Eliciting User Gestures for the Interaction with a Pen-Based 3D Modeling Device

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Abstract

In the past couple of years the cost of 3D printing fell constantly so it became affordable for a more diverse user group. A problem that still remains is the creation of 3D models without 3D modeling software knowledge. A device called iWand aims to address this issue. The motions of the pen-like device are tracked and translated into a 3D model. In this thesis, a user study will be conducted in which the behavior and gestures of the users are observed while they solve a task using the iWand. Also, a survey will be performed in order to find and categorize the objects that users want to recreate and augment with 3D printing technology. This study will elicit useful, easy to remember gestures for the device, which will make interaction more natural and user friendly.

Überblick

Innerhalb der letzten Jahre fielen die Kosten des 3D Druckens immer weiter, sodass die Technologie für eine größere Nutzergruppe erreichbar wurde. Ein Problem, das dennoch besteht, ist das Erschaffen von 3D Modellen ohne den Umgang von 3D Modellierungssoftware zu beherrschen. Ein Gerät, genannt iWand, soll diesen Umstand ändern. Die Bewegungen des stiftartigen Geräts werden aufgenommen und in ein 3D Modell übersetzt. In dieser Arbeit wird eine Nutzerstudie durchgeführt, in der das Verhalten und die Gesten der Nutzer beobachtet werden während sie den iWand zum Lösen einer Aufgabe benutzen. Darüberhinaus wird eine Erhebung durchgeführt, um Arten und Kategorien von Gegenständen herauszufinden, die Nutzer mit Hilfe von 3D Druck Technologien erschaffen oder augmentieren möchten. Diese Studie wird hilfreiche, für den Nutzer einfach zu erinnernde Gesten für das Gerät hervorbringen, um die Interaktion natürlicher und nutzerfreundlicher zu gestalten.

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Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition: *Excursus*

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in American English.

Download links are set off in coloured boxes.

File: myFile[a]

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

Chapter 1

Introduction

While new technology gets cheaper and high functional devices are brought onto the market, companies put research into Natural User Interfaces (NUIs) to bring users new experiences. The goal of these NUIs is to make the interface completely invisible to the user, which leads to intuitive, easy-to-use controls.

Natural User Interfaces give users a new way of interacting with technology.

While some researchers argue that NUIs are not as natural because using them properly must still be learned [Norman, 2010], it is common consensus that these interfaces do provide a more immersive user experience than common mouse and keyboard desktop environments. Most devices still have the so called WIMP-paradigm as their default input and interaction model. The abbreviation WIMP stands for "Windows", "Icons", "Menus", "Pointer" and refers to the dominant design paradigm of Graphical User Interfaces that has been popularized in the 80s with the Apple MacIntosh and Windows OS. Smartphones, tablets and other devices with multi-touchscreens are gradually designed for letting the user explore different kinds of interaction in the form of gestures, still, often just as an additional optional feature. There are also researches and developments that give the backside of the phone a new surface such that it is sensitive to user touch and tap motions Shimon et al. [2015].

3D printing, also known as additive manufacturing, was first invented by Hideo Kodama in 1981 Kodama [April

3D printers prices dropped dramatically and became popular with private users.

1981]. Different techniques were developed and commercialized. However, it took until the early 2000 to become popular with open source hardware development communities. In these communities customization is a great part, so printers go through a lot of development levels. After 2010, 3D printers had a dramatic price drop and therefore paved a way for printers in private homes and other non-commercial groups of users. For example, some machines cost 20,000 USD in 2010, the same one costs about 1,000 USD in 2013. Today a 3D printer that fits any desktop can be easily ordered on the market starting from 400 USD, an example is shown in Figure 1.1. There are already 3D printers in the form of pens at 30 USD.

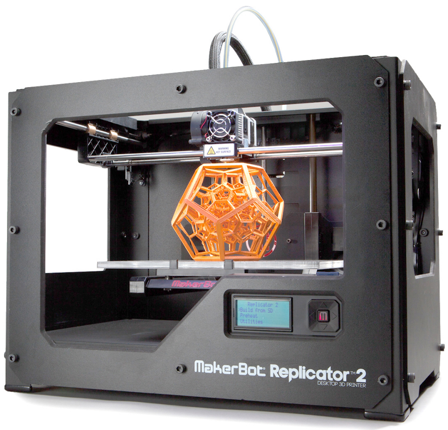

Figure 1.1: A MakerBot Replicator 2. One of many desktop 3D printer available on the market. Source: Tageswoche.ch [2017]

The technical realization of 3D printing makes use of a continuous line of thermoplastic, which adds up to several layers of an object. In printers using this technique, the material is molten by a heated printer head and is forced through the nozzle on top of the printing space. A layer of thermoplastic usually solidifies quickly once it is in contact with the workspace or with another layer but for other materials the printer might have to idle for a short duration to allow the material to solidify.

Creating a model is an obstacle in making full use of a 3D printer.

In order to employ a 3D printer, a 3D model is required. That means a mathematical representation of the object that is to be printed. Usually, 3D models are created either by scanning or by 3D modeling software. It still remains a universal task to construct these mathematical representations. First, 3D scans can already be made with actual smartphones. However, the objects that are recreated are limited to objects already existing. In the case of modeling a new object, the user is restricted to 3D software tools. This software, however, is usually very complex for unexperienced users. Hence, these softwares suffer under a steep learning process.

A pen-based device lets users create models without knowing much about modeling software.

