IMPORTANT:*</u> **Interview Date and Time**

Under the following URL/QR-code, you can tell me when you have time for the interview. The time slots are set for two hours for flexibility, but the interview will not last two hours.

Thank you so much for participating.

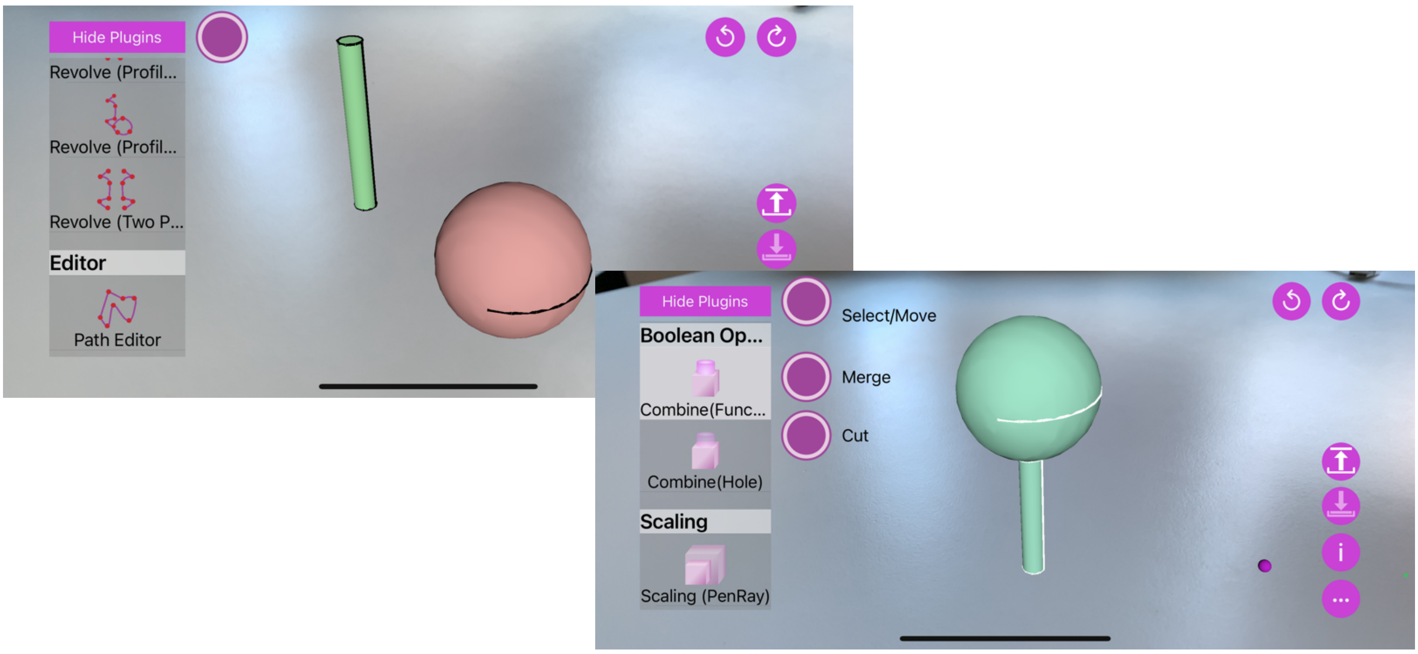
Day 1 - Boolean Operations and Scaling

Task No	Difficulty level	Plugins used
Task 1	Easy	Sphere, Cylinder, Combine (Function)
Task 2	Easy	Cube, Combine (Function)
Task 3	Medium	Scaling (PenRay)

Task 1 - Tree

Description:
"Oh no - your garden seems so empty, and your guests are coming over any minute now. Better put your gardener skills to work and plant a new tree! Luckily you possess the magical powers of 3D-object-generation. Take matters into your own hands and follow these steps."

Steps:
1. Under the category "Primitives" you will find the plugins "Sphere" and "Cylinder". Use these plugins for the creation of a sphere and a cylinder.
2. Once you have done that, you can find the plugin "Combine (Function)" under the category "Modeling". Select the plugin and arrange the objects as shown in the pictures below. Then merge them. The color change will indicate whether or not they are one object now.

