SAARLAND UNIVERSITY

Faculty of Natural Sciences and Technology I
Department of Computer Science
Bachelor's thesis

TAROC:
A Tangible Augmented Reality System for Object Configuration

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October 2018

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Submitted
1st October, 2018

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Acknowledgments

First of all, I sincerely thank Prof. Dr. Antonio Krüger for giving me the opportunity to work on this project and to write about it. Furthermore, I would like to thank him and Dr. Gerrit Kahl for reviewing my thesis.

A special thanks goes to Denise Kahl and particularly to Nico Herbing for advising me, whenever I struggled with any kind of difficulties during this project and for giving me feedback on different iterations of this work.

In addition, I want to thank my family and my friends from the Merge-Squad, who discussed several issues with me and helped me to overcome them.

Lastly, I would like to thank everyone from the UMTL who helped me at some point during my work, be it by showing me how to use different tools, by giving me access to special hardware and software, by providing the LaTeX template used for this thesis or by expressing different point of views for several topics.

Abstract

The tangible augmented reality system for object configuration (TAROC) provides tangible elements which can be combined to a physical model. Based on this model's composition, a digital counterpart is computed in real-time and rendered onto it in augmented reality (AR). Thereby, each of the undetailed tangibles represents a specific part of the target object, such that different combinations lead to different detailed, virtual prototypes. TAROC combines embedded computation with visual marker tracking to enable robust and accurate real-time tracking. Using microprocessors inside the tangibles, the composition of the model can be determined independently of the blocks being visible to the tracking device. Furthermore, fiducial markers are used to track an element's spatial information, such that the computed visual model can be attached to the physical one in real-time. One of the core features of a configuration tool is the possibility to individualize different properties of the configured item. Next to the composition tangible augmented reality (TAR) interface, a further marker-based TAR interface enables users to choose between different attribute values. These interfaces provide visual as well as haptic feedback to the user, leading to a more realistic configuration experience.

In this work, the given approach is presented in detail and important design decisions are explained. A sofa configuration tool is shown as a practical implementation and is used to figure out advantages and disadvantages of this concept. Users can combine tangible representatives of a single-seater, corner pieces, a two-seater and a chaise longue. Furthermore, the base type, the color and the texture of their sofa can be manipulated using configuration wheels. These wheels are divided into three parts, each representing another value of the corresponding attribute. Depending on a wheels rotation, a value is chosen and the visual model of the sofa updates in real-time. Next to each part of a wheel, a tangible representation of the attribute value can be seen and touched. Thereby, a user will receive realistic visual and haptic feedback, improving the user experience.

To justify the combination of embedded computation and marker tracking, a technical evaluation is documented. Thereby, two scenarios occurring in user interactions are simulated and a comparison between the given approach and an application based on marker tracking only is drawn. In the first scenario, markers are being occluded and thus not visible to the tracking device. While the marker-only-based application needs to detect one fiducial marker on each element to render the full model, it is sufficient to track one marker in total for TAROC. The second scenario addresses perspective distortions, which appear if a user rotates connected cubes. As one marker being visible to the tracking device is sufficient for TAROC, the visual model stays in place and rotates correctly with the physical model. In contrast, the marker-only-based application loses track of the perspectively distorted markers at a rotation of 50 degrees or higher, leading to the corresponding visual counterpart not being rendered.

Last, a user evaluation is conducted to investigate the usability of a configuration tool based on the given TAR approach. Seven participants are asked for their experiences with configuration tools. Afterwards, TAROC is introduced to them such that each participant can configure a couch. With help of the System Usability Scale and the AttrakDiff questionnaires the usability is rated and furthermore, the participants express their opinion on TAROC in an interview as well as with help of several Likert scales. Although the tracking performance of TAROC can be improved, it provides a good usability and the participants report it to be fun to use.

Contents

Abbreviations

AR	augmented reality
AVG	average
cm	centimeters
CNN	convolutional neural networks
GND	ground pin
GUI	graphical user interface
ID	identifier
I/O	input/output
HMD	head-mounted display
HQ-I	hedonic quality - identity
HQ-S	hedonic quality - stimulation
MAX	maximum
MIN	minimum
mm	millimeters
MR	mixed reality
MVC	Model-View-Controller
OPT	optimal
RX	receiver pin
RFID	radio-frequency identification
RNN	recursive neural networks
SD	standard deviation
SUS	System Usability Scale
TAR	tangible augmented reality
TAROC	tangible augmented reality system for object configuration
TX	transmitter pin
TUI	tangible user interface
FOV	field of view
3D	three dimensional, three dimensions
6-DOF	six degrees of freedom

Chapter 1
Introduction

Nowadays, the concept of mass customization is an important factor in several industrial fields [8]. Thereby, companies have to provide a large variety of products and services such that nearly everyone finds exactly what he wants at a reasonable price. Customers like to be able to purchase a customized product for the cost of a mass-produced item, so the companies have to manufacture one-of-a-kind products to their specifications without sacrificing scale economies [8]. At this point, integrating users into the design and production process is a promising strategy [9]. Therefore, configuration tools can be used, which reduce the design process nearly to a series of selections of attribute values. This leads not only to an increase of the customers' satisfaction [29], but also has a positive impact on the product quality in general [26]. For those reasons, many established manufacturers in different areas offer configuration tools, for example Mercedes-Benz® [1] (Figure 1.1).

Many of these tools rely on a web-based interface, offering users the possibility to configure their products with a few clicks. However, in general, such tools show the configured product in a clean, unnatural environment. Furthermore, the look of a configured item always varies with the chosen display as colors often look different on different output mediums. Another disadvantage of web-based configuration tools is the restriction to two dimensions as the possibility to see a product in the three dimensional (3D) space is in many cases simply not given. Last, haptic feedback is not integrated in the configuration process at all. For products like chairs, beds or couches, it is crucial to have a comfortable surface, which is why a realistic tactile feedback is essential for the design process and should also be provided by a configuration tool.

[1] `https://www.mercedes-benz.de/passengercars/configurator.html` (accessed on September 29, 2018)

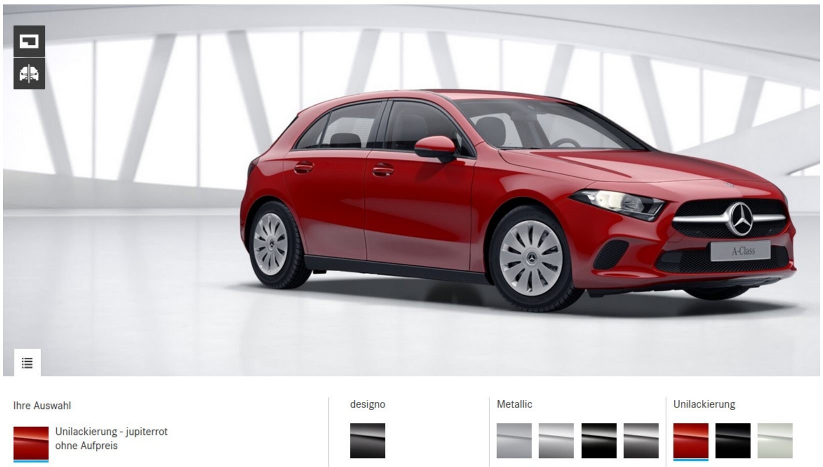


Figure 1.1: The Mercedes-Benz® online configurator allows users to personalize a car.[1]

Summarizing, up-to-date configuration tools lack usability and further do not provide an appropriate user experience. By integrating state-of-the-art techniques into the configuration process, user interfaces can be developed, which overcome many of the web-based interfaces' disadvantages and thus provide an improved usability and user experience.

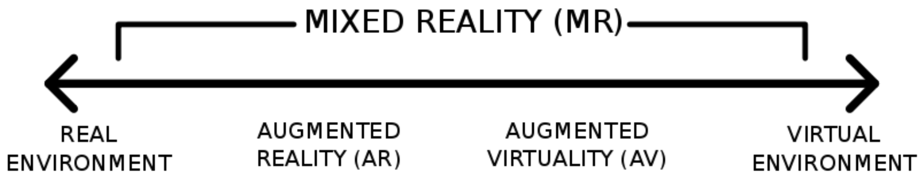


Figure 1.2: The virtuality continuum shows the transition between the real and the virtual environment.[2]

1.1 Augmented Reality

In mixed reality (MR), elements of the real and the virtual world are combined. Thereby, objects of both worlds are presented together within a single display. To describe the transmission between the real world and a virtual environment, the concept of a *virtuality continuum* (Figure 1.2) has been introduced [22]. On the left, the real world can be seen. By adding virtual objects and replacing real ones, the augmented reality and later on the augmented virtuality is reached.

[2] https://commons.wikimedia.org/wiki/File:Reality-Virtuality_Continuum.svg (accessed on September 29, 2018)

Last, the virtual reality depicts a totally virtual environment, replacing every visual feature from the real world. All of these four labeled positions on the continuum describe the ratio of real and virtual elements, which results in fluid transitions between them. Augmented reality (AR) describes one of these labeled positions. It depicts any case in which an otherwise real environment is *augmented* with virtual objects [22]. Hence, AR supplements the real world instead of replacing it. Ronald Azuma [2] defines AR as any system that combines real and virtual elements, is interactive in real-time, and is registered in three dimensions. He further states that AR enhances a user's perception of and interaction with the real world, wherefore it is useful to combine real and virtual objects in 3D.

In the context of configuration tools, AR introduces one major advantage, namely the possibility of a 3D display. By that, users perceive a more realistic preview of their configured item and further, they are able to move around the product to receive an impression on what it looks like from different angles, which is not supported by online configuration tools. On the other hand, users often have to learn new interaction techniques to interact with AR systems, wherefore these applications often only support indirect and unintuitive interaction possibilities. This so called *cognitive seam* [5] has to be overcome to enhance configuration tools with a realistic and three dimensional AR preview of the configured product. Additionally, an augmented reality configuration tool also does not include tactile feelings into the design process, which for many products is a factor that always has to be considered.

Figure 1.3: In the AR configuration tool by Ikea®, virtual chairs can be placed in your own home.[3]

Such AR-based approaches for product planning already exist, like the 'IKEA Place'[3] (Figure 1.3) app by Ikea®, which allows users to place virtual furniture in their own home. However, besides the general disadvantages of AR configuration tools, 'IKEA Place' only enables users to place different pieces of furniture freely in a room, while the configuration of items themselves is not possible. Furthermore, such applications simply render 3D models on a two dimensional

[3] `https://www.ikea.com/au/en/apps/IKEAPlace.html` (accessed on September 29, 2018)

display. In contrast, relying on different AR displays, for example on the Microsoft HoloLens[4], enables users to perceive a realistic preview of their configured item in the real 3D space.

1.2 Tangible User Interfaces

The tangible user interface (TUI) paradigm is an alternative to the graphical user interface (GUI) paradigm, which in contrast to AR interfaces mostly provides direct interaction and thus tactile feedback. Over thousands of years, humans have developed excellent haptic skills for interacting with their environment. TUIs take advantage of these skills by giving digital information a physical form [16]. In contrast to GUIs, where information is presented as pixels on a bitmapped display and people need some kind of remote controller or touch pad for interactions, TUIs enable users to interact with the physical representative of the digital information in a direct and natural way. By combining the input device and the representation of information, TUIs have the ability to fit seamlessly into a user's physical environment [16].
With Urp [28], Underkoffler and Ishii give an example of a TUI. The application allows multiple urban planners to use tangible representatives of buildings and streets for accurate city modeling. By using a special clock, different times of a day and the corresponding lighting situation can be simulated and furthermore, different weather conditions and their impact on the modeled situation can be seen. The tangible elements of Urp can be seen in Figure 1.4.

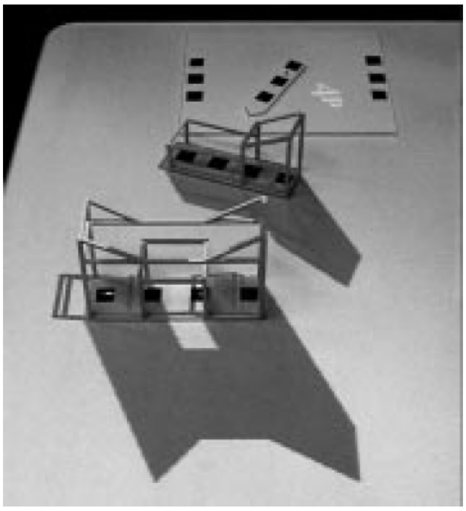


Figure 1.4: Two tangible elements representing buildings with their simulated shadows and a special clock to manipulate the time of day. [28]

[4]https://www.microsoft.com/de-de/hololens (accessed on September 29, 2018)

Configuration tools following the TUI paradigm are able to support intuitive, direct interactions and also provide tactile feedback by giving digital information a physical representation. Hence, users receive a real impression of the material and of the color, which their product will consist of at the end. On the other hand, tangibles are in general not able to update their appearance as they are physical objects. Therefore, users often have to change the interaction space, e.g. looking at a monitor, to receive proper visual feedback while interacting with TUIs. This issue is known as *functional seam* [5] and has to be overcome by tangible configuration tools.

1.3 Tangible Augmented Reality

In general, AR applications have the disadvantage of a *cognitive seam*, which basically means that they only support non-intuitive, indirect interaction without any haptic feedback [15]. Contrary, Tangible User Interfaces support intuitive, direct interaction and also provide a good haptic feedback. In return, TUIs lack the capability to adapt their physical appearance [16], which is an essential property for many use cases. To overcome this *functional seam*, Billinghurst et al. [5] developed an alternative approach, called Tangible Augmented Reality (TAR). Thereby, tangible objects are used for haptic interactions and are overlayed in AR to enhance their flexibility. This approach combines the advantages of both techniques and offers the possibility of designing various interfaces which provide seamless, intuitive and direct interaction.
An example for a TAR interface is the tabletop game by Ulbricht and Schmalstieg [27]. Each of two players has a virtual catapult, three virtual balloons and a virtual windmill (Figure 1.5). The catapult and the windmill are rendered in AR on top of small pieces of paper, containing optical markers that are tracked by a camera. By moving these markers, the players are enabled to move the corresponding game elements. The balloons are also rendered in AR but not attached to any tangible counterpiece. The goal of the game is to destroy the balloons of the opposite player using the catapult. Using the windmill, the balloons can be moved to avoid shots of the enemy's catapult.

Relying on a TAR interface in the context of object configuration has several advantages in comparison to the current standard and both, AR or TUI, approaches. First of all, a realistic 3D preview of a configured object gives a more detailed and more accurate impression than a two dimensional preview in a web browser. Second, direct interaction with the tangible counterpiece of a configured item is much more intuitive than controlling a GUI using a keyboard and a computer mouse. Last, haptic feedback gives an impression on how the configured item will feel like at the end, which is not supported by web-based interfaces at all. For these reasons, it makes sense to explore a tangible augmented reality system for object configuration.

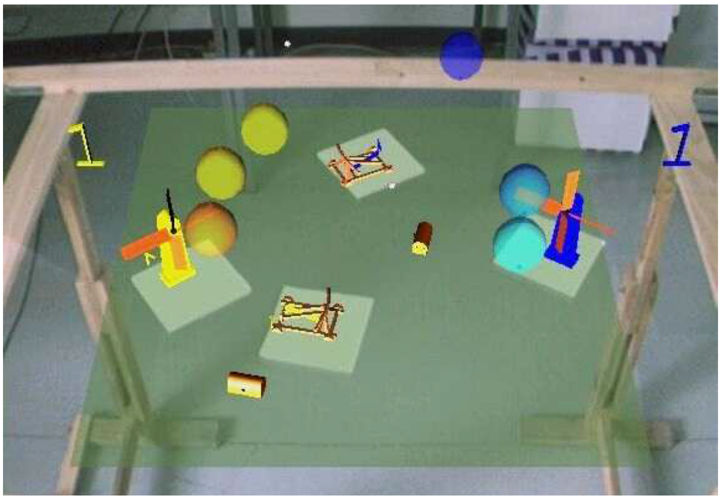


Figure 1.5: The game elements of the TAR game by Ulbricht and Schmalstieg. [27]

1.4 Outline

In this work, a TAR interface for product configuration is developed. Hereby, plain tangible blocks can be combined to a physical model. The combination of the blocks is determined in real-time and overlayed with a corresponding virtual counterpiece. Furthermore, this interface is used to have a closer look at the advantages of TAR in context of product configuration. For that, different approaches for TUIs and TAR applications are reviewed and discussed in Chapter 2. Important design decisions are justified and also critical aspects in designing TAR interfaces are considered. Afterwards, the final concept is explained in Chapter 3 and a sofa design application based on this concept is presented. The implementation part in Chapter 4 explains how this application was realized. In Chapter 5, a technical evaluation and a user evaluation show advantages and disadvantages of the developed TAR configuration tool. At last, limitations of the given approach and future work are stated in Chapter 6.