To solve this issue, a new pen-based device named iWand is a promising solution. Due to its pen-like shape users will find holding it to be familiar. The function of the device is to track the users movements and translate them into a 3D model. The advantage of such a device is that it can be used in two different ways: first, the user can use it in a similar way to a 3D scanner. When tracing the outlines of objects they can simply recreate them. Second, users can draw out lines in thin air and therefore either augment already existing objects or create completely new ones. The pen is tracked in a predefined field by cameras that define the point of movement by millimeters. Since the field of tracking is fixed by the cameras, the problem of controlling the pen arises. This delivers two options: using the pen in parallel to other input devices or make the pen a standalone input device.

Controlling the iWand with gestures proves to be intuitive.

In the first option users have to use their usual PC input devices, mouse and keyboard, in addition to the pen. However, this leads to several problems: the user is limited in creating a tracking space for the iWand, as other input devices must be in close proximity. The user has to switch between these devices to use atomic functions. This is on the one hand time consuming, on the other a clunky and unnatural way of using a pen and does not lead the user far from usual modeling software. The other option is to develop the pen itself as an input device. 2D modeling pens are already established on the market, however, those pens usually have buttons on them and rely on a tablet or a drawing board as an additional piece of hardware underneath to send input.

The goal of this thesis is to elicit gestures for the control of the iWand in a most intuitive manner. This is achieved by a user study where participants' gestures are analyzed while using a mock-up of the device. To do this elicitation study, it needs to be evaluated what objects are relevant for everyday 3D printing projects. A survey needs to be done to identify some of these objects and to integrate them into the final user study.

The structure of this thesis is as follows:
Chapter two is a review of the state of the art of 3D modeling in general and gesture elicitation.
Chapter three describes the survey on publicly available 3D models.
Chapter four is used for describing the following user study to elicit gestures.
Chapter five present the results of the study in an analyzation, followed by a brief discussion.
Chapter six concludes the thesis by summarizing it and giving an outlook of future work.

Chapter 2

Related work

The focus of this thesis lies on eliciting gestures for a modeling device that can be used in 3D space. Consequently, the reviewed divisions of research we are interested in include projects that elicited gestures for various input methods. Research on gesture control has been done with input devices or free hand gestures. In the following chapter elicitation studies and limitations are presented.

Focus was laid on elicitation research.

Most user studies eliciting gestures in correlation to Human Computer Interaction are based on the elicitation study Wobbrock et al. conducted in 2009 [Wobbrock et al., 2009]. The aim of the study is to find user defined gestures for a surface controlled computer. So called referents, i.e. effects, are shown to the participants who are then asked to produce a sign, i.e. the cause, of this effect. In contrast to testing prototypes, participants do not get feedback to their actions in these studies. This way of proceeding lets the researchers discover gestures that users spontaneously perform while using a particular technology, in contrast to having a set of gestures that is made up by professionals in the Human Computer Interaction (HCI) department. The researchers also present the advantage of this approach in their results: while the researchers designed their own set of gestures, only 60% of user gestures were covered. This means that the incorporation of a higher number of users also increases the amount of gestures and therefore possibilities elicited. The agreement rate between the gestures

Guessability studies let users propose a set of gestures for a given set of referents.

suggested is computed by:

$$A = \sum_{r \in R} \sum_{P_i \subseteq P_r} \frac{\left(\frac{|P_i|}{|P_r|}\right)^2}{|R|} \tag{2.1}$$

where R is the set of all referents, and r a single one. P_r represents the set of all gestures made by users to a referent and P_i is the subset of identical gestures. This formula computes an agreement rate A between 1 and 0, where 1 indicates 100% consensus between all participants and 0 indicates none. In addition to letting participants decide on which gestures they think fits an effect, they also reversed this procedure. Hence, users were shown a gesture and its effect, but should now rate this gesture in terms of usability and easiness to perform.

Giving users more freedom in defining system behavior also increased their creativity with gestures.

In Gesturing on the Steering Wheel: a User-elicited taxonomy [Angelini et al., 2014] researchers explored how users performed gestures on an object to control the radio in their cars. Angelini et al. especially looked into how interfaces of touch devices influenced the gestures. For their elicitation study, they divided the participants into two groups: group one was asked to perform gestures for a set of given commands, while group two was asked to perform gestures and define the system behavior themselves. In their analysis they found that users of group two performed a more diverse set of gestures and had more variability in which body parts they used.

Piumsomboon et al. did a elicitation study on gestures used for Augmented Reality [Piumsomboon et al., 2013]. This work goes beyond the previous studies because instead of using 2D surfaces, users could now use more dimensions to create gestures. The researches found that even with empty hands, users preferred one handed gestures and used their non-dominant hand mainly for static gestures. Overall, this setup allowed participants to perform more expressive movements. Their gestures became in some cases more of symbolic real-life gestures, such as thumbs up for the *accept*-function, and derived further from imitations of popular Graphical User Interface (GUI) gestures. Another fact they found out was that users were irritated by their own hands occluding the object they were currently interacting with, so they proposed translucent hands or visible outlines of the object to prevent this phenomenon.

Even natural interfaces need to be learned.

Even though users are accepting Natural Interfaces, Norman warns developers of not overusing it in his article *Natural User Interfaces Are Not Natural* [Norman, 2010]. He argues that GUIs have the advantage of providing visibility of the systems' functions by menus and icons. Therefore, users can learn and explore a system easily. Interfaces that only support gesture input do not give tracing feedback of perceived movements, so users have a harder time recognizing their mistakes and adapting their gestures. Norman proposed that a lot of gesture input is going to be standardized either by formal standards body or by convention. Standardized gestures can already be seen today on touchscreen devices, for example a swipe to the left or right for the next and last page respectively.