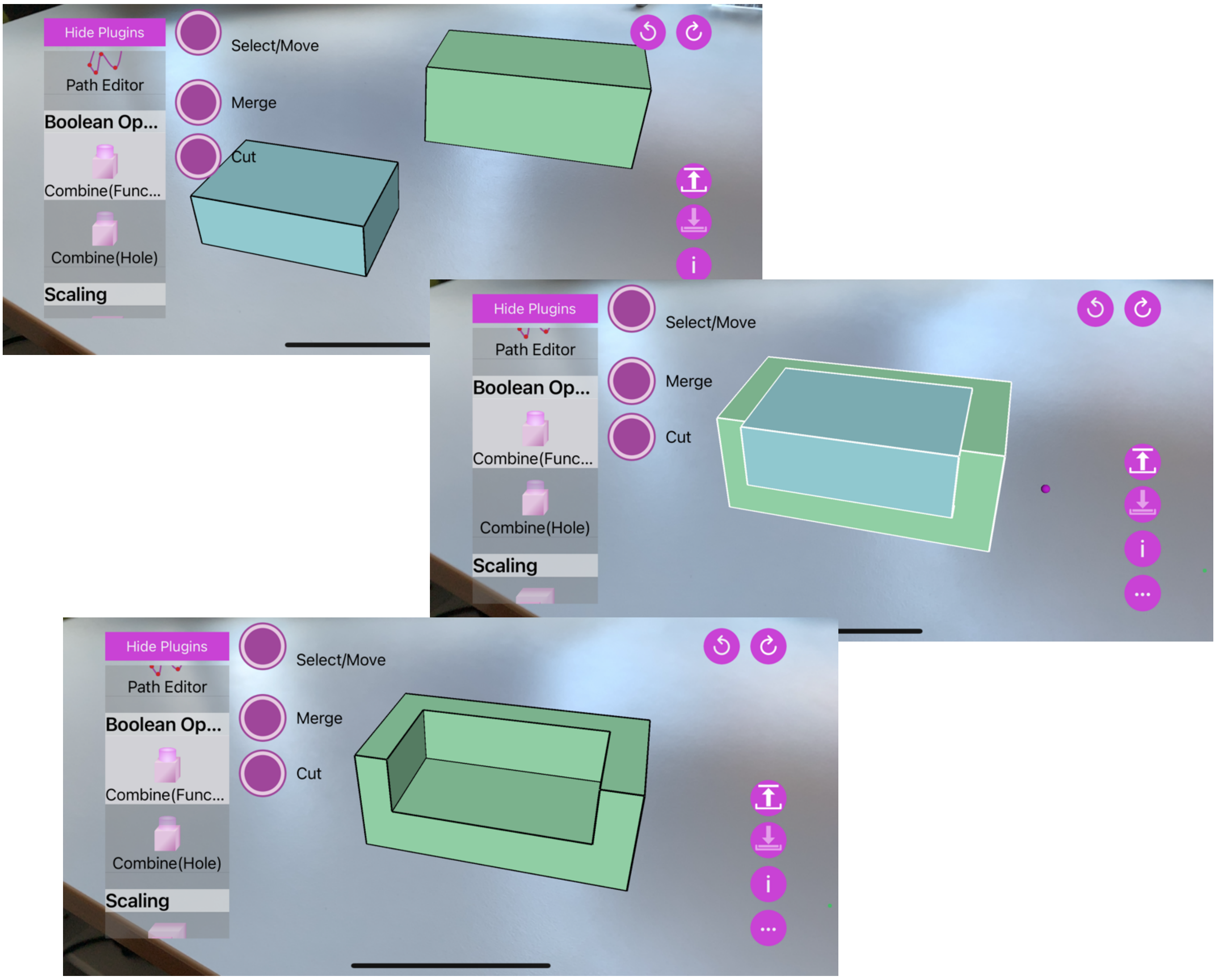


Task 2 - Couch

Description:
“Great, you have a tree now! But where are your guests going to sit? You better build a place to chill. Try using your awe-inspiring powers to build a couch.”

Steps:

1. Find the plugin “Cube” under the category “Primitives”. Use the plugin to create two rectangles, one being slightly smaller.
2. Once you have done that, you can find the plugin “Combine (Function)” under the category “Modeling”. Select the plugin and arrange the objects as shown in the pictures below.
3. Then cut them. Make sure you select the two objects in the correct order. First, select the object that shall be the cutter, then the object which shall be cut. As a result, you should get a nice and comfy couch.



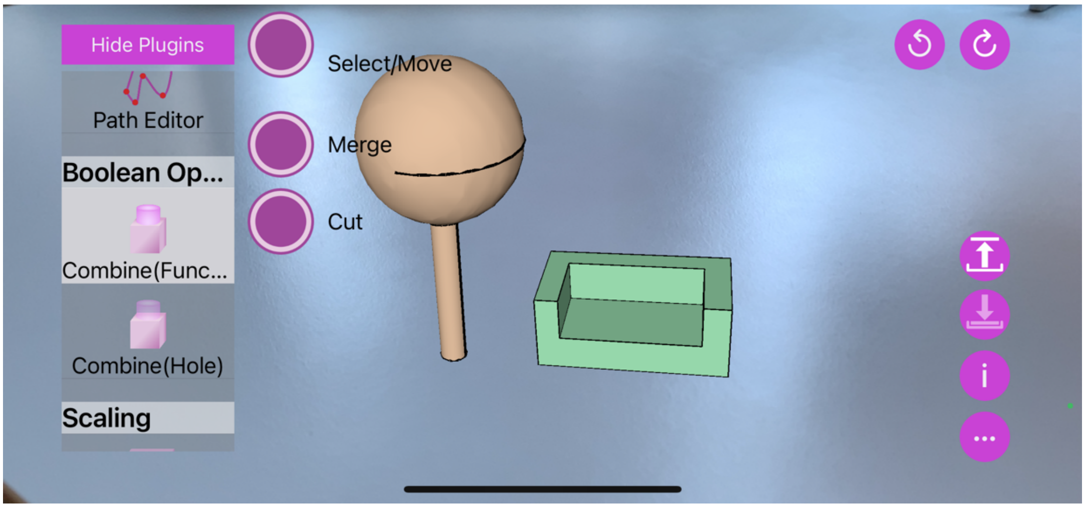
Task 3 – “Judge me by my size, do you?”