Chapter 2
Related Work

To realize the tangible augmented reality system for object configuration (TAROC), a proper tangible user interface in combination with an augmented reality application needs to be designed. Anderson et al. [1] state two different approaches for tangible modeling interfaces: either augmenting the elements of the user interface with computational devices such that they can determine their combination themselves, or using external sensors to track them. Therefore, systems, which rely on embedded computation will be presented next, followed by systems that use external sensors for tangible AR modeling.

2.1 Embedded Computation Approaches

Anderson et al. [1] provide a tangible user interface to simplify 3D modeling. The interface consists of Lego™ [5] alike building bricks with integrated computational devices, which can be combined to a physical structure. The composition of the structure is determined and used to render a virtual model.
Each brick contains a microprocessor and has eight plugs on the top and eight jacks on the bottom. Those plugs and jacks are not only used as physical connectors, which enable stacking (Figure 2.1), but also contain communication lines, which enables transmitting data between connected blocks. Each microprocessor carries an identifier (ID) and each connector of a block has a specific number. After a physical model is constructed, it determines its own geometry in three phases. First of all, each block identifies which of its connectors is connected. Second, each block transmits its ID and the number of the corresponding connector

[5] `https://www.lego.com/en-gb/?ignorereferer=true` (accessed on September 29, 2018)

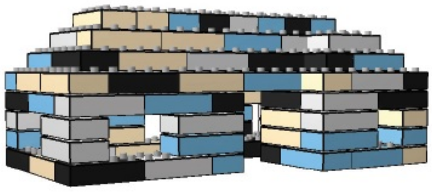


Figure 2.1: Multiple blocks can be stacked to a physical model. [1]

to its attached neighbors. Last, each block sends its connectivity information to a special block, which has a serial connection to a host computer. Integrating all connectivity information, the computer renders a virtual model based on the blocks' shape data, which is recorded when a block is built.
Anderson et al. [1] combine their building bricks to create a physical model, which is interpreted and used to render a virtual model. TAROC adapts this principle and additionally displays the rendered model in AR. In the system of Anderson et al., every change in the structure of the physical model leads to a time-consuming re-determination of the whole model. Contrary, TAROC updates its model in real-time. Lastly, the system of Anderson et al. does not provide a functionality to change properties of the virtual model, wherefore no tactile feedback has to be provided. In contrast, users of the TAROC system are able to change the model's texture for example. To provide a realistic impression of the configured item, TAROC includes appropriate haptic feedback.

Similar to the building bricks of Anderson et al. [1], the ActiveCube system by Watanabe et al. [30] is a tangible user interface, which can be used for 3D modeling. It consists of cubic blocks with embedded computation and a slightly different base cube. The base cube communicates with a host computer and supplies power to the system. All blocks contain a microprocessor, holding a unique ID and also each of its faces has an ID. On each side of the cubes, four hooks are used for physical connections (Figure 2.2). Three of them are able to supply power and the last one is used as an input terminal for communication between connected blocks. If a child cube is connected to a parent cube, which is already connected to the system, the child is supplied with power and communicates its cube ID and the ID of the connected face to the host computer. Also, the parent cube broadcasts the corresponding information, such that the virtual model can be updated correctly in real-time. A similarity between the system of Anderson et al. [1] and the ActiveCube system by Watanabe et al. [30] is that both consist of tangible blocks, which can be combined to a physical model. Both determine the structure of their model and use it to build a visual counterpart. This approach is also followed by TAROC. The main difference between the systems of Anderson et al. [1] and Watanabe et al. [30] is the time required to determine changes in the structure of the physical model. While Watanabe et al. support real-time detection of changes and updates of the 3D model, Anderson et al. need to

Figure 2.2: Several cubes are connected with a hook system. [30]

compute the combination of the whole structure again, which leads to a delay in updating the visual model. TAROC follows the approach of Watanabe et al. to maintain the 3D model in real-time so that the visual and physical models are always consistent. In contrast to the ActiveCube system, TAROC displays the visual model in AR and enables a user to change specific properties, e.g. the texture. Therefore, TAROC includes real samples of these properties, which is also not given by ActiveCube. Both of the published systems [1, 30] support direct manipulation as they do not require any additional device to change the model. They also provide interaction in six degrees of freedom (6-DOF) as a user is able to pick the model up and rotate it as he likes to, with only the small restriction of the connection cable between the base blocks and the host computers. To overcome this problem, Hochenbaum and Kapur [14] use XBee wireless radio-frequency transmitters[6]. The 2.438cm x 2.761cm small modules are connected to and supplied with power by an Arduino Funnel IO[7]. TAROC also adapts these principles of the embedded computation systems [1, 30] integrating the wireless connection to the host computer by Hochenbaum and Kapur [14]. Thus, it provides direct manipulation and interaction in 6-DOF.

[6] `http://www.nex-robotics.com/products/wireless-devices/xbee-wireless-communication-module-wire-antenna.html` (accessed on September 29, 2018)

[7] `https://www.sparkfun.com/products/retired/8957` (accessed on September 29, 2018)

2.2 External Sensor Approaches

The main issues that need to be addressed in systems relying on external sensors are availability and restrictions of sensors themselves. For example, Girouard et al. [10] designed an application which uses a radio frequency identification (RFID) reader to determine a combination of tangible blocks being augmented with RFID tags. To identify the tags, the reader needs to be proximate to them. Therefore, Girouard et al. decided to integrate the reader into a table surface, which restricts users in picking up the block structure.
The TAROC system uses the Microsoft HoloLens as output medium. As the HoloLens has an integrated camera, it makes sense to have a closer look at systems which rely on cameras as sensors and use computer vision techniques to determine tangible objects.

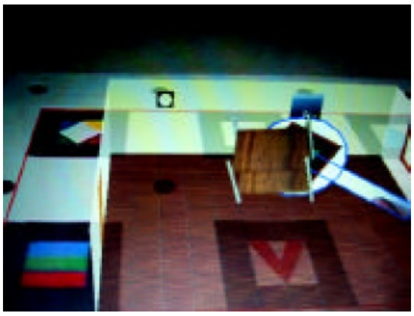


Figure 2.3: A shelf is placed in the virtual room by tilting the paddle. [5]

Billinghurst et al. [5] introduce Vomar, a marker-based system, which enables a user to choose between several virtual furniture models and combine them in a virtual room. Vomar consists of three main components: a book, a paddle and a large piece of paper. The book serves as a virtual furniture menu. On different pages, the user, wearing a head-mounted display (HMD), can see different sets of furniture models. These can be picked up by placing the paddle besides them, then be moved and dropped by tilting the paddle on the piece of paper (Figure 2.3), which is the virtual workspace and initially shows an empty room. The system also supports further interaction possibilities, for example deleting models from the paddle by shaking it. The three main components are tagged with markers to detect their identity, position and orientation in space. Furthermore, each tag in the book represents a specific piece of furniture, which is displayed on top of it. All markers are tracked with the help of a camera and used to correctly detect which models need to be displayed at which positions.
The marker-based modeling system Vomar by Billinghurst et al. [5] enables users to configure a visual model. The configuration can be changed in real-time and is displayed in AR to users wearing a HMD. These aspects are also supported by the TAROC system. Vomar does not provide physical representatives of the visual

models. Thus, indirect manipulation is supported as a user needs the paddle to interact with the scene. Contrary, TAROC enables users to interact with the physical counterparts of the virtual models directly and therefore supports direct interaction. Furthermore, users interacting with the TAROC system are able to personalize visual properties of the configured item, which is not supported by Vomar.

Another system, which uses a marker-based approach in conjuction with a camera as a sensor, is the city-planning system of Kato et al. [17]. It enables users to combine different virtual objects to a 3D city model that is displayed in AR. The system consists of a main and a side table, a transparent cup (Figure 2.4a) and a video see-through HMD. Both tables and the cup are augmented with markers, which are tracked by two cameras attached to the display. While the main table serves as visual workspace, showing the current state of the city-model (Figure 2.4b), the side table proposes a variety of different models, which can be picked up and placed in the workspace using the cup. A model can be picked up by holding the cup upside-down and covering it. Afterwards, while moving the cup, the model stays locked in it and can be placed in the workspace by putting the cup at the desired position (Figure 2.4c). In addition, light position and intensity can be varied to simulate shadows.

(a) The cup interface of the system. (b) The virtual model of a playground. (c) A chute is added to the model.

Figure 2.4: The city-planning system of Kato et al. [17]

In parallel to the Vomar system by Billinghurst et al. [5], the city-planning system of Kato et al. [17] enables users to configure a virtual model in real-time. Besides the possibility of adding and removing parts of the configuration, users are also enabled to change specific properties of the model itself. However, the city-planning system does not include real representatives of these properties offering original and realistic feedback. The configuration of the city is displayed to users wearing a HMD in AR. All of these features are supported by TAROC. In contrast to TAROC, which supports direct manipulation, the system of Kato et al. [17] supports only indirect interaction with a cup as no physical representatives of the visual models exist.

The Augmented Foam system of Lee and Park [19] overlays foam mock-ups with a virtual 3D model to include realistic tactile feelings into the design process of products. The mock-ups need to be modeled using computer aided design

(a) A physical prototype is built, based on the virtual model.

(b) The virtual model of a cup is laid over the corresponding physical prototype.

Figure 2.5: The Augmented Foam system combines virtual and physical prototypes. [19]

tools and can then be produced by computer numerical control (Figure 2.5a). Afterwards, an artificial marker is attached to the mock-up, such that a camera in conjunction with computer vision algorithms is able to detect it and to compute its spacial information. A virtual model is created based on the mock-up's shape data and laid over the physical prototype in an AR video (Figure 2.5b). Using a software, colors and textures of the virtual model can be changed in real-time. Furthermore, the designer can pick up the foam prototype and move it in 6-DOF. Designers, who use the Augmented Foam system [19], are able to overlay a physical prototype with a corresponding virtual one. They can change specific properties of the model, for example its color or texture in real-time, and interact directly in 6-DOF. All of these features are also supported by TAROC. While Augmented Foam does not support real-time changes of the prototype's physical shape, TAROC enables users to add and remove parts of the physical model. Furthermore, the Augmented Foam system does not provide real counterpieces of properties being personalizable by users, which contrarily are included by TAROC.

2.3 Discussion

Both systems, which rely on embedded computation [1, 30], do not provide an AR view of their created virtual model. In contrast, the TAROC system and the marker-based approaches [5, 17, 19] do all support AR. On the other hand, none of the marker-based systems enable a user to create a physical structure using tangible blocks, which is the core concept of both of the systems presented in Section 2.1 and also of the TAROC system. As tangible representatives are necessary to make direct manipulation possible, just the embedded computation approach systems and Augmented Foam of Lee and Park [19] provide it. Those are also the only applications that support interacting in 6-DOF, as Vomar by

System	Direct Manipulation	6-DOF Interaction	Real-Time Extension	Real-Time Manipulation	Haptic Feedback	AR-Blending
Building Bricks [1]	✓	✓	✗	✗	-*	-*
ActiveCube [30]	✓	✓	✓	✗	-*	-*
Vomar [5]	✗	✗	✓	✗	-*	✓
City-Planner [17]	✗	✗	✓	✓	✗	✓
Augmented Foam [19]	✓	✓	✗	✓	✗	✓
TAROC	✓	✓	✓	✓	✓	✓

* Is not relevant for the system's concept.

Table 2.1: A comparison of the most important features provided by the presented systems.

Billinghurst et al. [5] and the city-planning system of Kato et al. [17] need a fixed work space. Real-time extension of the physical or virtual model is provided not only by marker-based concepts like Vomar or the city-planning system, but also by the system of Watanabe et al. [30], which uses embedded computation. Last, Watanabe et al. and Lee and Park are the only ones that provide the possibility of changing specific properties of the whole model.
The main disadvantage of the embedded computation-based systems is the absence of any spatial information of the physical model. Without additional sensors, it is not possible to determine its position and orientation relative to the user, which is essential to provide AR feedback. While the computation of spatial information is easy for marker-based systems, they lack robustness if the model is not visible to the camera properly. In this case, no attached marker can be tracked and the system cannot compute a virtual model. To overcome these issues, TAROC relies on both techniques. This solves not only the described problems, but also combines the intuitive, direct interaction possibilities in 6-DOF of tangible blocks with the advantage of AR to easily change properties of a model itself, like colors or textures. Contrary to the presented related work, TAROC includes real samples of these properties, enabling tactile feedback to be included into the design process, which is an important factor for a variety of contexts, e.g. for couches.
TAROC combines tangible blocks with embedded computation and computer vision-based object tracking to determine the configuration of a physical model and overlays this model with a corresponding visual one in AR. As a user can simply pick up the tangible model using his hands and move it as he likes to, the system provides direct manipulation in 6-DOF. Furthermore, it enables a user to extend the physical model with additional parts and also to manipulate several properties of the visual model in real-time. In Table **??**, an overview of the presented systems in comparison to the concept of the TAROC system can be seen.

2.4 Designing a TAR Application

In the following, remainig issues regarding the design of tangible blocks are addressed. Furthermore, the problem of occlusion in context of an AR application is discussed followed by different approaches for visual object recognition. Last, the discontinuity between the haptic perception of the tangible object and the visual perception of the AR model is addressed.

2.4.1 Design of Tangible Blocks

Anderson et al. [1] state four fundamental engineering problems, which need to be addressed in the design process of tangible blocks. Most of them have already been discussed in Section 2.1. The remaining issues are the physical connection of the blocks and their power supply. Gorbet et al. [11] reviewed multiple different techniques to attach tangible triangles, for example slotted edges, snaps, zippers, conductive Velcro® fasteners and magnets. They conclude that magnets are the most suitable technique because they do not only prevent incorrect combinations using clever arrangement of their polarity, they also do not require lateral motion for attaching, which simplifies creating complex forms. This is important for TAROC, as users have to build physical models while dealing with a restricted field of view (FOV) due to wearing the Microsoft HoloLens. For these reasons, the TAR system for object configuration also relies on magnets as physical connectors. Regarding the power supply, Anderson et al. [1] state two different approaches. Either blocks are powered externally, or self-powered blocks are used. The system of Anderson et al. [1] and also the one of Watanabe et al. [30] base on the first approach. Therefore, they require an additional connection between the tangible components to spread the power among the structure. The alternative is using microprocessors like the Qduino[8], which provide a battery connector. To keep the building process of the physical model as simple as possible, the second approach is prefered by the TAROC system.

2.4.2 Occlusion

As Breen et al. [6] state, a critical point in designing an AR application is to merge real and virtual objects seamlessly in order for AR to become fully accepted. Thereby, virtual items occluding real objects in an improper way are a problem which should be addressed.
To solve this issue, Lee and Park [19] rely on the approach of Kovač et al. [18] to use a color-based heuristic to identify human skin in a picture. Thereby, Kovač et al. apply heuristic rules to each pixel's color to determine whether it is part of a skin region or not. Afterwards, geometric properties of the human body are compared to detected skin regions and improper candidates are eliminated.

[8] `https://www.sparkfun.com/products/13614` (accessed on September 29, 2018)

(a) Color-based approach: A virtual cup is occluded by a user's hand. [19]

(b) Model-based approach: Two virtual chairs are occluded by a table. [6]

(c) Depth-based approach: Three virtual cubes are occluded by a wooden stand. [6]

Figure 2.6: Different approaches for occlusion handling.

Breen et al. [6] present two additional occlusion handling techniques. The model-based approach uses registered geometric models of real objects to decide which parts of an AR scene are occluded. First, a virtual model of the real scene is created and the augmenting objects are placed in this virtual scene at the same location and orientation as they will later appear in the AR video. A virtual camera is placed and oriented equally to a viewer's position, wherefore the camera has the same perspective to the augmenting objects as the viewer. This means that also the occlusions from the camera's point of view are the same as these from the viewer's point of view. As the rendering process overlays the live video of the real scene only with those parts of the virtual scene, which are not black, drawing the whole virtual scene except for the augmenting objects in black leads to a correct occlusion handling.
The depth-based method uses a depth map of the real scene to construct a corresponding polygonal surface. This surface does not really differ from a virtual model and therefore it can be used with the model-based approach to also correctly prevent occlusion errors. Results of the three presented occlusion handling techniques can be seen in Figure 2.6.
All of these techniques come with major difficulties in context of a TAR configuration system. First of all, the color-based approach used by Lee and Park [19] is not fitting, because different skin colors, gloves, jewelry etc. lead to incorrect results. The model-based approach is also not fitting, as it is complex to generate virtual models of all possible combinations of hand shapes and orientations. At last, the depth-based approach seems convenient, as the Microsoft HoloLens has a built-in depth-camera. However, the device only grants access to depth-information, which is within a minimum distance of 0.8 meters to a maximum distance of 3.1 meters in front of the camera[9]. This interval is out of interaction range for most users, wherefore the depth-based approach is also inapt for the TAROC system. Due to the given difficulties, this work does not focus on occlusion detection and handling for the rendering process.