Users are biased by the technology they already know well.

When conducting an elicitation study, most researches note that participants are highly biased by technology they already use, especially the WIMP paradigm which is still a standard on PCs. Users form their new mental model with the help of already existing models of similar things. Morris et al. [Morris et al., 2014] introduced techniques with which the creativity of users is increased in relation to eliciting gestures and interaction with new devices and interfaces. In total, three techniques are proposed:

- Production: The number of gestures the user performs should be increased, such that they surpass the standard gestures of technology already known.
- Priming: Priming techniques are used in order to let the user think more generally of a technology and expand the overall conception on the solvability of tasks. Priming techniques include e.g. watching videos of other people performing gestures, seeing gestures created by designers and performing tasks with physical objects.
- Partners: ongoing studies with pairs of participants can greatly increase the quality of gestures. Participants would often adapt each others ideas; another

approach is to let participants play games like Charade to increase intuitiveness of proposed gestures.

Chapter 3

Identifying Popular 3D Models: A Survey

This chapter deals with the survey that was conducted to find relevant objects for gesture elicitation. First, the goal and procedure will be introduced. Second, the results of the evaluation and the objects which were chosen for the user study are presented.

3.1 Goal and Procedure

Popular websites for sharing 3D models were analyzed.

The survey was conducted to find relevant objects for the user study and to find out which objects users want to create or augment with 3D printing technology. The Internet provided a variety of online resources where users can share their 3D printing models. The first step was to find websites that are popular.

A closer look was taken at the following websites:
`www.thingiverse.com`
`www.youmagine.com`
`www.cgtrader.com`
`www.myminifactory.com`
`www.123dapp.com`
`www.pinshape.com`

www.grabcads.com

The websites have a various range of models.

These websites have different areas of focus:
Thingiverse is the largest and most popular website and has a great variety of objects in most categories.
Almost half of Youmagine's most popular objects are for printing or modifying parts of a 3D printer.
CGtrader hosts a shop that offers mostly accessories, fashion and art & decoration.
123dapp is operated by Autodesk, a corporation that is famous for 3D modeling software like Maya. It offers models that show famous characters, art and food. The unusual about this site is that users can scan an object with Autodesk's app and share those scans directly on the website.
Myminifactory offers busts & miniatures, costumes & props and accessories. They even have a separated shop for printed jewelery.
Similar to Youmagine's variety is GrabCAD's offer in various 3D printer, electronic and mechanic parts and objects.

Analyzation is focused on two websites which provided enough data.

Even though there are a lot of websites that offer 3D models for download, a lot of them do not provide any functionality to sort the objects in reference to popularity, number of downloads or makes. Makes is feedback provided by users when they printed an object. Often, no specific numbers about views or downloads are provided. This is especially the case if the offered models are not free but need to be paid for. This circumstance made it difficult to compare data. Furthermore, the number of makes relies on users to report back on the website. The number of makes often was significantly lower than the number of downloads. However, downloads and likes are very similar and did not make a difference when looking at a bigger set of data. The two websites that offered enough data to sort and compare objects were thingiverse.com and youmagine.com. This is why the analyzation of objects is focused on these sites only.

For the analyzation the first 100 objects that showed up when sorting every available model by popularity, i.e. number of likes, were considered. Other data that was included in the survey include: number of downloads, number of makes, object title, semantic category and utilization,

Table 3.1: The roughly 100 most popular items sorted by semantic category of the 3D printing model websites `www.thingiverse.com` and `www.youmagine.com`

Category	Thingiverse	Youmagine	Total	Percentage
3D printing & parts	7	47	54	26.6%
Accessories	3	3	6	3.0%
Costumes	4	1	5	2.5%
Decor	15	9	24	11.8%
Electronics	7	3	10	4.9%
Gadgets	5	5	10	4.9%
Games	2	0	2	1.0%
Household	7	14	21	10.3%
Organization & Storage	18	4	22	10.8%
Parts	3	0	3	1.5%
Tools	8	2	10	4.9%
Toys	20	15	35	17.2%
Sports & Outdoors	1	0	1	0.5%

i.e. relation of the object to other objects.

3.2 Results

After the data has been collected, the first thing that was noticeable, was that a lot of objects offered are 3D printer parts. Nearly half of all objects on `youmagine.com` fall into this category. Even with only seven items of this category on `thingiverse.com`, this category is still the biggest one, making up nearly 27% of all objects. Since users should be able to take part in the study even if they are not experienced with 3D printing, it has been decided to leave the objects of this group out of further inspection. Participants should recreate things they are already familiar with, therefore objects are needed that users see in their everyday lives.

The category of 3D printer parts has been left out of the analysis.

The semantic categories apart from 3D printing parts provided four semantic categories that had a higher amount of objects than the others: *toys*, *decor*, *organization & stor-*

The most popular items are toys and objects that are complete on their own.

Table 3.2: Top 100 objects without 3D printing parts categorized by their relation to other objects and usage.

Category	Thingiverse	Youmagine	Total	Percentage
Standalone	57	32	89	59%
Attachment	7	4	11	7%
Wrap-around	7	5	12	8%
Storage	19	13	32	21%
Insertion	1	0	1	<1%
Underlay	4	2	6	4%

age and *household*. A complete list of categories and objects is referenced in Table 3.1. This provided some insights into users' interests. However, it was not enough information to choose the objects for this thesis. Second, objects were analyzed in respect to their relations to other objects. About 60% of all objects were stand alone items, i.e. they were complete on their own. Followed by storage items which made up nearly 21%. A complete list of these categories can be found in Table 3.2.