Description:

“What’s this? The couch is way too big in comparison to the tree. Either you have giants as guests, or you need to shrink down that couch. Get on the task!”

Steps:

1. Compare the couch to the tree and think about an excellent ratio between the two.
2. Under the category “Scaling” you will find the plugin “Scaling (Pen Ray)”. Select the plugin and scale down your couch, so it fits beside the tree.



End Day 1

REMINDER: Please share the scene with me (instructions above)

Day 2 – Modeling Operations I

Task No	Difficulty level	Plugins used
Task 1	Medium	Sweep (2 Profiles)
Task 2	Medium	Extrude, Combine (Function)
Task 3	Easy	Draw

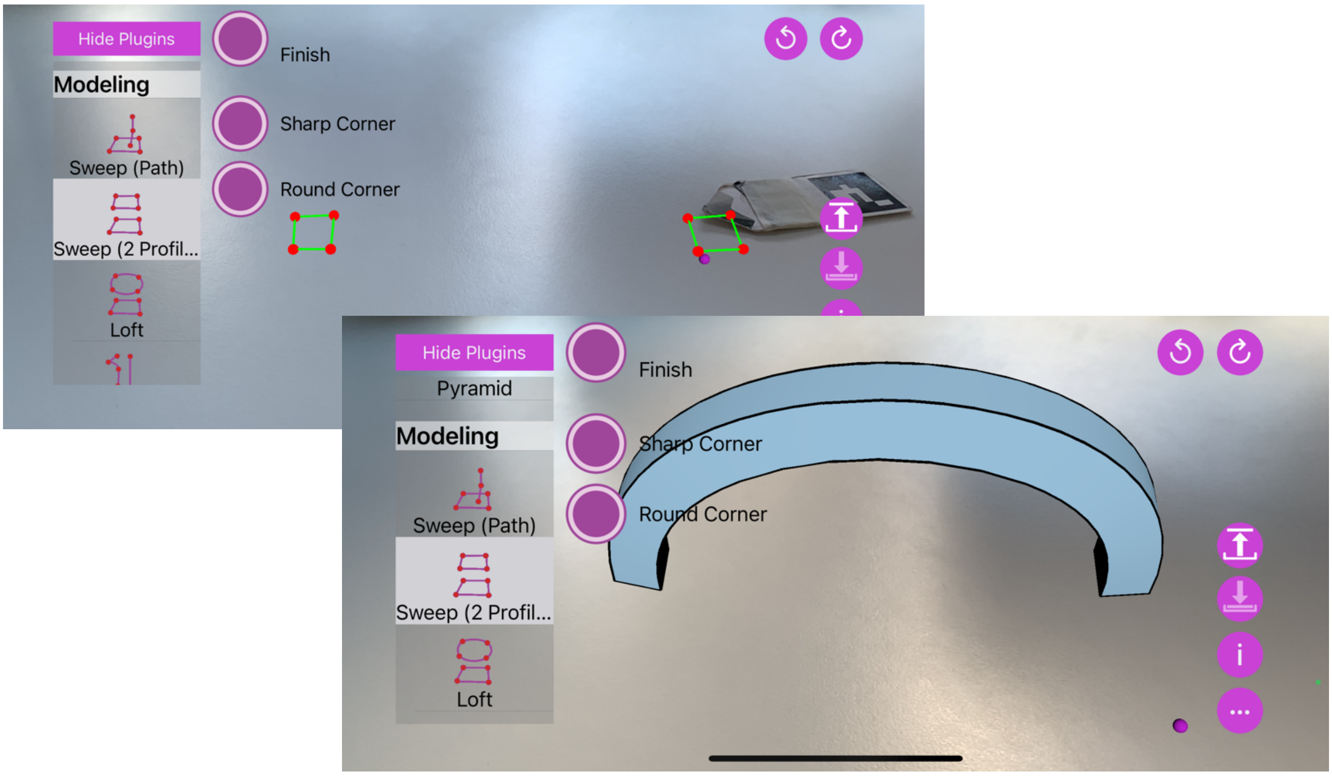
Tip: If you are unhappy with the result at any point, you can use the “Path Editor” (WIP) plugin and change nodes on the path!

Task 1 – Entrance

Description:
“To blow your guests away, you want to have a fancy entrance gate to your party! A nice bow would be the perfect fit for that. Once again, you rely on your amazing powers to get the job done.”