[9] https://developer.microsoft.com/en-us/windows/mixed-reality/spatial_mapping_design (accessed on September 29, 2018)

2.4.3 Visual Object Detection

As the TAROC system consists of a combination of tangible blocks using embedded computation and computer vision, it is important to understand how computer vision-based object detection fundamentally works. Three well-known approaches rely on marker detection, feature detection and deep-learning. Rekimoto [23] states that marker-based object recognition can be done in just a few steps. After attaching markers to the target objects, an image of the scene is binarized and thresholded to detect marker candidates. Next, the corners of a candidate's bounding area are used to compute transformation parameters for mapping the area to the corresponding marker's space. Now, the content of the area can be interpreted to determine the marker's ID, which is mapped to an object. At last, the border of a marker's bounding area is used to compute the spatial relation between the marker and the capturing device. An overview of the marker-based AR system of Rekimoto [23] can be seen in Figure 2.7.

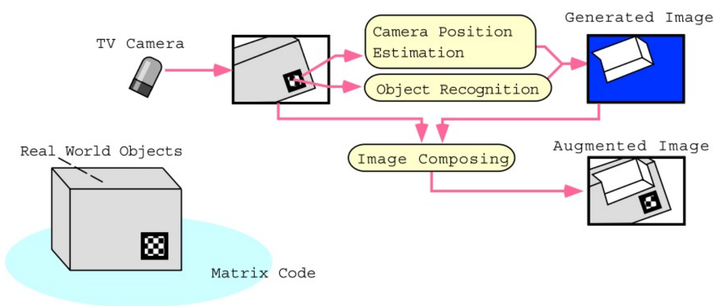


Figure 2.7: Overview of a marker-based AR system. [23]

Socher et al. [25] present an object recognition technique, following the deep-learning approach, based on a combination of convolutional neural networks (CCN) and recursive neural networks (RNN). After a CCN has been trained with two sets of random patches, one for color space and one for depth space, it extracts low-level features like edges from a picture by applying different filters. Multiple fixed-tree RNNs use these low-level features to determine features of a higher order. Combining all of them, a classifier determines the corresponding object.

The feature-based approach presented by Bay et al. [4] relies on the detection of so called interest points (Figure 2.8), which can be corners, T-junctions or blobs for example. In the next step, for each of these points a feature vector is computed representing its neighborhood. All feature vectors of an image are then matched to reference patterns, which are mapped to objects. Furthermore, the feature vectors can also be used to determine the spatial relation between their corresponding interest points and the capturing camera.

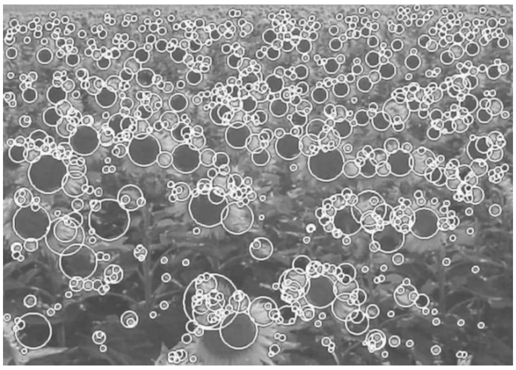


Figure 2.8: Interest points of a sunflower field. [4]

In contrast to the deep-learning approach, the marker-based [23] and feature-based [4] techniques have two advantages in the context of tangible augmented reality interfaces. First, it is easy to extend these interfaces with new objects by just attaching a specific pattern for feature detection or a marker for marker detection, while deep-learning algorithms need additional training data. Second, in contrast to the deep-learning approach, the marker-based and feature-based approaches are able to determine the spatial relation between a tangible object and the capturing device, which is essential for any AR application. As there exists a state-of-the-art library called Vuforia[10], which provides a feature-based object tracking and integrates well with the Microsoft HoloLens, the TAROC system relies on this approach using the Vuforia library.

2.4.4 Discontinuity in Visual and Haptic Feedback

TAROC combines the advantages of TUIs and AR by overlaying tangible blocks with detailed virtual models. Thereby, the blocks being as general as possible is a core feature of the system, enabling them to be reused in multiple different scenarios. As a consequence, the virtual models mostly do not have exactly the same shape as the tangible block, thus a user holding the physical model perceives different haptic and visual feedback regarding its shape. To study this discontinuity, Rock et al. [24] presented observers an object that differed in its tactual and visual shape due to an optical distortion. After interacting with this object, the observers were requested to draw its shape and it turned out that the visual perception is strongly dominant over the haptic perception. This phenomenon is also known as *visual dominance effect* and the TAROC system relies on it to argue that the user's perception of the visual model will not be disturbed by the shape of its physical counterpart.

[10] `https://vuforia.com/` (accessed on September 29, 2018)

Chapter 3
Concept

TAROC is a TAR approach for configuration tools. Undetailed, plain tangible elements containing microprocessors are augmented with fiducial markers. This enables them not only to notice and report occuring connections and disconnections by themselves, but further to be tracked by a computer vision-based AR application. Each of the tangibles corresponds to a virtual counterpiece which is registered in the augmented reality application. By integrating the connectivity information with the spatial data of the tracked elements, a virtual model of the tangible composition is created and aligned in real-time. This virtual model is then rendered on top of the physical structure, such that users wearing the Microsoft HoloLens are able to see their configured item instead of the tangible composition. This chapter goes into more detail regarding the concept of TAROC. The design of the tangible blocks is justified and the requirements of the augmented reality application are stated. Additionally, a TAR attribute value selection tool is conceptualized, offering a user the possibility to personalize different context dependent properties of the configured item, for example the color or texture. Last, a practical use case for TAROC is introduced. The interface is adapted to the context of a couch configuration tool, enabling users to combine different parts of a couch and choose between different types, colors and materials.

3.1 Tangible Elements

The core of TAROC are its tangible elements. These can be used to compose a physical model by attaching and afterwards separating them again. It is important to keep the connection and disconnection process as simple as possible for several reasons. First of all, a too complex mechanism contradicts the

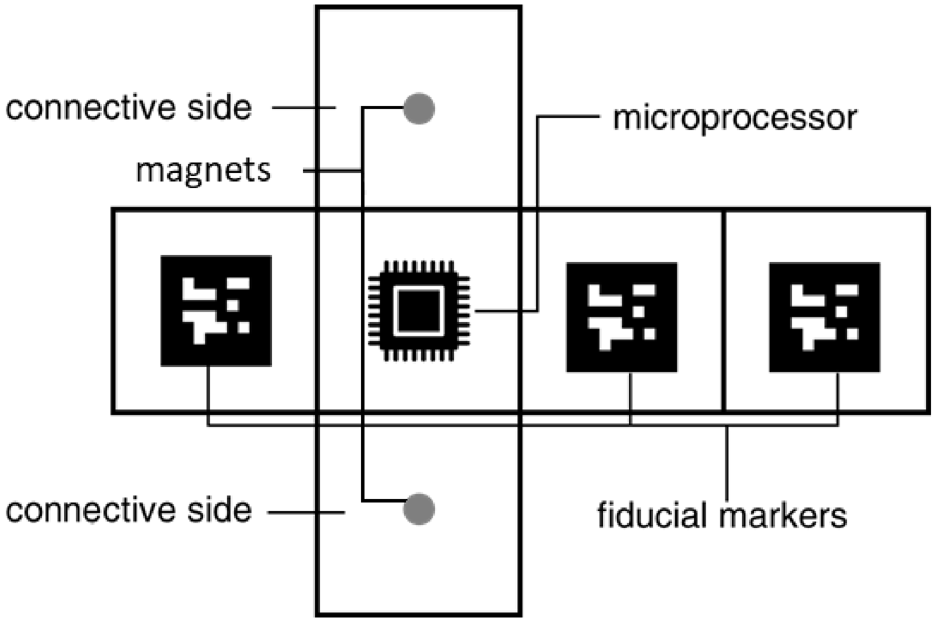


Figure 3.1: An unwrapped cube with all of its components.

intuitiveness of the system. Second, the user's field of view (FOV) is already restricted by the HoloLens, so the connection technique should not include too many details as they might not be visible to the user. For the given reasons, TAROC follows the approach of Gorbet et al. [11] and relies on magnets integrated into each side, supporting a connection for physical attachments. To further simplify the building process, each tangible has the shape of a cubic block. For connecting two of the cubes, a user simply needs to push together two of their sides containing magnets. Afterwards, the blocks can be disconnected by pulling them apart again. In the following, between all of an element's sides and those that provide connectivity functionality, the *connective sides*, is distinguished. Hence, the element's connective sides are a subset of its sides. In general, it depends on the use case how many connective sides are provided on a block, but it is possible that all sides of an element are connective. Magnets are only integrated into an element's connective sides (Figure 3.1), clarifying to users how blocks can be connected as the magnet's polarity prevents unfitting sides to be connected in an intuitive and natural manner.

In order to determine the spatial information of one of the elements, each of its sides are augmented with fiducial markers. An application running on the HoloLens and relying on its camera is now able to find the blocks and to compute their position and rotation relative to the camera. This way of tracking the physical blocks has a crucial disadvantage. If one of them cannot be found by the tracking application, the rendered virtual prototype is incomplete as no spatial information can be determined for this specific block. To overcome this, TAROC relies on embedded computational devices. Each element contains a microprocessor powered up by a battery, which supports wireless communication and

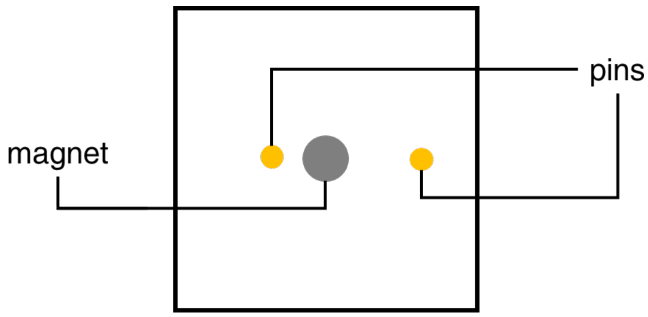


Figure 3.2: The transmitting connective side of the cubes. Pins are arranged on the left and on the right of a magnet in its center.

additionally is connected to the block's connective sides. By that, the tangible blocks know their own identity, which can be used to provide information on occuring connections and disconnections. To enable communication between the microprocessors in different blocks, such that connections and disconnections can be registered and the identities of the involved blocks can be communicated, the connective sides again are subdivided into two categories: On the one hand, *transmitting sides* have two integrated pins arranged on the right and on the left of the magnet (Figure 3.2). These pins are connected to the ground pin (GND) and transmitter pin (TX) of the microprocessor, such that transmitting sides serve as an output medium for the integrated hardware. *Receiving sides*, on the other hand, have two integrated conductive rings arranged around the magnet (Figure 3.3). These are connected to GND and a receiver pin (RX) of the corresponding microprocessor, such that the receiving side serves as the processor's input medium. Each cube has at least one transmitting and at least one receiving side but the maximal number of connective sides in general is only restricted by the total number of sides of the corresponding cube. Pushing together a transmitting side of a cube A and a receiving side of a cube B connects GND and TX of A to GND and RX of B, enabling the transmission of the identity of A to B (Figure 3.4). If A has only one single transmitting side, no additional information is needed as the

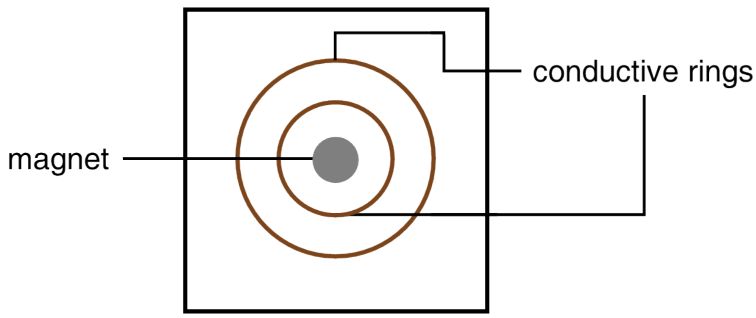


Figure 3.3: The receiving connective side of the cubes. Two conductive rings are arranged around the magnet in its center.

side's identity is already known. However, if A has more than one transmitting side, the corresponding side identity also has to be communicated. Afterwards, B holds all the necessary information for maintaining the virtual model, as B knows the identity of its involved side by its mapping to the actual pin of the processor. The connectivity information is then transmitted wirelessly to the AR application running on the HoloLens, where the virtual model is updated accordingly. There always have to be one transmitting and one receiving side involved in a connection. The usage of a combination of pins and rings as I/O interface for the microprocessors has two advantages compared to a simple plug system. It is not only easier to connect, having the user's restricted FOV in mind, it also enables elements to be rotated independently around the connection axis, which enables more complex structures to be built.
Concluding, the tangible AR system for object configuration relies on an embedded computation approach to determine the configuration of the tangible model, which then is transmitted to the AR application wirelessly. Fiducial markers are used to compute the spatial information of the physical structure. Afterwards, both information is combined to reproduce the current state of the structure including their configuration, position and orientation in space in a robust manner, such that the tangible components can easily be visually overlaid in real-time.

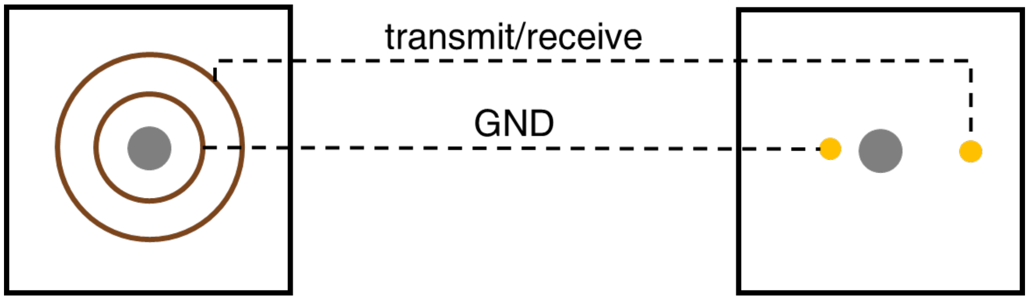


Figure 3.4: By connecting a transmitting side and a receiving side, the corresponding microprocessors are able to communicate.

3.2 Augmented Reality Application

To provide a realistic AR preview of the configured item, TAROC includes an augmented reality application, running on the Microsoft HoloLens. This application has to perform three tasks. First, a virtual counterpiece has to be registered for each of the tangible elements. Thereby, it is crucial that multiple of these counterpieces can be aligned without much effort, such that even complex combinations can be constructed in real-time. Second, the spatial information of the tangible elements has to be determined. As mentioned before, the TAROC system relies on a computer vision-based approach for that. On each of the elements' sides, a fiducial marker is attached. These markers include specific patterns and are preregistered, such that they can be found by computer vision algorithms in real-time. These algorithms also determine the position and rotation of the tracked elements relative to the tracking device. At last, the AR application has to combine the computed spatial information and the connectivity information received from the blocks on occuring connections and disconnections. Hereby, the connection and disconnection events are used to reconstruct a virtual model based on the composition of the cubes. This model has to contain the preregistered virtual counterpieces of included elements and at the end, the spatial information determined by the computer vision algorithms has to be taken into account to place the virtual model on the HoloLens' display correctly. Due to the blocks' integrated microprocessors and the wireless connection to the AR application, the composition of the tangible structure can be updated in real-time. As a consequence, the virtual counterpieces of connected elements can be aligned to each other before the rendering process, improving the accuracy and stability of the shown model. Overall, the AR application is the central point of the system, where all information comes together and is evaluated. Spatial information and connectivity information are combined to maintain and provide a realistic 3D preview of the configured item, which then overlays the physical structure in real-time.