Three items were chosen originally and two additionally after a pilot study.

The first three objects that were chosen for the user study are a toy boat, a box with a drawer and a wrench.

Figure 3.1: A toy boat that participants were supposed to model in the user study. Source: Air3 Blog

The toy boat, which is shown in Figure 3.1 was chosen because it represents popular categories: a standalone toy. Its form is rather complex and lets people use a variety of gestures when modeling. Even though the box with a drawer seems to be a standalone object, it consists of two separate items whose size must be considered. While the form is rather simple, it offers a chance to observe users modeling with precision. The picture that has been used in the user study is shown in Figure 3.2. The category of tools was not

Figure 3.2: The second object that was decided on for the user study: a box with a drawer. Source: Stabilo-Fachmarkt.de [2017].

very popular. However, the wrench as a single object was. It showed up in the all time popular top 10 of both websites. With a bolt as a real object, users need to create an item that fits tightly around another one. The picture of a wrench that was shown to users as a reference is depicted in Figure 3.3.

After a pilot study, described in chapter 5, there were two other objects added to the tasks. First, a sphere, since there were no round surfaces in the aforementioned objects. The second one was a single drawer that was supposed to fit inside a box which was presented as a real objects to the users during a task. With this task, we have a second item that users need to interact with to create a 3D model. This time however, participants need to model something that fits into it, rather than around.

Figure 3.3: The picture of a wrench that was used in the study. Source: wgb-werkzeuge.de [2017]

Chapter 4

Gesture Elicitation for the iWand: A user study

In this section the user study will be described in several steps: first the tasks and the overall procedure will be introduced. Then the changed after a pilot study will be described.

4.1 Procedure and Tasks

Participants were asked to create models of objects with a pen. Afterwards, they were interviewed.

Participants took part in the study individually. They sat at a desk with a camera facing to the front, slightly opposite of their main hand. Overall, there were five tasks participants were supposed to solve individually, i.e. objects they should create 3D models for. The objects include: a wrench, a drawer with a fitting box, a drawer that should fit into a given box, a sphere and a toy boat, shown in Chapter 3.2. After the purpose of the study was introduced to the participants and all their questions answered, they were given a picture of one object at a time and were then asked to create a 3D model with a pen that was supposed to represent the iWand. The objects were given in a random sequence to each participant. While performing on the tasks, participants were encouraged to think aloud. After each task when participants signified they have finished, they were asked questions to clarify gestures and approaches. Frequently, in the discussion it was required to remind them of parts of the objects they might have forgotten to create, especially if those parts require a special nuclear function to be used, e.g. creating windows for the cabin of the boat. After all tasks had been finished all objects were shown to the users again. During the review the participants were asked if they would do something different in the modeling process, because they are more experienced with the procedure. Finally, participants were interviewed in regard to statistical data and their knowledge with 3D modeling and gesture control in general. In addition, they were also questioned about their experience while doing the given tasks.

4.2 Pilot Study

After the pilot study, two tasks were added to the study.

After getting the procedure and setup worked out a pilot study was conducted with one participant. This lead to a few improvement in the procedure and tasks: a sphere was added as an additional task, because flat surfaces were predominant in the objects so far. Also, the task with the drawer has been expanded to a second part. Here, participants were supposed to create an extra drawer for a box which is presented as a real object, shown in Figure 4.1. Hence, they also need to solve a task in which they had to model an object fitting into another.

Figure 4.1: Participants were asked to create a drawer that fits this box.

Chapter 5

Evaluation

After finishing the user study, about 370 minutes of video material has been analyzed. This leads to an average time of 15-20 minutes per session. However, the maximum session was 42 minutes and sessions below ten minutes are rare. First, the approaches to 3D modeling of users are described. Then the nuclear functions that were used are presented with their respective gestures, followed by a brief discussion.

5.1 Group composition

The majority of participants had an academic background.

In total, there were 20 participants that volunteered. Their ages range from 22 to 47 (M = 28.1, SD = 6.75, nine female). Twelve of them were students, mostly with a background of computer science, one physics. Four participants were research assistants in CS and physics departments. Other occupations include office clerk and financial policewoman. Only one participants was left handed. While nine participants reported to have experience with 3D modeling, only two of them considered to have advanced knowledge. Four participants already used a 3D printer at some point.

5.2 Modeling approaches

There are three distinct approaches to modeling an object that could be clearly distinguished between the users. In general, the tasks were solved by going from the base of the model to the upper part of the object, and from its outside to the inside.

Users drew freely into the air and on the desk.

Drawing in 3D space The most common approach, used by 17 users, was to simply draw everything in 3D space. Most users would use the desk as a surface from which they would go up and draw the rest of the model into the air. In this approach, some participants were hesitant to put their hand and the pen to a position which they saw as the inside of their imagined model and were careful to place their hands around it.

Users limited themselves either onto the table or a vertical field in the air.

Drawing in 2D space Another approach used by one participant consistently and by two other partially during the tasks was to draw the object in 2D space as they saw it on the pictures. They expected that the software would calculate e.g. the real depth of an object according to the perspective projection they had drawn out on the surface of the desk. Two users would change their approach to drawing in 3D space in their second task when they were confronted with real objects which were supposed to be augmented. This might distort the results a little in this case, because other users started with those real objects.

Users preferred predefined shapes and manipulation with functions.