Steps:

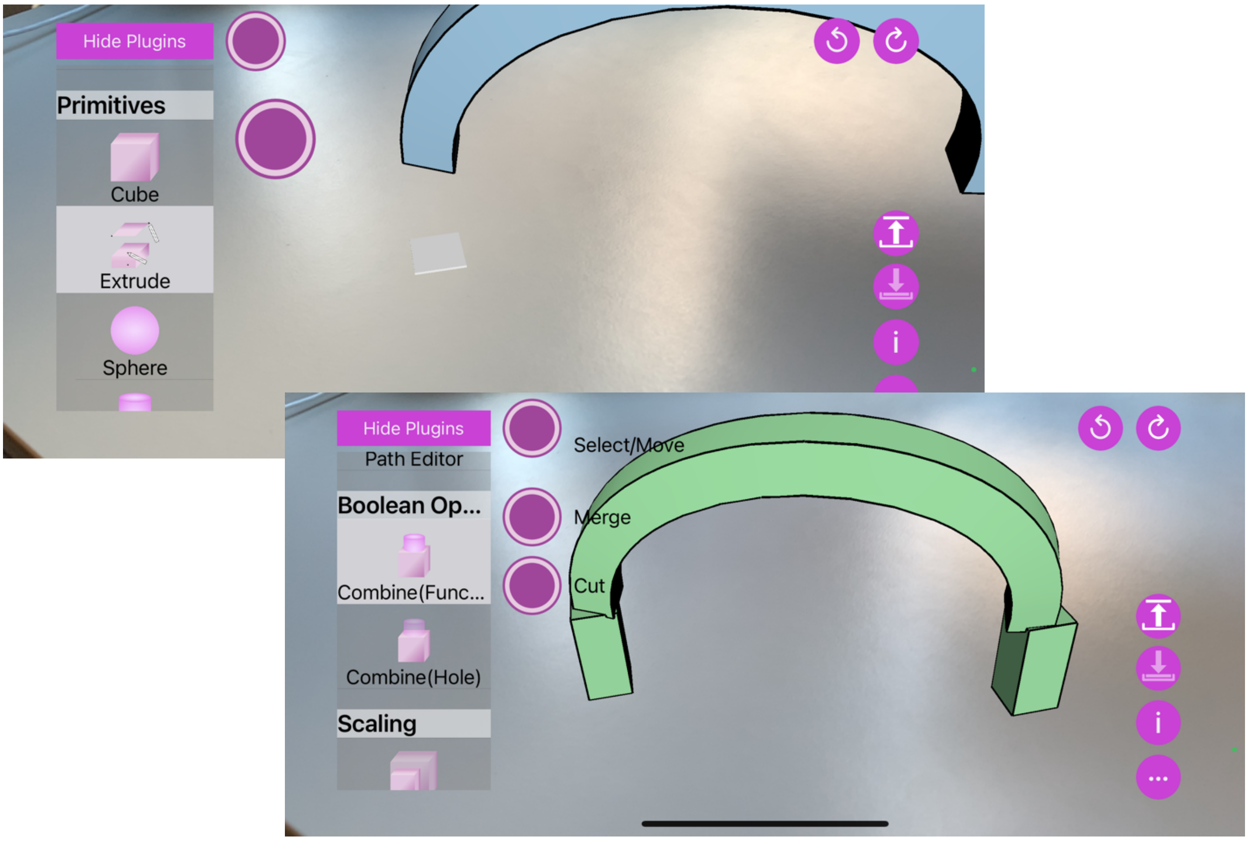
1. Under the category “Modeling”, select the Plugin “Sweep (2 Profiles)”.
2. Draw a sharp profile (not too big!). A profile is a closed path - indicated by the green color.
3. Draw a second profile that is aligned to the right so that the sweep will make a bow.



Task 2 – Entrance Contd.

Description:
"That gate sits a little low. Use your extruding powers to build two pedestals to raise it high enough!"

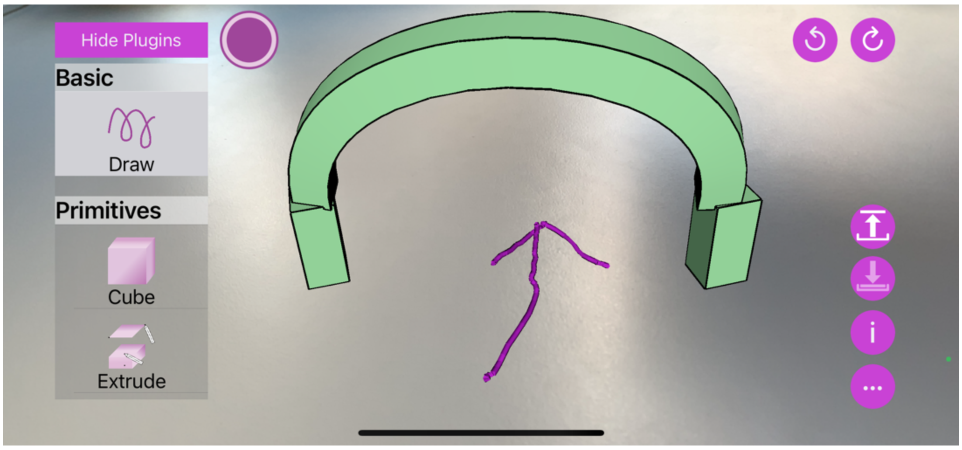
Steps:
1. Translate the bow with "Combine (Plugin)" up along the y-axis a little bit.
2. Under the category "Primitives" you will find the plugin "Extrude". Use it to create a plane first and then extrude it up so it touches the bow.
3. Then use the "Combine (Plugin)" to arrange the pedestals and the gate to fit together and combine/merge them!