3.3 Tangible Augmented Reality Configuration Wheel

So far, it is shown how the tangible elements are composed. Furthermore, an AR application is presented combining all of the available information to provide a realistic and 3D preview of the configured physical structure. The last core requirement of a configuration tool, which is missing so far, is the possibility to change specific attribute values of the configured item, for example the color of a car or the size of a bed. To enable users to manipulate the corresponding attribute values of the configured item, TAROC provides additional TAR configuration wheels. For attribute value personalization, the TAR approach is again preferred over buttons on a microprocessor or a web site to keep the interaction space and the interaction techniques of the overall system consistent and to thereby keep the system seamless.
The wheels consist of three different parts, which are stacked one onto the other (Figure 3.5). The first one is a small handle, on which the *attribute value circle* is placed. On the very top, the *reference circle* is attached, such that the attribute value circle is fixed in between the handle and the reference circle. Both of these circles are discs, whereby the attribute value disc is clearly bigger than the reference disc and furthermore, it is the only part of the wheel which can be rotated independently of the other parts around its center. Contrary to the handle, both of the discs are augmented with fiducial markers, enabling their rotation to be tracked by the augmented reality application. Each wheel can be used to select the value for a specific property. However, there can be several different configuration wheels for configuring different properties of a single item, for example one wheel to configure its color and another one to configure its

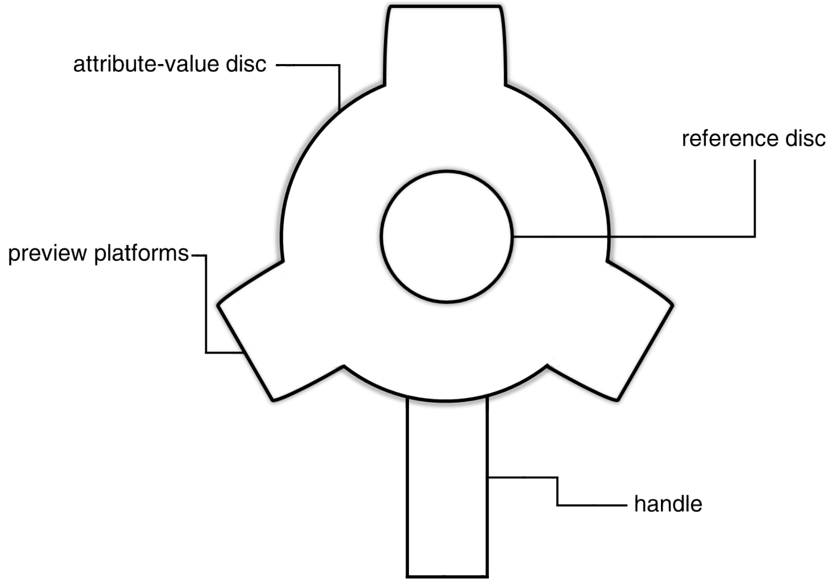
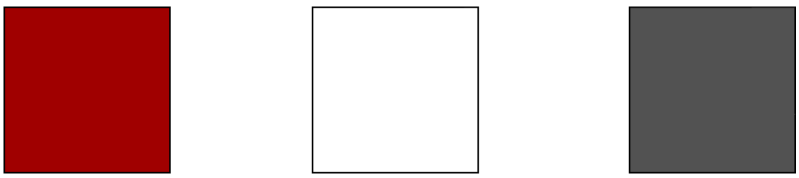


Figure 3.5: The three different parts of the configuration wheel are stacked onto each other.

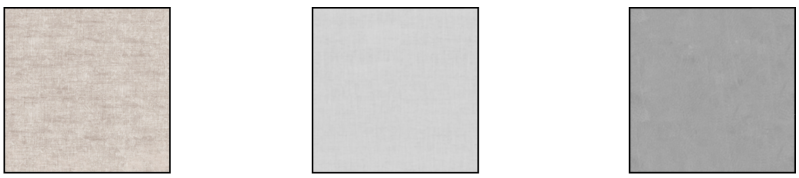
texture. The main interaction part of a configuration wheel is its attribute value disc, which is subdivided into several distinct sectors. Each sector represents one value for the attribute corresponding to the wheel and has an attached small platform giving place to real representatives of the value. Here, samples of e.g. materials and colors can be placed, providing original, realistic and tactile feedback. As the attribute value disc can be rotated around the wheel's center and the reference disc has a fixed rotation, a *selection area* can be defined above a wheel's reference disc. If a user rotates the attribute value disc, the position of the values' sectors relative to the selection area changes, enabling the value with minimal distance to be selected. As a consequence, users are able to manipulate visual attributes of an item by simply rotating the attribute value disc of the corresponding configuration wheels.
The handle's main purposes is to keep the attribute value disc and the reference disc into the HoloLens' camera's FOV. This is important, as both of them are augmented with fiducial markers, which need to be tracked. Additionally, users are given the possibility to hold the tool in one hand, while rotating and thereby selecting an attribute value with the other hand.
With TAROC's configuration wheels, users are given an easy to use TAR interface for attribute value selections. They can manipulate properties of their configured item in a direct and intuitive manner and further receive original, realistic and tactile feedback, which is not provided by up-to-date configuration tools.

3.4 Use Case: A Tangible Augmented Reality System for Sofa Configuration

To evaluate the given concept and to show a practical implementation of TAROC, a couch configuration tool is presented next. Hereby, a user can combine five tangible elements to configure a couch. The given tangibles are based on the most common couch elements available in online couch configuration tools, namely a one-seater, a two-seater, two corner-pieces and a chaise longue. These tangibles differ in their orientation of connective sides, their size and also in their aspect ratio to fit the corresponding couch element best. The couch configuration tool further includes three different configuration wheels, enabling users to manipulate the color, the material and the base type of their couch. Making use of them, users are capable of switching between the three colors red, white and dark-gray (Figure 3.6a). Furthermore, three different materials, namely leather, cloth and linen can be selected (Figure 3.6b) and last, the third wheel is used to choose between three different couch types[11,12,13] (Figure 3.6c). The different attribute values again were chosen based on their appearance in online configuration tools.



(a) Three different colors can be applied to the couches.



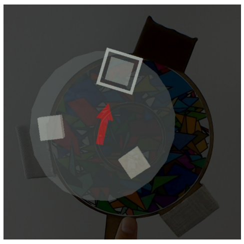
(b) Users can choose between linen, cloth and leather.

(c) The three different base types[11,12,13], represented by a corner piece, which can be selected by a user.

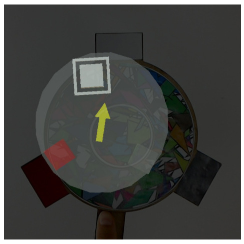
Figure 3.6: Besides the color, different materials and base types can be selected using the configuration wheels.

[11] `https://archive3d.net/?category=4859` (accessed on September 29, 2018)
[12] `https://archive3d.net/?category=4793` (accessed on September 29, 2018)
[13] `https://archive3d.net/?category=5178` (accessed on September 29, 2018)

A user is able to attach two tangibles in up to two dimensions, depending on the given elements, as vertical stacking is not reasonable in the chosen context. The connective sides of the elements are arranged in a way, which disables users to connect them incorrectly regarding their spatial orientation. Each of the cubes has one transmitting and one receiving side, wherefore each cube can be connected with up to two others at the same time. As there are no further restrictions regarding connections, each cube basically can be connected to every other one, allowing users to configure a huge variety of different couches. In Figure 3.7, different configured couches as well as the overlayed configuration wheels can be seen. The underlying implementation is documented in Chapter 4.
The presented use case of a couch configuration application is suitable to show the advantages of the tangible AR system for object configuration, because it covers all available features in a not too complex way. Additionally, TAROC has two advantages compared to conventional couch configuration tools. First, the feeling of a couch's material is an important design decision, which is not integrated in up-to-date, web-based configuration tools. Second, a realistic and 3D preview gives a more accurate and detailed impression of a couch and its dimensions compared to a simple two dimensional image.



(a) The wheel used to configure the material.



(b) The wheel used to configure the color.

(c) A couch of type one, consisting of a one-seater and a two-seater.

(d) A couch of type two, consisting of a corner-piece and a two-seater.

Figure 3.7: Two different configured couches and configuration wheels. The holograms seem to be offset on the pictures, because the HoloLens' camera is not positioned in the HMD's center, leading to a perspective displacement. Additionally, the live tracking of Vuforia has to be stopped in order to activate the mixed reality capture, resulting in further inaccuracies.

Chapter 4
Implementation

In Chapter 3, a concept for a TAR configuration tool is presented. Plain tangible blocks are combined with an AR application and an additional tangible attribute value selector enables the configuration and personalization of different objects. Additionally, the use case of a couch configurator is introduced. In this chapter, the implementation of the given use case relying on the presented concept is documented. First, the design of the tangible blocks is described, followed by the implementation of the tangible attribute value selector. An AR application, which augments the blocks and the attribute value selector, is documented last.

4.1 Tangible Blocks

Users interacting with TAROC are capable of composing different physical structures using tangible elements. To enable an easy adaption to a variety of different use cases, the elements have to be as generic as possible. Therefore, TAROC does not provide tangibles which match the shape of the corresponding virtual counterpieces perfectly, but rather plain and undetailed cubic blocks (Figure 4.1). Each block has to know its identity and has to be able to communicate it to connected other elements. Furthermore, the blocks have to detect occuring connections and disconnections by themselves and inform the AR application running on the Microsoft HoloLens about these events. Connected blocks further have to stay physically attached as long as they are not disconnected by the user. Last, the size of the blocks has to be considered. On the one hand, they have to provide enough space for the integrated hardware and also the fiducial markers require a specific size to enable proper tracking. On the other hand, large blocks are unhandy and furthermore require stronger physical connectors. Depending on the corresponding virtual counterpiece, the width and depth of the blocks differs

Figure 4.1: The tangible elements of TAROC are plain and undetailed blocks.

between 5.6 cm and 10 cm. All blocks have a height of 5.6 cm, which means that users easily can hold multiple blocks at the same time. To fulfill the given requirements, the following hardware is integrated into each of the tangible elements. First of all, the Wemos D1 Mini[14] is the microprocessor of choice. The arduino-based[15] chip has a length of 34.2 millimeters (mm), a width of 25.6 mm and weighs 3 grams. Next to its small size and its light weight, each processor has a built-in ESP-8266 WiFi chip[16], enabling wireless communication. Additionally, each block contains a suitable battery shield[17] in combination with a lithium-ion polymer rechargeable battery to supply the processor with power. The default JST-PH connector of the batteries are exchanged with a JST-XH connector, fitting into the port of the battery shield. Last, an USB charging cable is connected to the battery shield and integrated into the block's back, enabling the battery to be charged even though the hardware is not directly accessible anymore. The hardware integrated into an element can be seen in Figure 4.2.

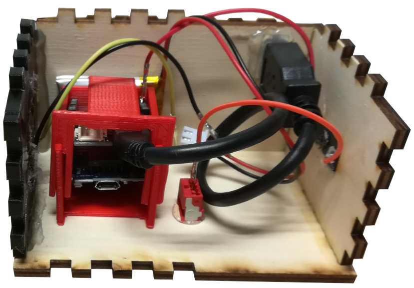
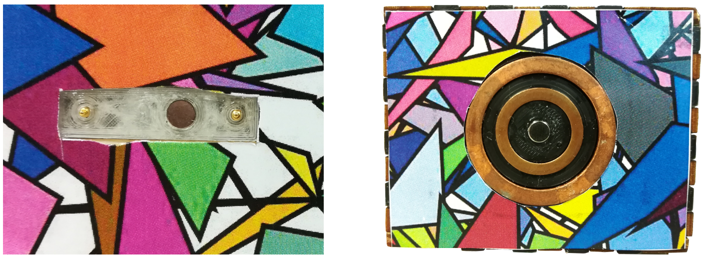


Figure 4.2: Each cube contains a microprocessor with a corresponding battery shield, a rechargeable battery and a charging cable, which is integrated into the block's back.

[14] `https://wiki.wemos.cc/products:d1:d1_mini` (accessed on September 29, 2018)
[15] `https://www.arduino.cc/en/Guide/Introduction` (accessed on September 29, 2018)
[16] `https://en.wikipedia.org/wiki/ESP8266` (accessed on September 29, 2018)
[17] `https://wiki.wemos.cc/products:d1_mini_shields:battery_shield` (accessed on September 29, 2018)

To enable a flawless data transfer from a cube A to another cube B, both cubes have to share the same GND and furthermore the transmitter pin (TX) of cube A has to be connected to the receiver pin (RX) of cube B. This means that transferring the ID of a cube to another one requires two separate connections between them, namely GND and transmit/receive. Therefore, each connective side has two integrated lines. The smaller ring of the receiving side as well as the more central pin of the transmitting side are connected to the corresponding microprocessors GND pin, while the outer ring is connected to RX and the second pin is connected to TX, enabling data transfer from one block to another. In each connective side (see Section 3.1), a magnet is integrated. By that, two connected cubes are pulled together. This enhances the robustness of the connection on the one hand, as a user explicitly has to disconnect the cubes, and on the other hand the polarity of the magnets prevent two transmitting sides or two receiving sides to connect. To further stabilize the connection between two cubes, *Pogo Pins*[18] are integrated into the transmitting sides instead of default pins. These pins have an integrated elastic spring, working against the bumpiness of the rings integrated into the receiving sides. Due to the integrated magnets, the material of the conductive rings not being magnetic is important, wherefore copper is the material of choice. All non-connective sides of a cube are laser-cutted wooden rectangles. The receiving sides are modeled using the software 'Fusion 360' by Autodesk[19] and afterwards 3D-printed. The transmitting sides consist of a laser-cutted frame in combination with a 3D-printed centerpiece, where the pins and the magnets are attached to. 3D-printing and laser-cutting is combined as printing is very time-consuming compared to cutting, but a laser cutter is not able to cut materials only halfway through, which is essential to attach the Pogo Pins as well as the copper rings.



(a) Pogo pins, integrated into a transmitting side, serve as output medium for the blocks.

(b) Two copper rings are integrated into each receiving side of a cube.

Figure 4.3: The connective sides of a tangible element.

[18] `https://www.harwin.com/products/P70-1000045R/#availability` (accessed on September 29, 2018)

[19] `https://www.autodesk.com/products/fusion-360/overview` (accessed on September 29, 2018)

```
while True do
    write ID to TX
    foreach RX receiver do
        if receiver.receivesID then
            if !receiver.hasConnection then
                sendConnectionEvent(cubeID, receiver.receivedID)
                receiver.hasConnection = true;
            end
        else
            if receiver.hasConnection then
                sendDisconnectionEvent(cubeID)
                receiver.hasConnection = false;
            end
        end
    end
end
```

Algorithm 1: Pseudocode describing the microprocessors' behavior.

In general, the presented concept enables a cube to be connected to up to six other blocks. As the integrated Wemos processors only offer a single TX and a single RX by default, the SoftwareSerial library for ESP-2866 boards[20] is used to support multiple connections at the same time. By that, all digital pins of a processor can serve either as TX or RX. In the following, the number of a cube's connective sides is restricted to two, a receiving and a transmitting one, as the implemented use case does not require more connections. As the identity of a cube's transmitting side is clearly distinct in the given context, transmitting only the cube ID is sufficient on an occuring connection. However, the number of possible connections can easily be increased by simply integrating more connective sides into the cube, connecting them to the microprocessor and add the transmitting side's identity to the connection event. The general behavior of the Wemos boards can be seen in Algorithm 1.

In each iteration of an infinite loop, a microprocessor writes its identity to all TX, such that connected cubes receive it permanently. Afterwards, each RX is tested for an incoming ID. For each of these RX it is stored whether it is currently connected to another tangible element or not. If a pin, which is not connected, starts receiving an ID, a new connection has been established and is communicated wirelessly. If a pin, which is connected, stops receiving, a disconnection occured and is reported, too. By that, connection events and disconnection events are detected and communicated with help of the integrated ESP-2866 WiFi chips, such that the virtual model can be maintained in real-time.

[20] `https://arduino-esp8266.readthedocs.io/en/2.4.2/libraries.html#softwareserial` (accessed on September 29, 2018)

Figure 4.4: Each configuration wheel consists of three parts.

4.2 Tangible Attribute Value Selector

One of the most important features of a configuration tool is the possibility to personalize specific attributes of the configured item. The adaptable attributes depend on the use case, in context of a couch configuration system the color, texture and base type can be adjusted. TAROC relies on configuration wheels to provide this utility. These wheels consist of three different, laser-cutted wooden parts (Figure 4.4), which are connected with a simple stack system and a single ball bearing. All connected components of the configuration wheel are fixed together using glue. The first and lowermost component is a simple handle, which again can be subdivided into two different parts. A connector square with a size of 5 cm x 5 cm is used for connecting the other components. A rectangle of size 18 cm x 3 cm is attached to the square and offers a comfortable way to hold the configuration wheel. The handle mainly has two purposes. First, it offers users the possibility to hold the wheel in their hands, such that they can have a closer look at the attached real samples without restricting the functionality. Second, the state of the attribute value disc and the reference disc are tracked by a computer vision algorithm, which means they both have to be in the FOV of the HoloLens' camera. As the camera is placed near the upper edge of the HMD, the wheels need to be right in front of the user's eyes to enable a proper tracking. This is achieved by relying on the handle, as it automatically brings both of the circles upwards into the camera's FOV.