Connection of primitives The third approach was more common with participants who already had experience with 3D modeling. User created a 2D shape and extrude it to get the desired 3D shape. They preferred to move these shapes around and use *add* and *substract* functions to get the final object. User who chose this approach tended to prefer predefined basic shapes to be selectable. This approach was used by two users and partly by another one.

5.3 Gestures

Each session is analyzed in regard to the gestures and corresponding meanings, e.g. nuclear functions, that participants intended. Overall, users created 155 different gestures. Those gestures were sorted into categories of their nuclear function. After the analyzation, 14 different nuclear functions could be categorized. Five of those functions were used by all participants, the remaining ones were used by six or less users.

Gestures are sorted into functional categories. Five basic functions were used by all participants in one or more ways.

Add edges Adding a line or an edge of an object in a free-hand drawing manner is the first nuclear function participants used. This was used by all users, some of them took more than one gesture to achieve this. A complete list of that division is shown in Table 5.1. The general approach was to mimic drawing with the tip of the pen either on the desk or into the air with the desired shape. This method is used by 19 of the 20 users. The other approach is to tip at a place to mark a point and then tip again at another place to mark a consecutive point. Users would assume that the software would automatically draw the line between those two points. One participant used this gesture consequently while three others used it partially.

Most users preferred to mimic drawing movements.

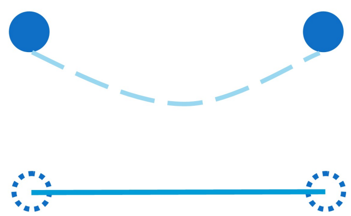

Figure 5.1: Illustration of setting points to create an edge. Users set two points by tapping and do an arbitrary movement between those points (top picture). Once the second point is determined, an edge is created between them.

Table 5.1: Gestures used to add edges to an object

Gesture	Used by # of users	Percentage	Agreement
Draw lines	19	83%	0.71
Set points	4	17%	

Table 5.2: Gestures used to create planes.

Gesture	Used by # of users	Percentage	Agreement
Automatic fill in	15	63%	0.43
Single tap	4	17%	
Hatching	3	12%	
Double tap	2	8%	

Most users expected automated filling of the inner side of their shape.

Create planes After creating edges for a shape, users created a complete, filled plane. While 75% of all participants expected the software to fill in automatically after a closed shape was created, four of them changed their gesture in the course of the session. Another way of filling the shapes three users came up with is to do a rough hatching gesture. Instead of putting the focus on the tip of the pen, users would hold it in a horizontal position for this gesture and center the edge of the pen. Tapping on a basic shape was a popular choice of doing a gesture. Here, there are three variants of the tapping movement used, each by two users: a single tap, a single tap while pushing a button located on the pen and a double-tap. An overview of the gestures is shown in Table 5.2.

While most users expect automated deletion, consensus on a single gesture could not be determined.

Delete parts This nuclear function is used to cut out partial shapes of a plane. Overall, users came up with 8 different gestures of executing this function. An overview is given in Table 5.3. The most common way was to draw a shape onto a plane and assume automatic deletion of the interior of the drawn shape. This was done by eight participants, all of them also came up with another way of achieving this. Five participants wanted to select a delete-function in either an additional software GUI or a button on the pen and draw the shape afterwards. Four users did a variant of the tap movement: three used a single tap and one user did a single tap while pushing a button on a pen.

Table 5.3: Gestures used to delete parts of an object.

Gesture	Used by # of users	Percentage	Agreement
Automatic	8	28%	
Select function & draw	5	17%	
Swipe	4	14%	
Punch	4	14%	0.17
Single tap	4	14%	
Redraw shape	3	10%	
X on shape	1	<1%	

A similar, yet distinct movement was made by four other users: they punched with the tip of the pen onto the shape. This movement stands out against the tap movement because participants used a bigger space to execute this gesture. While tapping only their hands or fingers moved onto the object and back again, for punching their arms helped with the movement and they considered the gesture done without moving back to the hands' starting position. This difference is illustrated in Figure 5.2. Four other participants made a swiping movement to any direction in order to delete a shape. Consistency with the direction of swiping could not be found. Another gesture three people used is to redraw the shape they wanted to delete two or three times. The least popular method done by one person was to draw a X onto the shape.

Extrude The extrude function participants used was supposed to pull a 2D shape they created into 3D space. When using this function participants expected the whole shape to have the same thickness at every point. Again, participants came up with multiple ways of executing this task, summarized in Table 5.4. Overall, there were three different kind of approaches. The first and most popular gesture was to select a point on the surface shape with the tip of the pen and hold it down for a short duration. Afterwards, they pulled into a direction until the desired thickness of the object is reached, as shown in Figure 5.3. This was done by 14 participants. Six other users would not use the pen for this function but rather set a variable in software that globally creates all planes with a thickness of e.g. 1cm. Finally, five users drew the same shape in the desired distance again

Most users thought about pulling a 2D shape into 3D space.

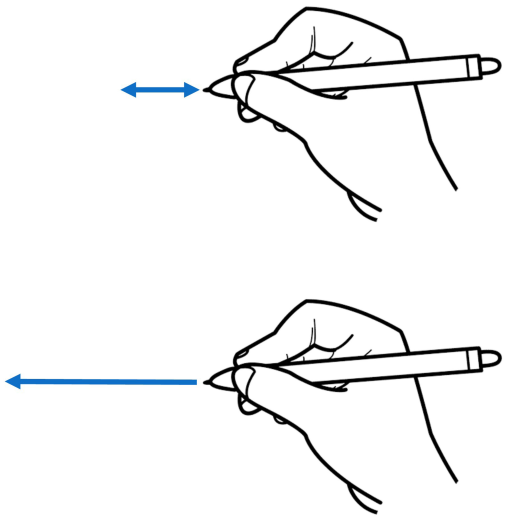

Figure 5.2: Illustration of tap (top) vs. punch (bottom) gestures. When tapping, users do a smaller movement and move the pen back to its origin position.