Task 3 - Arrow

Description:
"To help your guests manage to find the way, you really need to set up some signs!"

Steps:
1. Search for the plugin "Draw"
2. Press and hold to draw an arrow alongside your gate!



End Day 2

REMINDER: Please share the scene with me (instructions above)

Day 3 – Modeling Operations II

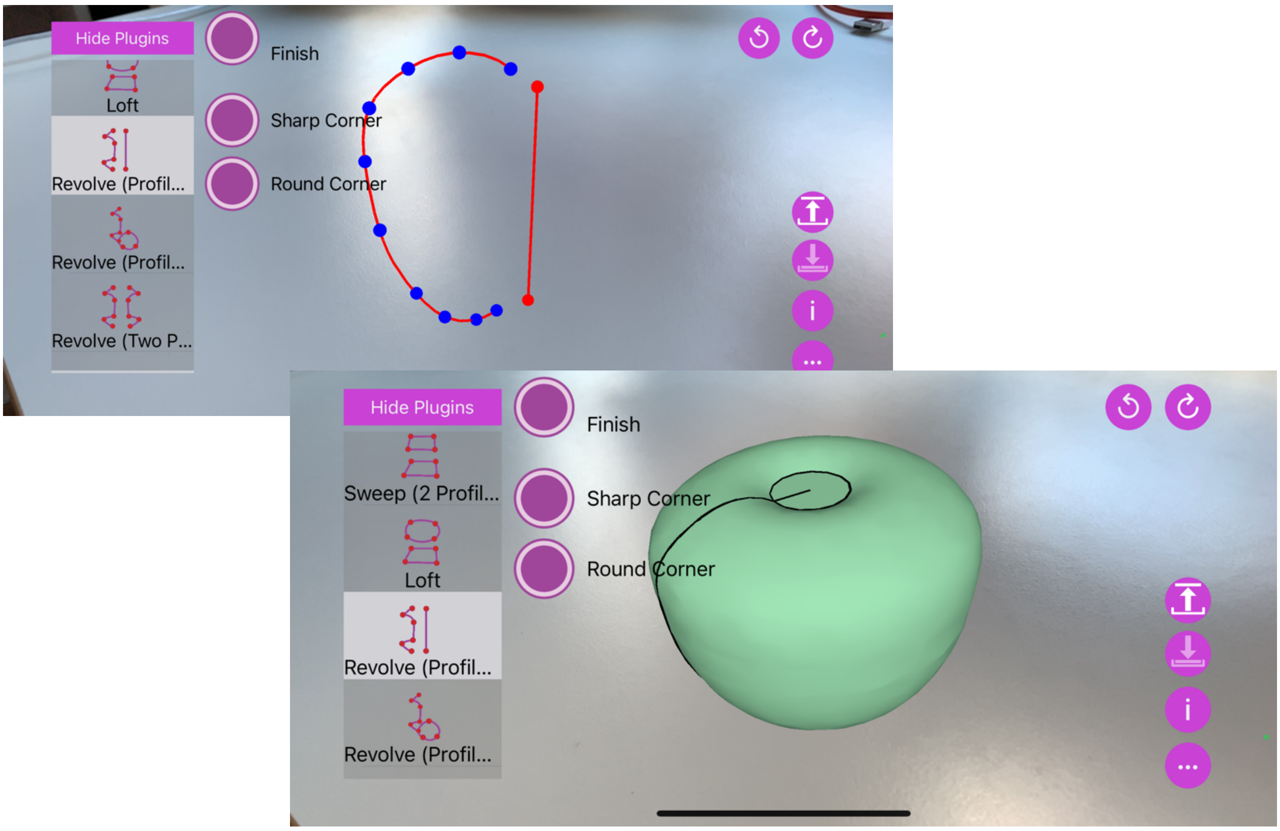
Task No	Difficulty level	Plugins used
Task 1	Medium	Revolve (Profile + Axis)
Task 2	Easy	Cylinder
Task 3	Medium	Sweep (Profile + Path)
Task 4	Medium	Rotate (Device), Combine (Function)

Task 1 - Apple

Description:
“Seems like your guests are hungry! To be a good host you should definitely consider handing out healthy snacks. You know the usual saying: »An apple a day keeps the doctor away! «. Use your enormous talent, to create a nice apple!