On top of the handle, the attribute value disc is placed. It has a diameter of 18 cm and three attached platforms of size 5 cm x 3 cm, which are distributed equally around the disc. Real samples of the corresponding attribute values are attached to these platforms, offering users to receive realistic visual feedback, which is not influenced by the properties of the used display and additionally haptic feedback. For the color wheel, these samples are pieces of paper dyed in the available colors (Figure 4.5a). Small pieces of actual cloth, leather and linen are attached to the material wheel (Figure 4.5b) and for the base types, small 3D-printed representatives can be seen (Figure 4.5c). In the center of the attribute

value disc, a ball bearing is fixed, enabling the attribute value disc to be rotated independently of the other parts of the configuration wheel. At last, the disc is augmented with one circular fiducial marker, whose rotation is tracked by the augmented reality application.
The last part on top of a wheel is the reference disc. With a diameter of 6.5 cm, it is the smallest component of the structure. Its surface is also completely covered by a fiducial marker. The size of both of the discs is justified by the attached markers, which require a specific minimal size to be tracked properly. The connector square of the handle, the ball bearing in the center of the attribute value disc and also the reference disc have a small hole in their center, such that the stack system, which connects all components, can be attached to them.

(a) On the color wheel, original samples of the available colors can be seen.

(b) The material wheel provides samples of leather, linen and cloth such that their tactile feeling can be included into the design process.

(c) 3D-printed miniature versions of the base types are attached to the preview platforms of the type wheel.

Figure 4.5: The configuration wheels provide realistic visual as well as haptic feedback for manipulable properties of the configured item.

Each value corresponds to a specific *value part* of its attribute value disc's fiducial marker, right next to its real representative, such that these markers overall consist of three distinct sections. The ball bearing is used to attach the attribute value disc to the other parts of the wheel, such that it can be rotated independently. By defining the selection area above of the reference disc and tracking the rotation of the attribute value disc relative to the reference disc, the value part which is currently rotated upwards can be determined and is chosen. This means that an attribute value can be changed by simply holding the corresponding wheel and rotating its attribute value disc. The values themselves are again displayed in AR on top of the corresponding part of the disc, enabling users to have a first impression on how the value looks like in augmented reality. The virtual representative of the chosen value is highlighted by a small frame, such that users exactly know their configuration all the time. If a user rotates an attribute value disc, such that the selected value changes, the frame switches to the newly chosen one and additionally, users receive auditive feedback by hearing a slight click-sound.

4.3 Augmented Reality Application

The augmented reality application is the central point of the system. The connectivity information, provided by the blocks, are integrated with the spatial information of the computer vision-based cube tracking. Furthermore, the state of the configuration wheels is tracked to enable the personalization of specific properties by users. Therefore, tracking several visual markers at the same time is the application's core requirement. Additionally, wireless communication with the tangible blocks needs to be supported, such that the connectivity information can be received and evaluated. Due to the existing integration with the Microsoft HoloLens, the application is developed using the Unity3D engine[21].

At least one of the tangible blocks as well as the state of the configuration wheels have to be tracked by the application, to display the corresponding virtual prototype of the configured item. For a correct reality augmentation, the spatial information of the blocks, namely their position and rotation relative to the HMD, has to be determined and applied to the virtual counterpieces. Moreover, the rotation of the configuration wheels' attribute value discs relative to the corresponding reference disc has to be known, such that the attributes of the virtual prototypes can be manipulated. TAROC relies on the Vuforia library[22] for the tracking process, which is a state-of-the-art computer vision-based tracking library integrating well with the Unity3D engine and the Microsoft HoloLens. Vuforia is a feature-based tracking library, which means that images of the tracked objects need to be registered to its service. These images are analyzed for feature points, namely color contrasts, edges and corners. The camera image, on which a Vuforia-based application relies, is also analyzed for these features and afterwards compared to the registered markers. By that, the library detects objects and is further able to compute and provide the spatial information of the monitored object in real-time.

User interactions with the tangible cubes lead to the generation of two different events. If the transmitting side of a block A is connected to the receiving side of another block B, B creates a connection event, containing the ID of A and its own one and communicates it. If the two blocks are separated again, B generates a disconnection event, containing only its own ID and sends, too. Therefor, TAROC relies on WiFi, making use of the microprocessor's integrated ESP-2866 chips. To enable multiple users to interact with TAROC at the same time, a simple web server running on a separate host computer is used to broadcast the generated events to several connected HMDs. On attribute value selections, corresponding events are generated and spread with help of the web server, too.

The implementation of the augmented reality application is based on the Model-View-Controller (MVC) design pattern (Figure 4.6). This means that the model, which is basically the current state of the system and does not contain computa-

[21]`https://unity3d.com/` (accessed on September 29, 2018)
[22]`https://www.vuforia.com/` (accessed on September 29, 2018)

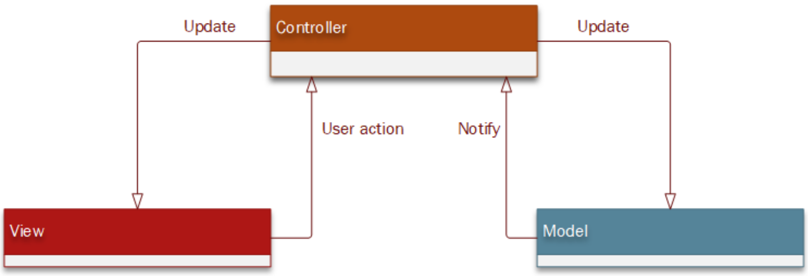


Figure 4.6: The MVC design pattern subdivides a program in three different modules.

tional logic but only data, is isolated from the programmatic logic contained in the controller. Furthermore, views, which in general are the interface for users or connected other modules, again are separated from the model and the controller. This approach offers the possibility to modulate a program in such a manner that the internal representation of data can be changed without the need to adapt the logic contained in the controller scripts or the user interfaces and vice versa. Furthermore, the separation of model and views enables multiple views to operate on the same data without the need to adapt the model, which simplifies the appending of additional views a lot.
Besides, Unity3D offers a parenting hierarchy, which is very useful for the given application. This means that several child objects can be attached to a parent in a tree alike structure. By changing the position and rotation of a parent node, all of its children are moved and rotated accordingly. Last, it has to be stated that applications developed for the HoloLens do not support socket-based networking techniques, which are supported by the Unity3D engine and vice versa. Therefore, two different network client scripts are required. The first one is based on a *MessageWebSocket*[23] and is enabled in the HoloLens app. The second one is based on the *SocketIO* unity asset[24] and is used to run TAROC in the Unity3D editor to simplify the development and debugging of the system.
The augmented reality application itself can be subdivided into two parts. The first one addresses the attribute value selection and the second one controls the maintenance of the virtual model.

4.3.1 Attribute Value Selection

To manipulate an attribute value, it has to be sufficient to simply rotate the corresponding attribute value disc, while the wheel is tracked by the AR application. To realize this approach, the reference disc and the attribute value disc are augmented with fiducial markers, which are registered to the Vuforia

[23] `https://docs.microsoft.com/en-us/uwp/api/windows.networking.sockets.messagewebsocket` (accessed on September 29, 2018)
[24] `https://assetstore.unity.com/packages/tools/network/socket-io-for-unity-21721` (accessed on September 29, 2018)

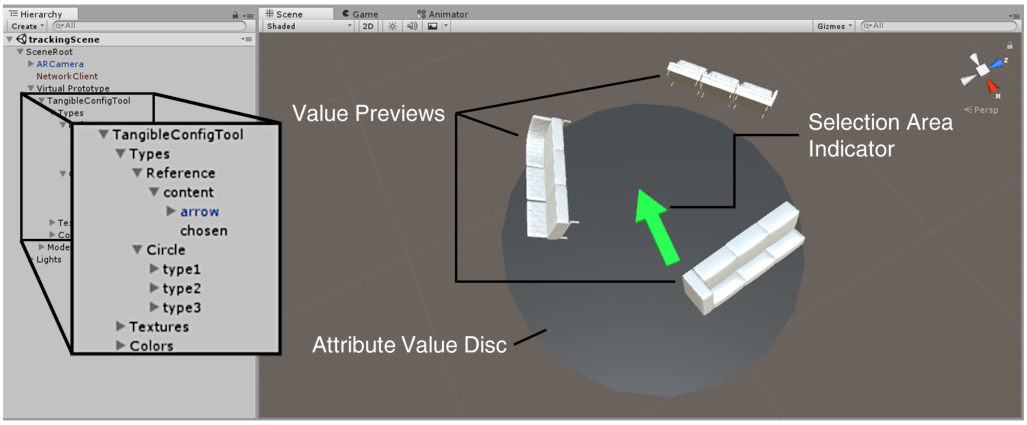


Figure 4.7: The setup of the type selection within the Unity3D engine.

service. Corresponding objects are modelled within the Unity3D scene and the gathered spatial information is applied to them. For each attribute value, a corresponding object as well as a virtual preview is attached to the disc's model. As a consequence of Unity3D's parenting functionality, the previews are moved according to user's rotations automatically. Additionally, an invisible object is used to mark the selection area, which is further highlighted with an arrow in AR. An example of an attribute value selection setup within the Unity3D scene is shown in Figure 4.7. The algorithm used to update the selected value is depicted in Algorithm 2.

```
Input: configWheel
while configWheel.referenceVisible & configWheel.attValVisible do
    chosen = configWheel.currentValue
    minDist = distance(configWheel.reference, chosen)
    foreach Value val do
        dist = distance(configWheel.reference, val)
        if dist < minDist then
            chosen = val
            minDist = dist
        end
    end
    if chosen != configWheel.currentValue then
        configWheel.updateCurrentValue(chosen)
    end
end
```

Algorithm 2: Pseudocode describing the attribute value selection process.

As long as both, the reference disc's marker and the attribute value disc's marker are being tracked, the distance of the currently chosen value to the selection area is computed as reference distance. For each of the different values' objects, the distance to the selection area is computed and compared to the reference. If it is smaller, the reference is updated accordingly and the corresponding object is stored temporarily. By that, the value object which has minimal distance to the selection area is determined. At the end, this value is compared to the currently selected value to figure out, if a change of selection occured. In this case, the model is updated accordingly.

4.3.2 Maintaining the Virtual Model

To overlay the tangible composition with a virtual model correctly, the received connectivity information has to be integrated and the position and rotation of the whole model has to be adjusted according to the spatial information provided by Vuforia. Therefore, each tangible element needs a virtual counterpiece within the AR application. Prefabs of these counterpieces are placed in the project directory and instantiated at run-time. The mapping of a tangible element's identity and a prefab as well as the identity of an element's connective sides are provided within a configuration file. By that, the received events, which contain only IDs, can be applied to the actual models. All components of the virtual model maintain a list of their connected neighbors, which result in a graph alike structure for each combination of tangibles. Furthermore, the elements of a composition are children of the same parent, which is also referred to as *root* of its model. As a consequence, it is sufficient to apply the gathered spatial information to a parent to position and rotate the corresponding virtual model correctly.
In the following, it is explained how the computed spatial information of a single element affects the whole corresponding virtual model. Additionally, it is shown how disconnection and connection events, which are generated by the embedded microprocessors and sent to the AR application, are evaluated.

Aligning the Physical and the Virtual Model

Objects, which have to be tracked by Vuforia, need to be preregistered on the Vuforia developer portal[25]. For each of these objects, the visibility status is accessible. Moreover, its rotation and the position of its center relative to the tracking device are provided, if the object is currently being tracked. Based on that, each root maintains a set, containing its visible child components to decide whether the corresponding composition of virtual counterpieces has to be rendered or not. If at least one of them is being tracked, the rendering of the whole composition is enabled and the alignment to its physical structure, making use of the spatial information of one of the monitored components, is activated. In general, the provided connectivity information are quite accurate, wherefore it is sufficient to rely on the rotation and the position of a single tracked object exclusively. This can be achieved by rotating and translating a model's root, as all virtual elements of the corresponding tangible combination are subordinated

[25] `https://developer.vuforia.com/` (accessed on September 29, 2018)

to it.
Vuforia provides the position of the observed object's center as well as its rotation, which in general does not match the center and the rotation of the corresponding model's root. As a consequence, the gathered information cannot be used directly to update the root and thereby the whole model. The positional information of a component **x** is applied to its root **r** by computing the difference of the component's current position and the new position provided by Vuforia and translating the root by that:

position(**r**) = position(**r**) + vuforiaPosition(**x**) - position(**x**)

To update the rotation, a similar approach is used, but instead of computing the difference of the current and the new one explicitly, inverse rotations are applied. Therefore, the rotation of **x** relative to **r** additionally has to be taken into account. Three different rotations have to be applied to **r** hence:

1. Inverse current rotation of **r**.
2. Inverse current rotation of **x** relative to **r**.
3. New rotation of **x**, provided by Vuforia.

It has to be considered that all of these rotations have to be performed around the tracked components center, and not around the roots center.

Evaluating Connectivity Information

To explain the evaluation of the connectivity events being generated by the tangibles and sent to the AR application, a representative scenario is introduced: A two-seater and a chaise longue are already connected and the chaise longue gets separated. Afterwards, a corner-piece is connected to the two-seater (Figure 4.8).

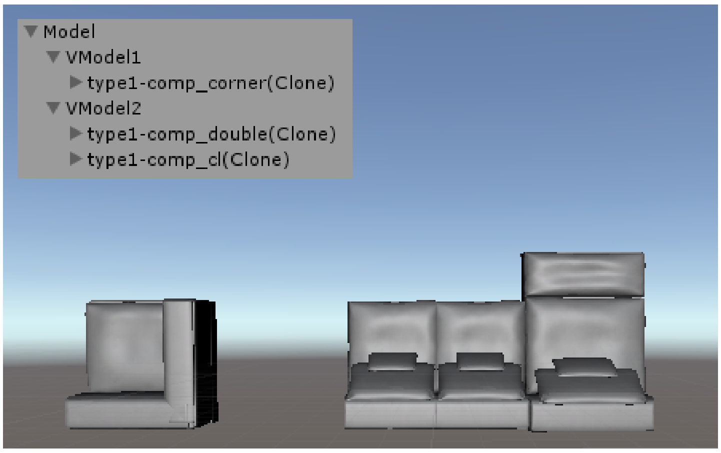
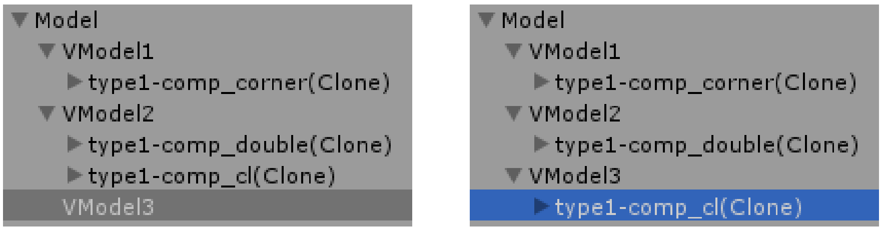


Figure 4.8: A chaise longue is connceted with a two-seater. Next to them, a corner-piece can be seen.



(a) An empty root is created.

(b) The speparated model is attached to the new root.

Figure 4.9: During the disconnection process, a new root has to be created to which the detached model is parented.

In detail, the transmitting side of the chaise longue is connected to the receiving side of the two-seater and gets pulled apart. Therefore, the two-seater block detects the disconnection and generates the corresponding event accordingly. As a consequence, the chaise longue is interpreted to be separated from the main physical structure.
The first step of the disconnection process is to create a new root, such that the separated model can be positioned and rotated later on (Figure 4.9a). Next, both elements are removed from each other's neighbor list, resulting in the underlying graph structure to be splitted. The root of the disconnected model is updated by setting the parent of all of its components to the new one. If the separated model consists of more than a single element, a breadth-first search algorithm is used to find its components and update their parent accordingly. In this specific scenario, only the parent of the chaise longue has to be set (Figure 4.9b). Afterwards, all elements are subordinated correctly, but the separated elements are still aligned relative to their former parent. Thus, their position and rotation has lastly to be set relative to the new root in order to enable the alignment to their physical counterpieces later on. Thereafter, the two-seater and the chaise longue can be moved and rotated independently (Figure 4.10).