Table 5.4: Gestures used to extrude an object.

Gesture	Used by # of users	Percentage	Agreement
Tap & hold, move to desired distance	14	56%	
Select in software	6	24%	0.41
Draw same shape in distance	5	20%	

and expect the software to fill the gap.

Drawing two circles shifted by 90° was the solution used by most participants.

Create a sphere For this task, every participant came up with one solution. An overview is given in Table 5.5. In total, there are seven different gestures, but some of them are quite similar. The most popular one was to create one circle and then a second circle but shifted by 90°. Users would usually start with a circle whose surface faced them and add the other shifted in the y-axis. An illustration of this gesture is depicted in Figure 5.4. Variants of this approach were used by two other users who would draw multiple circles around the y-axis, and another user who drew three circles in all 3D planes. Four further users picked a ”create sphere” function in software but had different approaches of execution: three users would do a tap for the origin and draw a line for the radius, while one user would rather

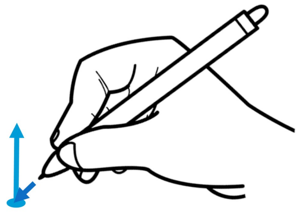

Figure 5.3: To extrude user tapped and hold onto a point of the object and pulled it into the desired position.

scale and move a predefined sphere by tapping and moving the pen to the desired size of the sphere. The other two users came up with unique gestures: one made a spiraling movement from bottom to the top of the sphere. The other one, who followed the 2D-drawing approach, would draw a circle and add some shadowing by doing a hatching gesture.

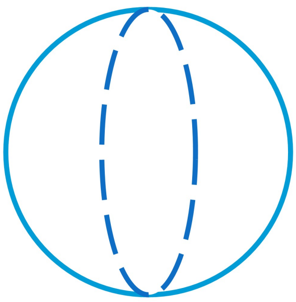

Figure 5.4: The most popular gesture for creating a sphere: drawing two circles in the air shifted by 90 degree.

Select an object This nuclear function was used by nine participants who created three different gestures, summarized in Table 5.6. When participants saw the object as selected and were finished with the gesture, they used functions in combination, e.g. move the object around or turn it. Six users made a single tap gesture. Two would push a

Users selected an object with a tap to apply additional transformations to it.

Table 5.5: Gestures used to create a sphere.

Gesture	Used by # of users	Percentage	Agreement
Two circles shifted by 90°	11	55%	
Tap for origin, line for radius	3	15%	
Circles in multiple planes	2	10%	
Circle in three planes	1	5%	0.35
Spiral	1	5%	
One circle with shadows	1	5%	
Pick function in software	1	5%	

button on the pen and the other person would select a tool in software to complete the task.

Table 5.6: Gestures used to select an object.

Gesture	Used by # of users	Percentage	Agreement
Single tap	6	66%	
Push button on pen	2	22%	0.51
Pick function in software	1	11%	

A few participants used the same approach as extruding an object.

Add curvature This function was used to subsequently add a curvature to an object or plane that was already extruded into 3D. Nevertheless, users did not specify the mathematical function or the amount of bending that was supposed to be applied. An overview is given in Table 5.7. Three users used a similar approach to extruding an object: they tapped onto one point of the shape and moved with the pen into the desired spot. The other user just drew the desired curvature multiple times while starting and ending the movements at the vertices of the edge which is supposed to bend.

Table 5.7: Gestures used to add curvature to a flat object.

Gesture	Used by # of users	Percentage	Agreement
Tap & hold, pull	3	66%	0.63
Multiple drawings of curve	1	25%	

Only a quarter of participants used this function.

Create new object related to another object This function was used by participants who split up their object into different parts and wanted to have space for a different part. This function did not delete the previous shape but rather put them to the side or some kind of buffer and can be retrieved at any time. In summary, five participants made use of this function and came up with two different gestures, summarized in Table 5.8. Four users did a sweeping swipe-movement to the back or the side using the full range of their arms. The other user did a line on his right side on the table that should mimic a scrolling function like it is used on touchscreens.

Table 5.8: Gestures used to put an object temporarily away.

Gesture	Used by # of users	Percentage	Agreement
Big swipe	4	80%	0.68
Scrolling - lines	1	20%	

Take measurements Five users made use of this function during the tasks and all of them had the same gestural approach: They selected a saving measurements function in an additional GUI and traced the measurements they wanted to save with the pen. When reusing this data participants referred to some GUI to add edges and planes with the desired sizes.

Copy an object For this function users expected to have the copy of an object immediately attached to the tip of the pen, so they could move and place it. Four participants used this function with three different approaches, summarized in Table 5.9. Two users did a double tap; one did a single tap while pushing down a button on the pen. The other user would select this function in an additional GUI. Users were not always clear on how to place the copied object into position but those who did used a single tap gesture.

Participants copied an object to apply transformations to the copy.

Mirror an object This function was used by two users. They executed this after a object was attached to the pen either by copying or selecting it. Both users came up with different gestures. One participant used a half-circle movement, the other expected some kind of anchor point at

Few users mirrored objects to get perfect symmetry.