Steps:

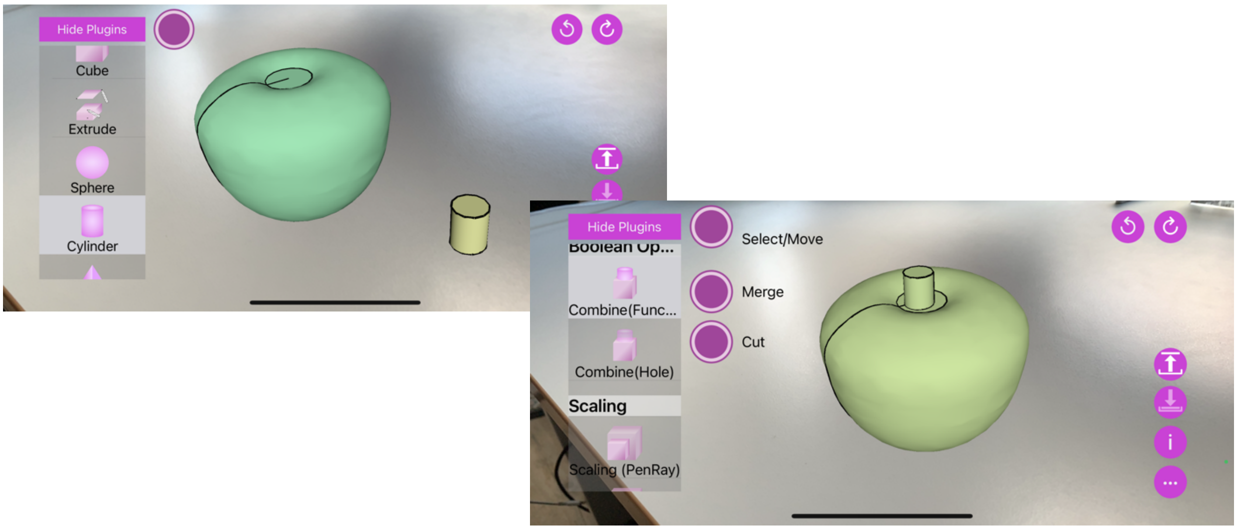
1. Under the category “Modeling” you will find the plugin “Revolve (Profile + Axis)”.
2. Create the axis! Ideally you select to sharp corners to create an axis around which the profile will revolve.
3. Draw a revolve which looks similar to the silhouette of a halved apple!
4. Add a small cylinder to the scene, translate it to the top, and combine the objects!



Task 2 – Apple contd.

Description:
“Add a small stem to your apple, to get that fresh look!”

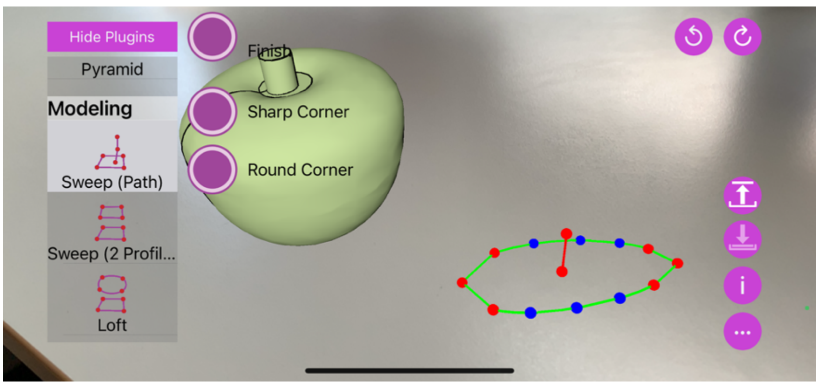
Steps:
1. Form a small cylinder with the “Cylinder” plugin.
2. Use the “Combine (Function)” plugin to combine the stem with the apple



Task 3 – Apple contd.

Description:
“To make your apple look like it’s straight from the field, you decide to also add a small leave!

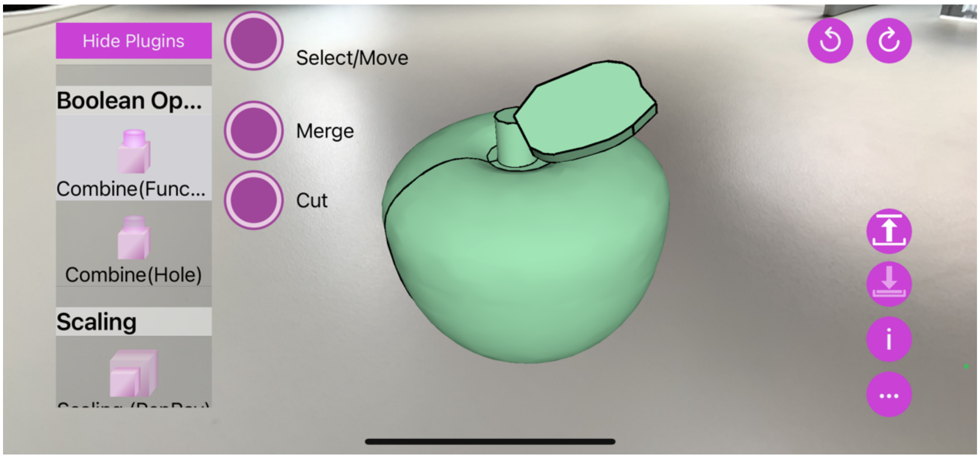
Steps:
1. Under the category “Modeling”, select the plugin “Sweep (Path)”.
2. Form a profile that looks somewhat like a leave!
3. Then build a path (not too high!) after which the profile will be swept!