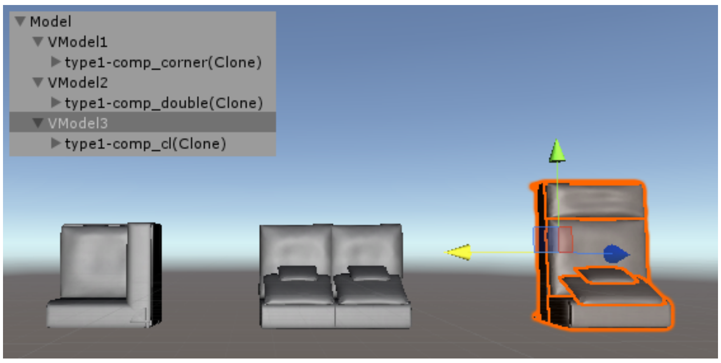


Figure 4.10: After the disconnection is finished, both models can be moved independently.

(a) First, the rotation is adjusted. (b) Afterwards, the position is updated.

Figure 4.11: The corner-piece is aligned to the two-seater.

The next part of the scenario addresses a connection process: The transmitting side of a corner-piece is pushed against the receiving side of the two-seater. As a consequence, the two-seater detects the connection, generates a connection event and communicates it. The corner-piece is interpreted to be connected to the main physical structure hence.
To attach the virtual corner-piece to the virtual two-seater accordingly, they firstly are added to each other's neighbor list in order to update the underlying graph structure. The corner-piece's root is rotated next according to the connected physical sides of the corner-piece and the two-seater (Figure 4.11a). As a consequence of rotating the root, the alignment of its model's components to each other is obtained, if it consists of multiple elements.
Afterwards, the components of the attached composition are translated. For each component **c** that has to be moved, due to an occuring connection between a block **a** and a block **b**, where **a** is a part of the same composition as **c** and gets attached to **b**, the updated position can be computed as following:

$$\text{position}(\mathbf{c}) = \text{position}(\mathbf{b}) + \mathit{connectionDirection} * [\text{extent}(\mathbf{a}) + \text{extent}(\mathbf{b})] + [\text{position}(\mathbf{a}) - \text{position}(\mathbf{c})],$$

where *connectionDirection*, as well as the considered extents are determined by the arrangement of the, into the connection process involved, connective sides of **a** and **b**. In the given example, only the corner-piece has to be translated (Figure 4.11b).

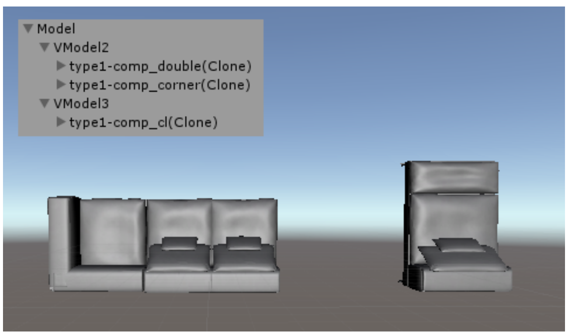


Figure 4.12: The final state of the representative scenario.

However, for compositions consisting of multiple components, the translation has to be applied to every single one.
Lastly, the root of the attached model is updated and the former one is detroyed. The final state of the scenario can be seen in Figure 4.12.

Chapter 5
Evaluation

In contrast to common configuration tools, the tangible AR system for object configuration combines augmented reality techniques with a tangible user interface for an improved usability and user experience. To provide robust tracking and reality augmentation, the system relies on embedded microprocessors in combination with computer vision-based marker tracking. This approach is relatively complex compared to other TAR techniques, which for example only rely on marker tracking [20, 5]. Therefore, it has to be shown that relying on the combination of embedded computation and fiducial markers really is more valuable. This section will go into more detail regarding both of these aspects. First, the advantages of combining embedded computational devices with fiducial markers will be discussed in a technical evaluation. Afterwards, the usability and user experience of the TAROC system will be evaluated.

5.1 Technical Evaluation

Using a marker-based approach for a TAR interface has many advantages. A camera as external sensor, which is already integrated in many HMDs[26,27], is sufficient, wherefore no additional capturing device needs to be used. Furthermore, there are excellent computer vision frameworks[28,29] simplifying the tracking process to a minimum. However, relying only on a single camera also has one crucial issue. If markers are not visible to the camera properly, the tracking breaks and no spatial information can be computed. In the following, two different sce-

[26] `https://x.company/glass/` (accessed on September 29, 2018)
[27] `https://www.microsoft.com/de-de/hololens` (accessed on September 29, 2018)
[28] `https://github.com/artoolkit` (accessed on September 29, 2018)
[29] `https://www.vuforia.com/` (accessed on September 29, 2018)

narios potentially leading to a loss of correct tracking are investigated. It will be evaluated, how the TAROC system behaves in these scenarios compared to an application relying on marker tracking only.

5.1.1 Occlusion

Users interact with TAROC in a direct way using their hands. The different tangibles can be picked up, moved around and rotated freely in 6-DOF. Thereby, the possibility of a user's hand occluding one or more tangible elements to the camera is high (Figure 5.1). For marker-based applications, this is a crucial point because a marker being occluded leads to its virtual counterpiece not being rendered as no spatial information can be computed. For structures consisting of multiple blocks, TAROC softens this issue by precomputing the corresponding 3D model with help of the integrated microprocessors. Thus, the number of markers which have to be detected and tracked by the tracking application decreases to a single one. In contrast, applications based only on fiducial markers need to track each element separately, wherefore occlusions lead to an incomplete AR preview.

Method

To evaluate this, a combination of two tangible blocks is positioned in front of a webcam[30] with a fixed distance of 25 centimeters (cm). The webcam is used for the technical evaluation instead of the HoloLens as the HMD does not support taking screenshots while the Vuforia library accesses its camera for marker tracking. The distance of the blocks to the camera was chosen to approximately match the interaction distance of a user sitting on a chair and using the system. The first block has a width and a height of 5.6 cm and a depth of 7 cm and corresponds to a single-seater. The second one corresponds to a two-seater and has a width of 10 cm, a height of 5.6 cm and depth of 7 cm. The combination is frontal aligned to the camera such that for both of the blocks, only the front side can be used for tracking. To exclude lighting as a relevant factor for the occlusion problem, three

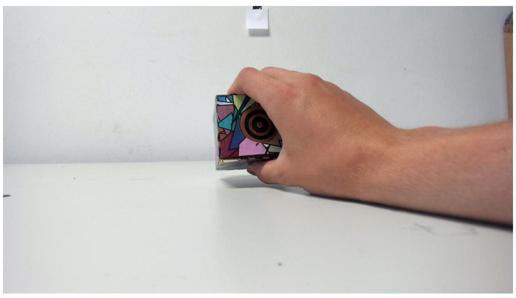


Figure 5.1: A block being partially occluded during user interaction.

[30] https://www.logitech.com/de-de/product/brio (accessed on September 29, 2018)

different lighting conditions are simulated using spotlights, including different light intensities and also different angles of incidence. Furthermore, four different wooden rectangles with a width of 10 cm and heights of 1.4 cm, 2.8 cm, 4.2 cm and 5.6 cm, respectively corresponding to 25%, 50%, 75% and 100% of a block's height, are used to occlude one of them (Figure 5.2).

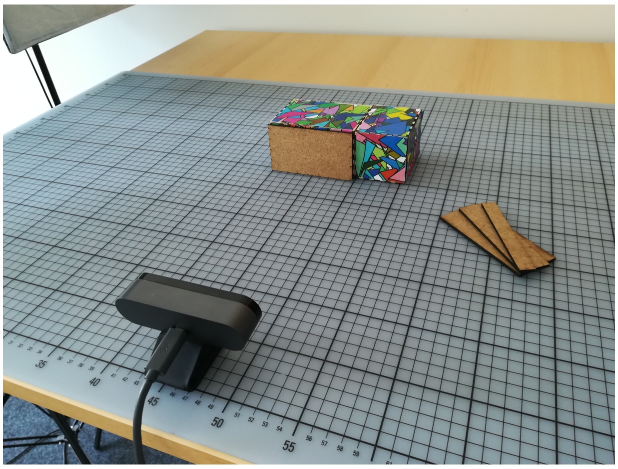


Figure 5.2: The setup for the technical evaluation of the occlusion scenario.

The Vuforia library[31] extracts feature points from registered markers and uses them for tracking. Thereby the tracking of a marker decreases if less of its feature points are visible to the camera. As the visible area of the two-seater tangible is bigger and offers more feature points, it is chosen to be the occluded block.

Results

Figure 5.3 depicts the results of the evaluation. Each row represents a different scenario, where the occlusion of the two-seater block increases with each row. On the left, the scenario is shown without augmentations. In the center column, the augmentations of a marker-only-based application can be seen and finally on the right, the TAROC system was used to track and augment the tangible model. The results of the occlusion scenario are the same for all three tested lighting conditions, which shows that the advantage of TAROC in context of occlusions during the tracking process is not influenced by lighting. With few occlusions (0% and 25%), tracking works for both approaches (Figure 5.3a and Figure 5.3b). If only 50% of a marker is visible (Figure 5.3c), the precision of the marker-only-based approach decreases and the virtual model flickers around the actual position of the tangible counterpiece. Contrary, TAROC still renders the virtual model completely without any loss of precision or flickering. At last, a marker being occluded by 75% or more cannot be tracked anymore such that the marker-only-based approach is not able to render the corresponding

[31] `https://www.vuforia.com/` (accessed on September 29, 2018

Model **Marker-only-based** **TAROC**

(a) 0% occluded

(b) 25% occluded

(c) 50% occluded

(d) 75% occluded

(e) 100% occluded

Figure 5.3: With increasing occlusion, the application based only on marker tracking is not able to overlay all parts of the model. Contrary, TAROC shows the virtual counterpieces of all blocks independent of occlusions.

virtual model. In contrast, TAROC shows the virtual model of the one-seater, as well as the one of the two-seater (Figure 5.3d and Figure 5.3e). As can be seen, one of the blocks being occluded does not have a negative impact on the tracking and augmentation provided by the TAR system for object configuration. These observations can be explained with the cubes' embedded computational devices. By determining the composition of the physical model independent of its visibility, TAROC is able to align the counterpieces of the connected blocks to each other without the need to track the elements. Hence, the complete virtual model can be positioned correctly according to the spatial information of a single fiducial marker, enabling a correct augmentation of partially occluded compositions. Contrary, the AR application, which is based purely on marker tracking, is not able to put the virtual counterpieces in relation. This means that each block has to be tracked on its own to be augmented, wherefore only the visible elements of a partially occluded composition can be overlayed properly.

5.1.2 Perspective Distortion

While interacting with TAROC, users rotate tangible structures to look at all sides of their corresponding virtual previews. Thereby, the image of a marker, which is attached to one of the tangible blocks, received by the camera is distorted perspectively due to the rotations. At some point, this has a negative impact on the marker tracking, because the distorted marker on the camera image cannot be matched to its registered pattern anymore. As the provided tangible elements have a marker attached to each of their sides, this is not an issue for single blocks because a rotation leading to the distortion of one of the markers will bring another one to the front, which then can be tracked instead. Contrary, if two or more blocks are connected and rotated, some of them will be occluded by others in a way that only distorted markers are visible to the camera for them (Figure 5.4). This results in an incomplete AR preview, as the distorted markers cannot be tracked properly, thus no spatial information is computed and the corresponding virtual models cannot be rendered. The TAROC system overcomes this issue using the connectivity information provided by the integrated microprocessors. As the virtual model is computed and built without the need of any marker being visible to the camera, the spatial information of a single marker is sufficient to align and render the complete AR preview correctly. This condition is always fulfilled in the given context as rotations which lead to distortions of some of the structures markers also bring others to the front, enabling them to be tracked correctly.

Figure 5.4: Due to the rotation, one of both blocks is almost invisible to the camera.

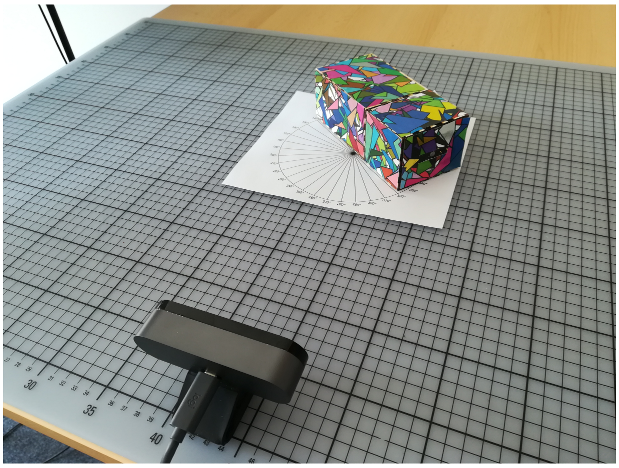


Figure 5.5: The setup for the evaluation of the perspective distortion scenario.

Method

To evaluate on that, a combination of two tangible blocks is placed on a fixed position with a distance of 25 cm to a webcam. Instead of the HoloLens, the webcam is used for the technical evaluation as it is not possible to take screenshots with the HMD while the Vuforia library accesses its camera. The distance between the block composition and the camera was chosen to approximately match the interaction distance of a user sitting on a chair and interacting with the system. To analyze the best and worst case, which depend on the quality of tracking of a cube and hence on its feature points, the one-seater block, which has the smallest sides and therefore the fewest feature points, and the two-seater block, which has the largest sides and thus the most feature points, are used. Three different lighting conditions including different intensities and angles of incidence are simulated using spotlights, to exclude lighting as a relevant factor for the given issue. Next, the combination of these blocks is rotated stepwise by 10° between -70° and 70°, such that each of both cubes is distorted once. To rotate the composition correctly, a printed circle including lines to indicate 10° steps is used for the rotations. The setup for the evaluation of the perspective distortion can be seen in Figure 5.5.

Results

In Figure 5.6, the results of the evaluation are depicted. In the left column, the rotated blocks in different scenarios can be seen without any augmentation. In the center, an application relying on marker tracking only was used to track and augment the cubes and last, in the right column, the outcome of the TAROC system is presented. For minor rotations, the perspective distortion does not have an impact on the tracking performance, as both of the approaches are able to track both cubes and render their corresponding virtual counterpieces (Figure 5.6a and Figure 5.6b). At a rotation which is greater or equal to 40°, the block of

Model **Marker-only-based** **TAROC**

(a) Block combination rotated by 0°. The initial situation for the investigation of the perspective distortion scenario.

(b) Block combination rotated by 30°. For minor rotations, both approaches are able to track the composition correctly.

(c) Block combination rotated by 40°. The single-seater cannot be tracked anymore by the application based only on marker tracking, due to the perspective distortion

(d) Block combination rotated by -40°. Because of the higher number of feature points, the two-seater still can be tracked by both approaches.

(e) Block combination rotated by -50°. In contrast to the marker-only-based approach, TAROC is still able to overlay the complete composition.

Figure 5.6: With increasing rotation angle (40°for the single-seater and 50°for the two-seater), the marker-tracking-only-based application (center) is not able to overlay all parts of the model anymore. Contrary, TAROC (right) shows the virtual counterpieces of all of the given blocks independent of the perspective distortions.

the single-seater cannot be tracked anymore by the marker-tracking-only-based application (Figure 5.6c). In contrast, the TAROC system still renders the complete virtual model. For the larger block such a rotation is not a problem due to the higher number of feature points in the visible area, regardless of the used application (Figure 5.6d). However, for rotations which are greater or equal to 50°, tracking the two-seater's block is also not possible anymore, wherefore the corresponding virtual counterpiece is not rendered by the application that is based only on marker tracking. Contrary, TAROC again is able to display the virtual models of all involved tangibles, independent of the model's rotation. Similar to the occlusion scenario, the lighting situation does not influence the distortion scenario's results as both approaches behave the same in all of the tested lighting setups. This results can be explained with the embedded hardware again. As TAROC aligns the virtual counterpieces to each other on connections, the complete virtual model can be positioned and rotated to the tracked marker of the front block, wherefore perspective distortions do not impact the reality augmentation provided by TAROC negatively. In contrast, the application based only on marker tracking needs to track each tangible element separatly to position its virtual counterpiece correctly. As the backmost cube cannot be tracked due to the perspective distortion, the application is not able to provide spatial information for the corresponding virtual model, which leads to the block not being overlayed.