Table 5.9: Gestures used to copy an object.

Gesture	Used by # of users	Percentage	Agreement
Double tap	2	50%	
Single tap	1	25%	0.375
Select function	1	25%	

the edge of the existing plane where mirroring would take place automatically.

Delete complete object One user made a big swiping movement in several directions to complete this function. He was the only one who used this task.

Users relied on additional hardware and software features.

Rotate an object Two users wanted to rotate their objects and used the same approach in doing so: both would describe a button that can be turned in different directions and is located at the end of the pen. One user imagined a button that can be turned in two directions, the other one referred to some kind of ball which can be turned in all axes.

Create squares and circles This special kind of creating planes was used by two users. Both would select a predefined function in some GUI. The following gestures were determined whether they used the "drawing lines" or "placing points" approaches to creating general planes. They either drew a line for the diagonal of a square or set two points of a diagonal for the circle.

5.4 Interview and comments

An interview was conducted to find out about participants' pre-knowledge and experience during the tasks.

The goal of the interview was to figure out how much pre-knowledge participants already have with gesture controlled devices and how they experiences the tasks. But also to gain additional comments on what technology they think could improve the usability of the iWand. All participants reported to use touchscreens on smartphones, tablets or laptops on a regular basis. Additionally, four of them used game controllers for 3D interaction (Nintendo wii, Microsoft Kinect) and two also used pens for drawing tablets. Only four participants said they rarely used speech input.

Additional input methods like touchscreens and speech input were mentioned.

One question of the interview was whether participants could imagine using some additional input method in combination while modeling with the iWand. Seven participants argued that the pen itself was sufficient in its use, other participants named multiple methods: an additional touchscreen that could be controlled with the free hand was mentioned six times. The screen would provide selectable options and functions but also visual feedback of the modeled object. Speech input was proposed by five participants. Four participants like their hands to be recognized by the cameras to expand the possibilities of gesture interaction. One or several buttons on the pen was mentioned by four other participants as an additional feature. Those participants were influenced by their experience with graphic tablets which include buttons on their pens, as an example in Figure 5.5 shows.

Figure 5.5: Example of a digital graphic pen that includes buttons to execute functions. Source: Amazon [2017].

The biggest obstacle while modeling was the lack of visual feedback.

Participants were also questioned about the difficulties they experienced during the tasks. 13 persons found it difficult to have some kind of orientation about their imagined model, which they attribute to the lack of visual feedback. Another six participants reported to have difficulties with precision and size relations, which can also be partly explained by "drawing blindly". Another hardship nine participants mentioned was simply thinking in 3D, i.e. transferring the 2D picture of an object into a model in 3D space. As mentioned in 5.2, some people slightly simplified this challenge by creating the object from a 2D perspective or breaking the objects into different parts that can be drawn easily in 2D space. Two participants said they had difficulties with finding ways to reduce the work to get the desired 3D model, as some objects could be composed of several basic shapes like squares or triangles.

Generally, people responded positively to the idea of pen-based device.

Another issue addressed was which aspects people found easy or intuitive. Eight participants mentioned basic shapes like squares, circles and triangles to be easy to create. In addition to this, two people mentioned the extrusion of those shapes to create basic 3D models as easy. Another three persons even found the task of the sphere to be solved intuitively. Six of them especially liked the pen-based control, as they "would feel lost in programs that had a huge amount of menus and functions" like one participant explained.

In addition to these questions, participants were also encouraged to give generally comment on how they think usability could be improved for the iWand. Having additional rulers or patterns as real objects would be a nice feature for five participants. Eight others (especially those participants who already had some experience with 3D modeling) would rather have a set of predefined standard shapes which can be further deformed by the user.

One thing that was rather interesting to observe was participants' behavior towards real objects. When they needed to create a drawer that would fit into a given box, only nine participants actually drew along the inner edges of the box. The other persons came up with different ways of avoiding this: they either drew in front of the box, on the outside or copied & deformed it.

Apart from 3D modeling, one user found the idea useful as a way to present ideas and text to a group of people. Instead of using a touchscreen device with a pen and a writing program, he would simply write and draw on paper and expect his creations to be directly send to a display or overhead projector for everyone to see.

5.5 Discussion

Five essential nuclear functions could be determined.

Previously, all gestures and comments participants made during the study sessions were listed. Since the users created their own set of functions and the correlated gesture, it is possible to define a set of nuclear functions that everyone used and therefore are essential, namely: *add edge*, *add plane*, *cut out*, *extrude* and *create sphere*. These functions with their most popular execution are listed in Table 5.10. There are additional functions used only by a smaller group of users that had a unique set of gestures. Functions with gestures that would rely on hardware and software features, such as buttons on the pen, are not included here.

Automation might hinder users with different modeling approaches.

These gestures worked well for the participants during the study sessions, but automatic fill-ins can be an obstacle to users who follow different approaches of modeling. For example, creating a hollow object could be realized easily for people with a 3D-drawing approach: they simply draw each wall as squares into the air. In contrast, users who modeled by connecting primitives are hindered by automatic fill-ins of all their shapes: they would take a square in 2D with a given edge width and extrude it. Therefore, alternative gestures are provided and automation should be considered as an option which can be switched on and off to consider any user requirements.

Users were biased by regular use of touchscreen devices.

In general, the gestures sometimes contradict each other. For example, the tap-gesture is very popular. Some of the participants use a single-tap to select an object, others tapped to delete something and yet another few users tapped to fill-in a plane. Since all participants regularly use touchscreen-devices, this might be an explanation. A tap on a smartphone that has a GUI designed with the WIMP-

Table 5.10: List of basic functions that had a unique set of gestures without using additional software or hardware features.