Task 4 – Apple contd.

Description:
"After modeling your leave, you need to rotate and arrange it, so it fits to the apple!"

Steps:
1. Under the category "Rotation" you will find plugin "Rotation (Device)". Select the plugin and start rotating the object!
2. Then again use the "Combine (Function)" plugin to combine the apple with the leave!



End Day 3

REMINDER: Please share the scene with me (instructions above)

Day 4 – Existing Objects

Task No	Difficulty level	Plugins used
Task 1	HARD	?

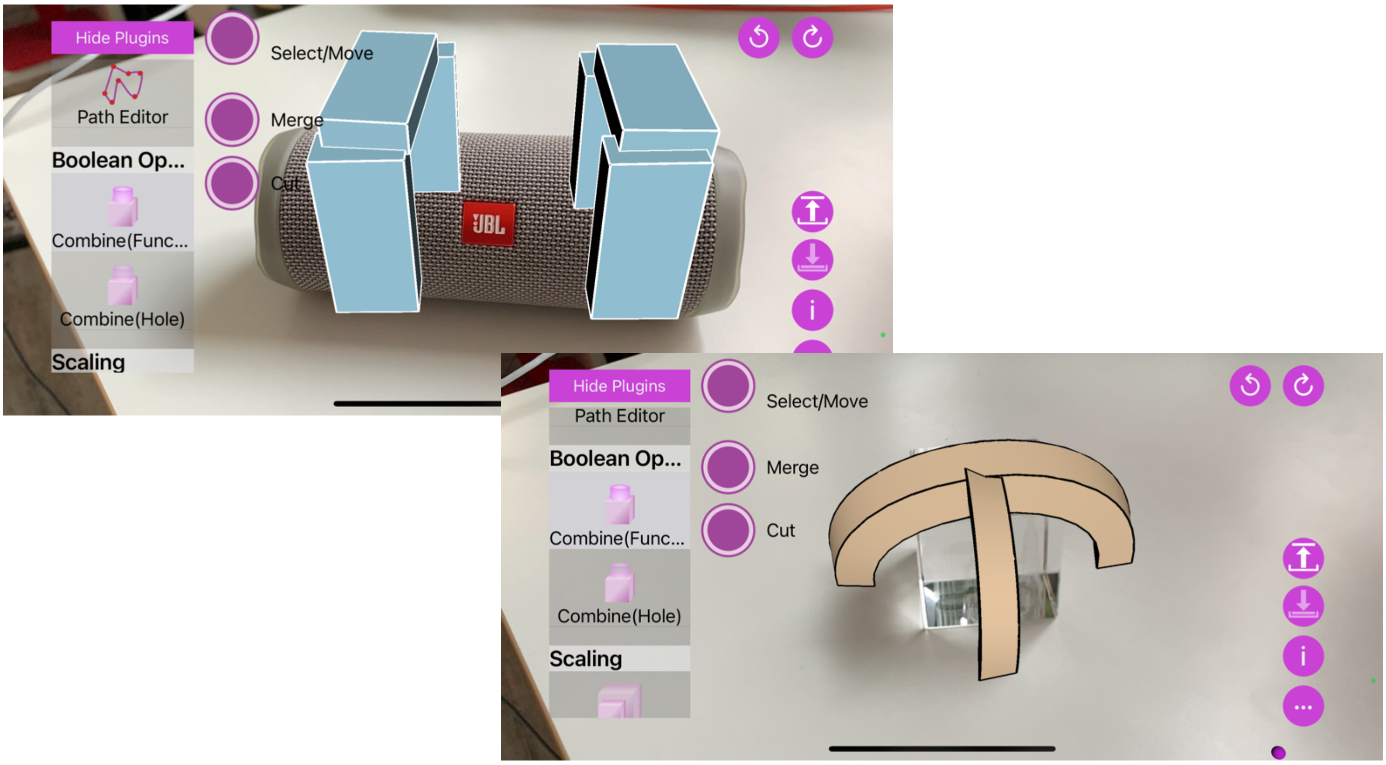
Task

Description:

"Oh no – you have been hacked and cannot see what the task is about. Wait – there is a message coming through! The hacker is trying to steal objects on your desk
You better secure your inventory with your newly learned powers."