5.1.3 Discussion

Computer vision-based applications, which rely on fiducial markers to track objects, depend on a good tracking quality to ensure a flawless user experience. This quality is impacted negatively by multiple aspects.
Firstly, the lighting situation has a major impact on the image received by the tracking device. On a very dark image, the computer vision algorithms are not able to detect the tracked objects. On the other hand, the image being to bright results in a bad tracking experience as well. Additionally, light highlights on the tracked objects also have a negative impact. Secondly, there are several aspects occuring during user interactions which need to be considered. With an increasing distance between the tracking device and the markers being tracked, the size of their camera image decreases leading to difficulties detecting their points of interest and hence, the items cannot be tracked properly anymore. As a result of fast motions, similar effects can be observerd. Lastly, occlusions as well as perspective distortions lead to fiducial markers not being visible to the tracking camera in a proper manner. As a consequence, the underlying algorithm is not able to recognize the corresponding items such that the tracking breaks.
To soften these negative impacts on the tracking performance, TAROC relies on embedded microprocessors in each of its tangible elements. The processors are connected to copper rings and pins being integrated into the blocks sides and serving as their I/O interface. Thereby, the blocks are able to detect occuring connections and disconnections and to communicate them to the AR application, which evaluates this connectivity information to compute and align a virtual model before the rendering process. As a consequence, the number of fiducial

markers which have to be observed to ensure a flawless augmentation of tangible compositions decreases. Instead of detecting one marker for each block separately, it is sufficient to track a single marker for each combination of tangibles and to rotate and position the precomputed virtual model accordingly. The presented technical evaluation investigates on this approach by simulating two different scenarios occuring during user interactions in combination with different light settings, and by comparing it to a marker-tracking-only-based approach for an AR application.
The first scenario addresses occlusions of tracked elements by a user. It shows that markers being occluded by more than approximately 50° cannot be detected properly anymore. As a consequence, the spatial information of their corresponding tangibles cannot be computed, wherefore the approach based exclusively on marker tracking overlays compositions including such blocks only partially. Contrary, by precomputing and aligning the whole virtual model beforehand, TAROC provides a complete reality augmentation despite of several elements being occluded, as long as a single marker can be tracked properly. Similar findings can be reported for the second scenario, which addresses perspective distortions, resulting from rotations during user interactions. Depending on the size of the attached fiducial markers, parts of compositions, which are rotated by more than approximately 50° cannot be tracked anymore. For the approach based only on marker tracking, this again results in an incomplete reality augmentation, as the spatial information of these parts cannot be computed. In contrast, TAROC again is able to overlay such block compositions correctly and completely as long as a single marker is being tracked. Additionally, blocks being completely invisible to the camera and also highlights on several blocks do not impact the reality augmentation of TAROC negatively if at least one marker is being observed properly, because the complete virtual model is precomputed and aligned beforehand.
Concluding, it is shown that relying on connectivity information determined by embedded computational devices really is valuable, as it enhances the robustness of the tracking and thereby the quality of a user's reality augmentation experience a lot.

5.1.4 Limitations

Although the presented study investigates important aspects occuring during user interactions, several additional factors that affect the tracking, are not considered. Firstly, fast movements of the tangibles result in their image received by the tracking camera to become blurry. Secondly, even small changes of the lighting situation, leading to highlights on the monitored markers for example, can have a major impact on the tracking quality. Lastly, the distance between the camera and the tangibles varies in a real interaction scenario. Increasing this distance leads to a decrease of a marker's size on the image received by the tracking device, which makes it difficult to find them.

These aspects limit the validity of the presented evaluation. However, all these negative impacts on the tracking quality also affect applications based only on marker tracking similarly, wherefore TAROC's approach still seems to be superior.

5.2 User Evaluation

By combining AR and a TUI including real materials samples for a configuration tool, users are not only enabled to see a realistic preview of their configured item in 3D, they further get an impression on how the product will feel like in the end. Both of these techniques are supposed to increase the usability and user experience of the interface, which overall is one of the most important motivations to provide a TAR interface for object configuration instead of following the current standard and relying on a simple web interface. In this section, a user evaluation is presented to investigate the advantages and disadvantages of this approach in context of couch configuration.

5.2.1 Participants

To investigate TAROC's usability, seven young adults volunteered to participate in this user study without any reward. Three of them are males at the age of 22 to 25 and the remaining four are females at the age of 23 to 26. Two of them already have experience with AR and also have a basic knowledge about difficulties from relying on fiducial markers. Three attendants live with their parents, two others live with their partner, one participant shares an apartment with a friend and the last one lives alone. Their living situation is interesting, as it influences their experiences with configuration tools as well as the relevance of such applications for them. Last, none of the participants reports to have a poor eyesight at the time of the evaluation, being considerable during interactions with an HMD.

5.2.2 Method

The study setup consists of a desk on which all seven charged tangible blocks, as well as the three configuration wheels are placed. A HoloLens is provided to run the AR application and a laptop is used to host the web server during the configuration process. Additionally, three spotlights are used to enlighten the study room, optimizing the marker tracking. The evaluation itself can be structured in seven consecutive steps, which are depicted in Figure 5.7. After a short welcoming, the participants are asked about their previous experiences with configuration tools. The HoloLens is introduced to enable the composition and personalization of a couch with TAROC and after the configuration process, the system has to be rated with help of two standardized usability questionnaires. Additional personal feedback is gathered by interviewing the participants and

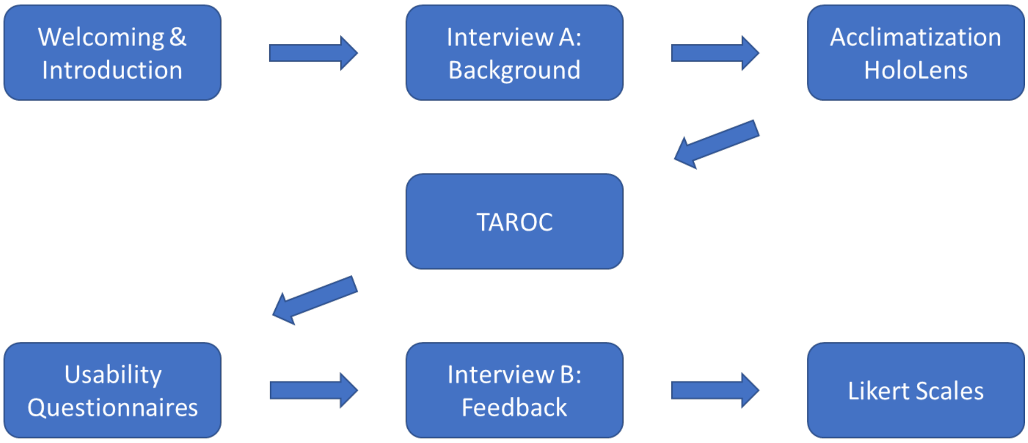


Figure 5.7: To evaluate TAROC's usability, a study consisting of seven consecutive steps is conducted.

presenting them several statements, which have to be rated in terms of a Likert scale. In the following parts of this sections, the different steps of the described user evaluation are presented in more detail.

Step 1: Welcoming and Introduction

After a short welcoming, all attendants have to sign a consent form to give their agreement on the collection and anonymous publishing of specific personal data. This consent form is based on a similar one, which is approved by a data security officer of the German Research Center for Artificial Intelligence[32]. Afterwards, the evaluation's goal, namely to investigate a novel approach for a couch configuration tool, and its general procedure are introduced to the participants, such that they roughly know what they can expect and how long it will take.

Step 2: Interview A - Background

The participants are asked about their experience with configuring and buying couches, as well as with configuration tools in general. They are asked to point out advantages and disadvantages of their experienced concepts and to state and reason whether they plan to follow similar or different approaches in the future. This interview provides insight about the participants' general opinions on configuration tools, especially in the context of couches, which might also influence their rating of TAROC. Furthermore, it helps them to get even closer to the context of the study, as they have to think about what is important for them while choosing and buying a couch.

[32] `https://www.dfki.de/web` (accessed on September 29, 2018)

Step 3: Acclimatization to the HoloLens

To introduce and familiarize all participants with the HoloLens, the *Use gestures*[33] app by Microsoft is used. By that, it is ensured that all participants wear the HoloLens correctly and moreover, they get a feeling for the restricted FOV. Novelty effects are furthermore softened, as participants who never came in touch with AR before are enabled to see and interact with holograms.

Step 4: Configuring a Couch with TAROC

In the main task of the study, the participants have to configure a couch by combining several of the provided tangible elements and by personalizing them using the configuration wheels. To simulate a realistic configuration process, a short explanation is given first. Afterwards, the participants are free to interact with the system as they like to configure a pleasurable couch, without any further specific target.

Step 5: Usability Questionnaires

To rate TAROC, the participants are asked to fill in the System Usability Scale (SUS) [7] as well as the AttrakDiff [12][34] questionnaires. Both of them are standardized and can be used to evaluate a system's usability and several further aspects. According to Lewis and Sauro [21], the SUS can be used to rate a system's learnability as well. The AttrakDiff on the other hand also determines its hedonic and pragmatic qualities, which address the human needs for stimulation and identification [12].

Step 6: Interview B - General Feedback

A second interview enables the participants to give feedback on whether they like TAROC in general or not. Moreover, they are asked for additional properties of a couch, which should be configurable and for application features the participants were missing during the configuration process. Thereupon, example features are provided by the conductor in terms of a real-sized preview or manipulating the lighting setup within the AR scene. Feedback on these ideas is gathered on the one hand and on the other hand, the participants are inspired to come up with additional features, which can be stated afterwards.

[33] `https://support.microsoft.com/de-de/help/12644/hololens-use-gestures` (accessed on September 29, 2018)

[34] `http://www.attrakdiff.de/` (accessed on September 29, 2018)

Step 7: Likert Scales

To collect additional feedback, several statements about TAROC in general and also specifically about the tangible blocks, the configuration wheels and the reality augmentation are presented to the participants. All of them can be found in Section 5.2.3. These statements have to be rated in terms of a six point Likert scale. Here, a six point scale is preferred over a five point scale to catch the participants tendencies even if they do not totally agree or disagree with the given statements.

5.2.3 Results

In this section, the gathered feedback and ratings are presented in depth in chronological order according to the corresponding steps of the evaluation.

Interview A - Background

Before interacting with TAROC, five of the seven participants state that they were already somehow involved in the process of buying a couch in the past. All of them report that their first approach was to visit a furniture store and search for a pleasant couch prefab locally. They did not research the internet beforehand, as they were not aware of online couch configuration tools and therefore, visiting a shop's website did not have any benefit in their opinion. Additionally, they wanted to receive real impressions of different couches, which is only possible in a furniture store. This also addresses the main advantage of visiting shops: The couch prefabs can be seen and touched. As a consequence, customers know exactly what the product looks and feels like, and hence, they can totally be sure about whether they like it or not. Besides the tactile feelings of the materials, the hardness can also be considered which cannot be supported by online tools.
On the other hand, wasting time by visiting a furniture store without finding a pleasant couch is pointed out as a crucial disadvantage by the participants. It is stated that in a big variety of couches, most of the products do not suit the personal taste or do not fit into the own home. Additionally, it is reported to be hard to imagine all possible combinations of base types, colors and materials, as the provided material and color samples cannot be applied to the couch prefabs. For the given disadvantages, six of the seven participants are not satisfied by their followed approach and plan to pursue a different strategy in the future. They will visit several web sites first to receive an overview over the shops' offers and prices. If configuration tools are provided, they will use them to personalize the look and size of a couch and only if they find pleasant ones online, they will visit the corresponding shop to receive further impressions on different materials and the hardness.

Usability Questionnaires

After interacting with TAROC, the system has to be rated with help of two standardized usability questionnaires. The filled-in SUS questionnaires result in a usability score of 70.5 and a learnability score of 70. According to Bangor et al. [3] this corresponds to an overall ‘good’ usability. In detail, the participants tend to need technical support and furthermore, not all of them would like to use TAROC frequently. On the other hand, the simplicity and intuitiveness of TAROC is underlined by the given rates. An overview of the most interesting subscales is given in Table 5.1.

Subscale	OPT	AVG	MIN	MAX	SD
I think that I would like to use this system frequently..	5	2.71	1	5	1.38
I think that I would need the support of a technical person to be able to use this system.	5	2.42	1	5	1.39
I found the system very cumbersome to use.	1	1.43	1	3	0.78
I needed to learn a lot of things before I could get going with this system.	1	1.43	1	3	0.78

Table 5.1: An overview of the most interesting subscales of the SUS. Each subscale is presented with an optimal (OPT) rate’s value, the average (AVG) of the given rates, the minimum (MIN) and maximum (MAX) rate and the standard deviation (SD).

With help of the AttrakDiff questionnaire, a system is rated in terms of pragmatic quality, hedonic quality and attractiveness. The pragmatic quality of a system refers to its usefulness and addresses the human needs for security, control and confidence. On the other hand, the hedonic quality, addressing the human needs for excitement and pride, refers to quality aspects such as ‘innovative’, ‘exciting’ or ‘exclusive’ [13]. Lastly, the attractiveness describes an overall impression of the system, e.g. ‘good’ or ‘motivating’ [12].
The AttrakDiff questionnaire itself can be subdivided into four different subscales, addressing the pragmatic quality, the hedonic quality, which consists of an identity (HQ-I) and a stimulation (HQ-S) category, as well as the attractiveness. Each of theses subscales consists of seven items, which are rated on a scale of -3 to 3. A subscale is represented by the average of the corresponding rates, and HQ-I and HQ-S can be combined to determine an overall score for a system’s hedonic quality. The hedonic quality as well as the pragmatic quality can be seen in Figure 5.8. With a pragmatic quality score of 0.82, a hedonic quality score

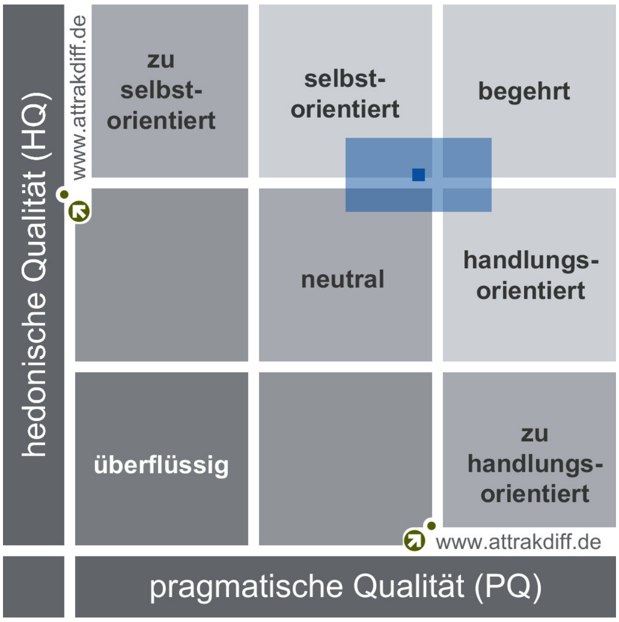


Figure 5.8: TAROC's hedonic quality in terms of action-orientedness and its pragmatic quality in terms of self-orientedness.

of 1.13 (HQ-I = 0.86, HQ-S = 1.41) and an attractiveness score of 1.41, TAROC is positive in all three aspects, indicating a good usability overall. To improve TAROC, the pragmatic quality, as well as HQ-I, should be enhanced first being the only subscales with an average score lower than 1. In detail, TAROC is rated to be too technology focused, which decreases the pragmatic quality, and too isolating, which decreases HQ-I. The rated technology focus can be explained by TAROC's TAR approach, which none of the participants has experienced before. The reported isolation probably results from the usage of a single HoloLens. As a consequence, the current user is the only one being able to see the configured couch, wherefore it is not possible to discuss its composition and personalization. However, TAROC works out of the box with several HMDs at the same time, such that multiple users are able to see and manipulate the same prototype. Thereby, the isolation can be softened and hence, TAROC's HQ-I score be increased.

Interview B - Feedback

In the second interview, the participants are asked to give personal feedback on TAROC. Four of the seven attendants criticize the tracking in general, as well as the HoloLens' viewport, which make it difficult to look at couches consisting of four or more elements. Regarding the material samples, two participators state that their small size is not sufficient to offer a realistic impression of their tactile feeling on a couch. The possibility to test and choose between different degrees of hardness is missed by four attendees and lastly, three participants criticize

the configuration wheels, because they repeatedly require a complete shift of attention to pick them up and select a value.
On the other hand, three attendants explicitly mention the simplicity and intuitiveness of TAROC positively and also like the auditive feedback on connections, disconnections and attribute value changes. The attachment of the virtual models to the tangible blocks is stated to be fascinating by two of the participants. Furthermore, three of them report that the material samples are useful and that they were considered during the configuration process, as well as that the 3D AR preview is more realistic and thus preferred over a two dimensional representation. Last, one of the participators even denotes TAROC as the configuration tool of the future and states that it is imaginable to find similar systems in stores of well-known furniture companies in a few years.
To get inspired for future work, the participants are furthermore asked for additional features, which should be integrated into TAROC. In general, most of the participators request to have a bigger variety of values to personalize the prototype's attributes, e.g. more different colors and materials. It is also stated that being able to configure an element's functionality, e.g. to integrate drawers, as well as being able to observe price changes on the connection of additional elements or changes of the material would be helpful. Providing a real sized version of the configured couch is requested by five of the attendants. Additionally, it is reported that being able to roughly model a footprint of the own room, including lamps to consider different lighting situations, would be helpful to get a further impression on the real size, as well as the material of the couch. Two of the participants state that they did not know exactly with which part of the configuration process to start, wherefore an additional small tutorial within the application would be useful. To better integrate the personalization of the visual attributes into the interaction process with the actual model, an attendant suggests to show an additional live preview of the configured couch during attribute value selections. Furthermore, it is proposed to attach the wheels to a back wall of the interaction space, such that they do not have to be picked up anymore.