Basic Function	Gesture	Alternative	Alternative
Create edges	Draw lines		
Create planes	Automatically when shape is closed	Single tap	Hatching
Delete shape	Automatically when on other shape	Punch	Swipe
Extrude	Tap & hold, draw distance line		
Create Sphere	Two circles shifted by 90°		
Put object away	Big swipe		
Delete complete object	Multiple big swipes		
Copy	Double tap		
Mirror	Half circle		

paradigm can have very different meanings depending on which icon, bar, etc. the user taps.

Start and stop tracking were not considered by users.

One issue that no participant addressed is the information transfer to the system when exactly to track and when to stop. Between the gestures for modeling, users rarely hold their hands still and often stop and start again at different positions. Without prevention, this behavior leads to unintended edges and lines in the model. As mentioned before, some users proposed a button on the pen or speech control as additional input methods which delivers an option to avoid this obstacle.

Chapter 6

Summary and future work

The concluding chapter is divided into two parts: the first contains a summary of the given thesis. The second one offers the reader an outlook on future works.

6.1 Summary

First, publicly available 3D models needed to be analyzed

Since 3D printing becomes more affordable for private users, the need for creating 3D models without comprehensive knowledge of 3D modeling software also rises. A pen-based device called iWand should help users with constructing these models. In front of such a new device it is required to know how users naturally deal with the iWand. To design a user elicitation study for the observation and analyzation of user behavior, we first need to know the kind of objects people prefer to create with 3D printers. For this, a statistical survey on 3D models has been worked out. In the survey we searched for websites offering 3D models for download.

Most popular categories are determined.

For detailed analysis, the focus was laid on the two most popular websites for 3D printing objects: `thingiverse.com` and `youmagine.com`. In regard to semantic categories, the most popular one is toys (17%), followed by decor, household and storage (each about 10%). Comparing items on download numbers reveals similar findings. Another point evaluated is how these objects stand in relation to other, already existing objects. We found that 60% of all objects are standalone and independent of any other objects or measurements. Second, there is the category of storage of about 16% of all items, that means hollow things in which something can be put into. Both sites featured a lot of parts for 3D printer (nearly 25%), but those items were excluded from the search because objects are needed that people know and can recreate, regardless of experience with 3D printing.

Three different approaches to modeling could be observed.

After analyzing all objects, five items were chosen that people are considered to recreate as 3D models with a pen in the user study. The items consist of: a toy boat, a wrench, a drawer, a box with a fitting drawer and a sphere. For the study 20 people volunteered. Their approaches can be roughly categorized in three ways: The first and most common method of modeling was to redraw everything in 3D space using the tabletop and also the air as canvas. Some participants also recreated the objects in 2D from a 3D perspective. Another approach was to create simple shapes and primitives and connect them using different functions. The interview and think-aloud protocol provided additional feedback concerning the user experience during the tasks. Most users reported that the lack of visual feedback made it difficult to keep track of their models. Users also reported that additional input methods could be useful.

Five essential basic functions were used by all participants.

There are five essential nuclear functions used by all participants: *add edge*, *create plane*, *extrude*, *cut out* and *create sphere*. While a lot of participants expected automation of some functions, e.g. *cut out* and *create plane*, we were also able to identify a unique set of gestures for most nuclear functions. A list of functions and proposed gestures is presented in Table 5.10. Overall, 15 different nuclear functions could be identified. All participants regularly used touchscreen-devices, so often they used gestures they already knew, e.g. tap or swipe, to execute functions. Sometimes these were contradicting between users, e.g. one user tapped for selecting, another for deleting.

6.2 Future work

Additional user studies need to be done to confirm and improve the set of gestures.

With the evaluation of user behavior while using a 3D modeling device, further user studies can be conducted to confirm and expand the various gestures. A set of gestures is found for the 15 nuclear gestures used in this study, but only five of them were analyzed with a set of 20 participants contributing. Adding *turn on tracking* and *turn off tracking* to that list, there is a viable set of functions to perform a guessability study following the model of Wobbrock [Wobbrock et al., 2009]. Since participants performed two gestures maximum for a function and did not rate gesture goodness or ease for this thesis, this is another point that needs to be verified and improved in further research. Letting users perform three different gestures to a given set of functions might provide a higher variety of gestures that can be used to expand the usability. A rating of these functions would give more insight into the perceived intuitiveness of combining a certain gesture with system behavior.

Improvements in additional hardware need to be considered.

Another point is the realization of the hardware and additional input methods. Since all participants criticized the lack of visual feedback, this is a point that needs to be addressed in further research. There are various ways of realizing this point, e.g. some kind of app on a hand-held device, or a full display connected to a PC. While a few participants mentioned Head Mounted Displays as a good idea, this solution might be counterintuitive to the iWands' idea of providing an accessible solution to 3D modeling. Finally, with the realization of buttons on the iWand, ergonomics must be considered.

Appendix A

Interview Protocol

- What is your age?
- What is your occupation?
- Do you have experience with 3D modeling?
- Have you ever used a 3D printer?
- Do you use devices that are gesture controlled?
- Do you use other input methods apart from mouse & keyboard?
- Can you imagine using other input methods in addition to the iWand?
- What were difficulties during the tasks?
- What did you find easy?
- What did you like or dislike while doing the tasks?
- Do you have any other comments or ideas?

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