Steps:

1. Some inspiration is given in the photos below, but please be creative!



End Day 4

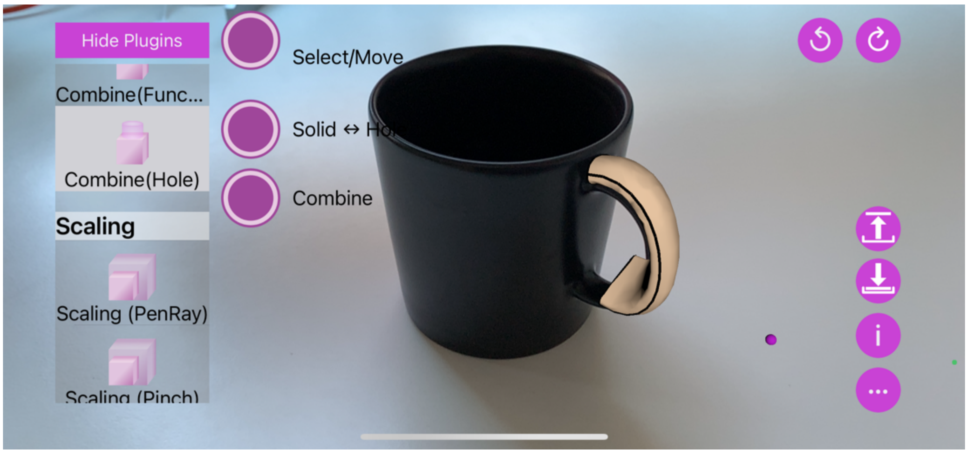
REMINDER: Please share the scene with me (instructions above)

Day 5 – Free Day

Task

Description:
This day is just meant you being creative. Draw your name, model a drawer, go back and do a task, use the plugins you never used and so on!

A Simple Inspiration:



End Day 5

REMINDER: Please share the scene with me (instructions above)

B.4 Concepts and Categories

The following pages show a complete list of all concepts and themes that emerged during the analysis. Themes (light blue) contain concepts (purple). If a concept has no parent theme, we chose to look at it independently as a theme.

- **Codesystem** — 686
  - Perception Problems affect Modeling Experience — 0
    - Perception Problems — 66
    - User Suggestions for Perception Problems Improvement — 19
    - Getting occluded by real objects — 7
  - Usability Problems with "node-based" M.Techs. — 0
    - Users' need for Previzualization for complex M.Techs. — 3
    - "Revolve(Profile+Circle)" Usage Difficult — 3
    - "Revolve(Profile+Path)" Usage Difficulties — 6
    - "Sweep(TwoProfiles)" Usage Difficulties — 8
    - "Revolve(TwoProfiles)" Usage Difficult — 8
    - "Sweep(Path)" Usage Difficulties - Bug — 11
    - Mismatch between intended Output and received Output — 18
    - Users shy away from more complex M.Techs. — 19
  - Problems with Understanding "node-based" M.Techs. — 0
    - Improving "Instructions" by playing a Video — 4
    - "Instructions" Feature has mixed Usefullness — 13
    - Users did not understand all M.Techs — 52
  - Positive Feedback for "non node-based" M.Techs. — 0
    - "Primitives" Feature Positive Feedback — 65
    - Users tend to enjoy "Extrude" — 3
  - Holding the Phone with one Hand is hard and painful — 0
    - Bi-Manual Use is hard — 18
    - Pinkie Grasp does not work and results in pain — 44
  - No User Confidence in Precision — 0
    - Precision Problems — 29
    - "Mid-Air" Use Problems — 17
    - User Suggestions for Precision Problems Improvement — 6
  - UI Usability and Effectiveness Problems — 0
    - Constantly switching Plug-Ins is exhausting and Suggestions — 7
    - UI Understanding Suggestions — 20
    - UI Reachability Suggestions — 21
  - ARPen's Difficulty level — 0
    - Users have mixed reactions to difficulty of App — 11
    - Users need Learning Period with App — 20
  - Tracking Problems — 0
    - Moving Coordinate System Bug — 11
    - QR Code Tracking Problems — 17
  - General Impressions of the App — 27
  - Users Trust in and Suggestions for Undo/Redo — 0
    - "Undo/Redo" Suggestions for Improvement — 6

"Undo/Redo" Positive Feedback	8
Users need Features to work around "Undo" History	11
Mixed User Feelings about all Types of Rotation	0
"PenRotation" Usage Difficulties	3
"Touch Screen Rotation" preferred over "DDR"	4
"TouchScreen Rotation" was not satisfying in use	2
Mostly negative reaction to DirectDeviceRotation	13
Multiple-Select-based-PlugIns Usability Problems	0
"Combine" Select is tricky	11
"Translation" Multiple Select Is Frustrating	9
Positive Feedback for "node-based" M.Techs.	0
"Revolve(Profile+Path)" Positive Feedback	2
"Sweep(Path)" Positive Feedback	14
"Sweep(TwoProfiles)" Positive Feedback	2
User Feedback and Suggestions for Features for working with ...	0
"Combine" General Positive Feedback	12
Difficulties working with already created 3D Models	5
Application Performance	14
Additional Manipulation Features	0
"Scaling" Positive Feedback	1
Users' Suggestions for Object Editor/Non Uniform Scaling	10
Pen-based interactions were preferred	0
Not all Interaction Ways were used and Pen was favorite	3
"PenRay" is Favorite Interaction For "Scaling"	3

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