Likert Scales

To gather additional feedback on the participants' opinion of TAROC, several six point Likert scales are used to rate different statements about the system. These statements can be subdivided into four categories, namely TAROC in general (Table 5.2), the tangible blocks (Table 5.3), the configuration wheels (Table 5.4) and the reality augmentation (Table 5.5). All rates of a single statement are averaged and presented in combination with the minimum and maximum of the given rates, as well as with the standard deviation.
Although three participants again note explicitly that the unstable tracking influences their given rates negatively, the participants overall like the system and would use it in a furniture store. Due to the tracking issue, the system does not

Statement	1 ≙ ...	6 ≙ ...	OPT	AVG	MIN	MAX	SD
I would use TAROC again.	totally disagree	totally agree	6	4.34	2	6	1.50
I would use TAROC in a furniture store.	totally disagree	totally agree	6	4.83	2	6	1.60
I prefer TAROC over a standard configuration tool.	totally disagree	totally agree	6	3.83	1	6	2.13
I will recommend TAROC.	totally disagree	totally agree	6	4.34	1	6	1.96
I liked TAROC.	totally disagree	totally agree	6	4.67	2	6	1.50
I had fun using TAROC.	totally disagree	totally agree	6	5.34	5	6	0.51
TAROC worked well.	totally disagree	totally agree	6	4.16	3	5	0.98

Table 5.2: An overview of TAROC's general user rating.

Statement	1 ≙ ...	6 ≙ ...	OPT	AVG	MIN	MAX	SD
The cubes were ...	too small	too big	3.5	3.29	3	4	0.49
The cubes were ...	unhandy	handy	6	5.14	4	6	0.69
Interacting with the cubes was fun.	totally disagree	totally agree	6	4.71	4	5	0.49
Interacting with the cubes worked well.	totally disagree	totally agree	6	4.14	2	6	1.21

Table 5.3: The user rating of TAROC's tangible elements.

work perfectly, but nevertheless, the participants have fun using it and are likely to recommend TAROC to others.
The cubes seem to have a good size as they are rated to be neither too small nor too big and handy. Interacting with them is fun according to the given rates, although they do not work perfectly, which again is reasoned by the tracking performance.
The configuration wheels also seem to be rather handy and work fine. Interacting with them is rated to be rather fun, too. Additionally, the participants state that the material samples are reasonable.
Last, the reality augmentation is rated. Regarding the match of the virtual models and the tangible elements, the participants report that the differences in their shape and also the colorful fiducial marker distract them a little. Nevertheless, the participants like the 3D AR preview in general and tend to prefer them over a visualization on a computer monitor. The size of the models fits the cubes well, but more details would improve the virtual preview.
Overall, interacting with the tangible elements is rated to be fun, justifying the usage of a TUI in context of object configuration. In combination with the mostly positive rates of the AR preview, the potential of relying on a TAR approach for a configuration tool is underlined.

Statement	1 ≙ ...	6 ≙ ...	OPT	AVG	MIN	MAX	SD
The wheels were ...	unhandy	handy	6	4.71	2	6	1.38
The material samples are reasonable.	totally disagree	totally agree	6	5.42	4	6	0.79
Interacting with the wheels was fun	totally disagree	totally agree	6	4.42	2	6	1.51
Interacting with the wheels worked well.	totally disagree	totally agree	6	4.57	2	6	1.81

Table 5.4: The user rating of TAROC's configuration wheels.

Statement	1 ≙ ...	6 ≙ ...	OPT	AVG	MIN	MAX	SD
I liked the 3D preview of the configured couch.	totally disagree	totally agree	6	5.28	4	6	0.76
I prefer the 3D preview over a visualization on a monitor.	totally disagree	totally agree	6	5.14	1	6	1.86
I was distracted by the difference of the virtual model's shape and the shape of the corresponding physical counterpiece.	totally disagree	totally agree	1	2.28	1	4	0.95
The virtual model's amount of details was sufficient.	totally disagree	totally agree	6	4.42	2	6	1.40
The size of the shown models matched the corresponding cube.	totally disagree	totally agree	6	5.57	5	6	0.53
I was distracted by the colorful markers.	totally disagree	totally agree	1	2.42	1	6	2.15

Table 5.5: An overview of the AR preview's user rating.

5.2.4 Discussion

The presented user study underlines advantages of TAROC compared to up-to-date configuration tools, but also reveals aspects which have to be improved in the future. The most crucial point is the often criticized quality of marker tracking. Another point, which has a negative impact on the user experience, is the viewport of the HoloLens preventing users from seeing all included virtual counterpieces of larger models at once.
In general, one of the strongest motivations to develop a configuration tool relying on TAR is to provide an enhanced usability and user experience. The results of the SUS and AttrakDiff questionnaires imply that TAROC does provide a good usability and furthermore, configuring a couch with it is repoted to be enjoyable and fun. In contrast to up-to-date configuration tools, the concept of TAROC integrates the tactile feelings of real material samples into the configuration process, which is in fact considered and mentioned positively by several participants. Additionally, the intuitiveness and simplicity of TAROC, which enable users

to configure a couch in a nearly playful manner, is another advantage over the web-based approach. Last, the evaluation shows that the 3D preview of the configured couch is liked and preferred over a visualization on a computer monitor. Concluding, the evaluation underlines many of TAROC's advantages compared to up-to-date configuration tools and shows that with minor improvements and a more accurate and stable marker tracking, TAROC could be the superior approach for configuration tools.

Next to determining TAROC's usability, the evaluation is also used to collect feature suggestions for future iterations. Besides increasing the amount of possible values of manipulable attributes, it is stated that configuring the functionality of different elements, e.g. integrating drawers, would be useful. Providing a real-sized preview of the configured couch is the most frequently mentioned feature request. Thereby, a more realistic impression of the actual size of the couch and furthermore, a higher degree of detail can be perceived. Moreover, a small tutorial within the application is requested to simplify getting started with TAROC. Last, the participants like to be able to personalize the couches environment by modeling their own room, such that the appearance of the couch can be adjusted even better.

5.2.5 Limitations

A limitation of the user study is the small sample of only seven participants, which are all approximately in the same age. Older people might have a different attitude towards new technologies and might therefore do not share the same opinion as the sampled attendants. Additionally, the significance of the results is not tested due to the small sample size. Furthermore, the presented results can hardly be used to compare the approach of TAROC to up-to-date configuration tools, because firstly, technical limitations of the system itself negatively impact the given ratings and secondly, TAROC and up-to-date configurators do not share exactly the same features.
However, although it is just a prototype, TAROC is rated highly in many aspects, underlying how promising the TAR approach for configuration tools really is.

5.2.6 On Improving TAROC

Based on the the user evaluation, different aspects of TAROC's implementation can be improved in the future.
The first one addresses the tracking performance, which is the main criticism of the participants of the user evaluation. By improvements in the field of computer vision and also by using a special kind of print and paper for the fiducial markers, such that highlights on the tangibles are avoided, the tracking can be enhanced. Secondly, changing the design of the tangible blocks, such that they can be opened without much effort at any time is reasonable. Thereby, exchanging defect hardware would be simplified a lot.

Regarding the configuration wheels, relying on different fiducial markers for the attribute value disc, as well as for the reference disc is not optimal, because the small size of the reference disc's marker results in tracking issues. By computing the rotation of the attribute value disc relative to the tracking device, the second, smaller marker can be eliminated, potentially improving the interaction with the wheels.

Relying on a different wheel for each property is also not an optimal approach, as items with many different personalizable properties require many different wheels. This is a disadvantage, because users often have to switch the interaction tool, which is time-consuming and bothersome during the configuration process. To overcome this, different approaches can be explored. One approach is to integrate multiple attribute value discs of different sizes into a single wheel by stacking them. Therefor, the sizes of these discs have to be considered carefully to ensure a proper AR experience.

Alternatively, a more generic approach is to provide one wheel to select the property, which is currently manipulable, and a second one to select the values accordingly. For example, the first wheel enables users to switch between 'Color', 'Texture' and 'Base type'. Depending on the chosen value, different colors, textures or base types are displayed on the second one and can be selected. By that, two wheels would be sufficient to personalize a large amount of attributes. Moreover, adding or exchanging manipulable properties is simplified a lot, as no additional wheels has to be constructed.

Lastly, integrating fixation techniques, holding the attribute value discs in place if a value is chosen, simplifies the personalization process and makes it more pleasant.

Chapter 6
Conclusion

In this work, a generic tangible augmented reality system for object configuration is presented. To overcome disadvantages of up-to-date configuration tools, TAROC combines a tangible user interface with augmented reality to provide haptic as well as realistic visual feedback.

Plain and undetailed tangible elements are augmented with fiducial markers such that their position and rotation relative to a user wearing the Microsoft HoloLens can be tracked. Each element corresponds to a specific part of an item and has a preregistered detailed virtual counterpiece. By that, TAROC is easily adaptable to a variety of use cases by simply exchanging these virtual counterpieces. Multiple tangibles can be attached and detached to configure an item. Magnets are used as physical connectors, providing a simple and intuitive connection mechanic and additionally preventing incorrect connections by their polarity. Relying on the computed spatial information, the tracked tangible composition is augmented in real-time with the corresponding virtual counterpieces. For improving the robustness of the reality augmentation regarding occlusions, TAROC combines embedded hardware with marker-based object tracking. Therewith, TAROC is the first TAR system relying on a combination of embedded computational devices and computer vision to the best of our knowledge. Each of the cubic tangibles contains a microprocessor, which know their identity and are able to communicate with a simple web server relying on an integrated WiFi chip. Copper rings and pins are integrated into several of the cubes sides and furthermore are connected to the embedded computational devices, such that processors of connected cubes are able to exchange their identity. Based on that, occuring connections and disconnections are communicated to the web server, which transmits this connectivity information to an AR application running on the HoloLens. The application uses the received events to maintain a virtual model based on the tangible composition. Thereby, the virtual counterpieces can be aligned to each other before the rendering process, ensuring a robust and accurate reality augmentation even when the physical model is partially occluded or strongly distorted to the tracking device. To enable the personalization of different visual attribute values, TAROC introduces tangible configuration wheels. Each wheel corresponds to a single visual property, such as color or texture, and enables users to choose between several predefined values. For materials, real samples of these values are attached to the main interaction part of a wheel, the attribute value disc, offering realistic and original visual as well as haptic feedback to users. The rotation of the attribute value disc is tracked with help of fiducial markers and computer vision algorithms, enabling the personalization of a configured item.

The practical use case of a couch configuration tool is introduced and implemented in this work, enabling users to configure couches relying on a single-seater, a two-seater, two corner-pieces and a chaise longue. Furthermore, the color, material and base type of the couches can be personalized using three different configuration wheels.

Relying on the couch configurator, a technical evaluation is conducted to investigate the advantages of combining embedded computational devices with computer vision-based marker tracking. Therefore, two different scenarios are simulated. The first one addresses the occlusion of tracked markers by users interacting with the system. In different lighting conditions, an augmented reality application relying only on marker tracking is compared to TAROC. A composition of two tangible elements is tracked, while one of the cubes is increasingly occluded. It shows that the tracking performance of the marker-based augmented reality application gets worse with increasing occlusion. Contrary, TAROC is able to augment both elements correctly independent of one of them being partially or even completely occluded, due to the integrated hardware. As a result, TAROC provides a superior reality augmentation, if one of the blocks is occluded by more than approximately 50%. While interacting with the blocks, users are enabled to move and rotate them freely, leading to the camera image of the attached markers being distorted perspectively. This also leads to a decrease of the augmentations accuracy as parts of a tangible composition cannot be properly tracked anymore due to the distortion. To investigate on the effect of distortions, a composition of two blocks with different sizes is rotated and tracked by TAROC as well as the marker-only-based augmented reality application. In different lighting setups, TAROC is able to augment both of the blocks independent of their rotation relative to the tracking device. Contrary, the augmented reality application is not able to overlay the distorted composition correctly. In fact, the reality augmentation of TAROC becomes prior if one of the blocks is distorted by more than approximately 50°.
Summarizing the technical evaluation, combining embedded computational devices and computer vision-based marker tracking increases the robustness of the tracking and augmentation process, as the virtual model can be computed and aligned based on the connectivity information before the rendering process

completely. The number of markers that have to be detected by the tracking device, is reduced to a single one, which softens the impact of occlusions and distortions to a minimum.

Additionally, a user evaluation is conducted to confirm that TAROC provides a good user experience. Hereby, seven participants configure a couch using TAROC and afterwards rate their experience with help of the SUS and AttrakDiff questionnaires. It shows that TAROC overall provides a good usability as well as a good learnability, too. An additional semi-strucutured interview in combination with several Likert scales is used to gather further personal feedback regarding the presented configuration tool. Due to technical limitations, the tracking performance provided by TAROC is not optimal and additionally, the viewport of the HoloLens restricts the users during interactions. However, these aspects cannot be led back to the implementation of TAROC and hopefully get resolved in the future. Nonetheless, the participants report that they like the system and have fun using it.

During the development of TAROC, several difficulties in designing and implementing a TAR interface became clear, from which can be learned for future projects. Although relying on a TAR interface in context of a configuration tool seems promising, there are still several technical aspects, which complicate a proper realization of such interfaces. Firstly, computer vision-based marker tracking often leads to an unstable AR experience, due to difficulties monitoring the markers correctly. Secondly, this tracking approach furthermore introduces several restrictions regarding the interaction space of the interface, due to its sensibility concerning the lighting situation, as well as a marker's distance to the tracking device. Additionally, the FOV of the tracking camera as well as the size and viewport of the used HMD are important factors, which have to be considered. Lastly, a more generic implementation of the configuration wheels is reasonable, as participants of the user evaluation proposed several additional attributes, which should be customizable.

In the remaining sections of this work, limitations of the presented system are stated and furthermore, possible future work based on TAROC is presented.

6.1 Limitations

One of the core features of TAROC is to be adaptable to a variety of use cases without much effort. Hence, TAROC relies on plain tangible elements, which are overlayed in AR. However, this approach excludes use cases, which require multiple elements to be nested, for example configuring the seats of a car. Besides, each tangible element relies on a minimum size and weight due to the integrated hardware and also, the connection possibilities of multiple cubes are restricted by the arrangement of their connective sides. If for example a configuration tool for buildings should be realized, there are some major difficulties which have to be considered. First, windows and doors can barely be represented by tangible

elements due to their minimum size and second, users are not able to attach an arbitrary number of windows or doors at positions of choice, as all connective ports have to be implemented beforehand.
The concept of TAROC enables multiple blocks to be connected in 3D and also supports multiple receiving as well as transmitting sides for each cube. The presented use case in contrast does not provide both of these aspects totally, as stacking couch elements or connecting them in an improper manner is not reasonable.

6.2 Future Work

First of all, the features presented in Section 5.2.4 as well as technical improvements stated in Section 5.2.6 should be realized in the future. Second, a comparative study to further investigate TAROC's advantages and disadvantages compared to up-to-date configuration tools is possible future work. To evaluate the TAR approach for other configuration contexts than couches, TAROC might be adapted to explore additional use cases, e.g. a street planner or other pieces of furniture.
Due to the universality of the tangible elements, and the detailedness of their virtual counterpieces, users of TAROC receive a discontinuity of haptic and visual feedback. This phenomenon has been a topic of research for years [24]. The so called *visual dominance effect* addresses the discontinuity and proposes the dominance of the visual impression over the haptic one. Using the TAROC system, the visual dominance effect can further be researched by investigating how much a virtual element is allowed to differ from its physical counterpiece, without disturbing a user.
Lastly, users interacting with TAROC occlude parts of the tangible composition during attaching and detaching the blocks. Without a proper occlusion handling technique, the virtual models overlay not only the tangible elements but also the user's hands, which might break the illusion of an augmented reality. In Section 2.4.2, various occlusion handling techniques are presented. It is concluded that a depth-based approach fits best for TAROC, but is not easily feasible with the used hardware. In the future, this might change, such that a proper occlusion handling technique can be implemented, increasing the quality of the reality augmentation.

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