

# **Augmented Laying Board**

## **Design and Evaluation of a System to Support Wire Harness Assembly using Augmented Reality**

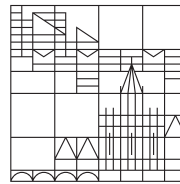
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## Abstract

In appliances and machines, the cabling is usually not installed one by one, but assembled in advance, bundled together and fitted in as one piece. These bundles are called *Wire Harnesses*. They provide multiple benefits, for example a simpler installation process or the ability to standardize their production. For their assembly, the workers at *Engeser*, a company manufacturing wire harnesses, employ so-called *Laying Boards*, upon which the cables are laid out, and printed instructions that tell them which cables to lay out where. As the *Wire Harnesses* are still hand-made, despite the advances in automation, the company sought ways to support their workers to increase their efficiency and to improve the training process for new workers. For this reason, this thesis explores how a system can be designed to support workers during the assembly process utilizing *Augmented Reality*.

To guide the development, the *Wheel UX Lifecycle* has been employed in this thesis. In accordance with it, the first part of this thesis explores the context of the application, the work environment as well as the requirements that are placed on such a system. Together with the analysis of related work for this topic, a design was then created from the results. As the next step, a prototype was then developed based on this design. The prototype, called *Augmented Laying Board*, uses the *Microsoft HoloLens 2* to project a digital overlay directly onto a laying board. This overlay displays the positions and route for a specific cable as given by assembly instructions. To evaluate the prototype, an *"in-the-wild"* study has been conducted at *Engeser*. The study highlighted the potential benefits a system like *Augmented Laying Board* can provide to support the workers and improve their training. Based on the findings of the study, a set of improvements and further evaluation directions were proposed.



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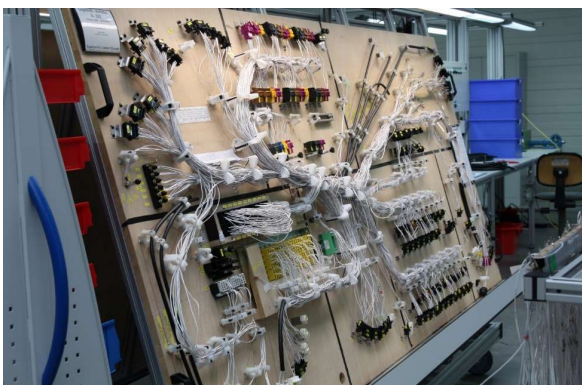
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# 1. Introduction

*Wire harnesses* or *cable harnesses* are an assembly of cables which are bound together either by cable ties or other sheathing materials (see figure 1.1a). They are an integral part of many electrical machines, from household appliances like dishwashers to cars to construction machinery. Most of these machines' cabling is assembled in one or more wire harnesses. Using wire harnesses enables manufacturers to assemble the cabling for a machine into a ready-to-install package prior to the actual installation. This provides several advantages over installing cables individually. First, by bundling the cables together tightly, it reduces the overall space needed by them and makes them more resistant to vibrations and other mechanical stress. Such an approach also saves time because the harness itself can be assembled before the installation in the actual machinery. Thereby, the assembly process can be standardized and the harnesses can then be installed as one piece instead of having to install multiple individual cables in possibly cramped spaces. In addition to that, the harnesses can be tested before the actual installation and their rigid shape and size, as well as the usage of different connectors reduce installation errors.

In the course of the manufacturing industry's ongoing efforts at automation and digitalization, many facets of assembling wire harnesses have been automate already. This includes for example the preparation of the cables, cutting them to the right length and crimping terminals onto them. Despite the automation around the process however, the actual assembly process itself is still mostly done the old fashioned way: workers assembly the harnesses by hand using instructions printed on paper and on the cables themselves (see figure 1.1b).



(a) Completed wire harness [1]



(b) Worker assembling a wire harness on a laying board [1]

Figure 1.1.: Wire harness assembly

### 1.1. Motivation

While there have been some attempts at automating the assembly of wire harnesses, the small batch sizes, continuously rising complexity and the different tasks involved simply make automation for most harnesses uneconomical. As an alternative, for almost three decades there has been ongoing research into how human workers can be supported before and during the assembly process by digital means to make the process more effective. Incidentally, as part of such a research project at *Boeing*, *Caudell et al.* [2] dreamed up the first *Augmented Reality* devices to help workers assembling the wire harnesses for the *Boeing 777*. Since then, there have been many attempts to apply similar technology to manufacturing processes to either reduce the workers' need to memorize or look up instructions [3, 4] or to improve their recall of important information [5].

Many of those attempts were only research prototypes, spearheaded by companies like *Boeing* and *Airbus* that produce the wire harnesses themselves. They probably never made it into production, however the companies are very reserved about information on the actual usage of these prototypes. The only systems for which can be said with some certainty that they are actually still in use are the ones developed and distributed by companies that have specialized in such software, like *ProjectionWorks* [6]. However both the majority of the prototypes and the commercial solutions were built with older hardware in mind that is obsolete by now from a technological viewpoint.

For this reason, *Engeser GmbH* [7] wanted to explore the feasibility of adopting modern digital tools which could support their assembly process. They are a cable and wire harness manufacturer based in Schramberg in the black forest. Their main goal was to boost the efficiency of their workers by providing them with tools allowing them to manufacture the harnesses faster and with less errors. As a secondary goal they were also looking for a way to improve the learning process for new employees, especially for ones coming from other company locations to spend a few weeks at site in Schramberg for training.

### 1.2. Solution Approach - Augmented Laying Board

This thesis was started with the support of *Engeser* to investigate how such a solution could be designed. Therefore, the primary goal of this work is:

Determine how to design a system that supports workers during the assembly of wire harnesses.

*Augmented Laying Board* is a proof of concept for such a system employing *Augmented Reality* to implement this goal.

It should work as an addition to the current assembly process and utilize the modern advances in *Augmented Reality* hardware to provide direct digital support for workers during the assembly. It should provide a digital overlay that is able to visualize the work instructions for a specific step in the assembly of a wire harness, to capitalize on the aforementioned benefits *Augmented Reality* can offer.

## 1.3. Methodology

This thesis employs the *UX Lifecycle* in the form of *The Wheel* model created by *Hartson and Pyla* in their book *The UX Book* [8]. *The Wheel* describes the *UX Lifecycle* as a perpetual cycle of four main activities (see figure 1.2).

1. The first activity is *Understand Needs*, the activity that concentrates on understanding the work and needs of the target users for a system. It includes the *contextual inquiry* as well as analyzing and modelling the data gained through it and establishing the requirements for the system.
2. After that, the next activity is the *Design* activity. During this activity, the general design as well as the interaction design is fleshed out, based on the data and models from the previous activity.
3. The end result of the previous activity, a design concept for the new system, is realized in the *Prototype Candidates* activity.
4. As the fourth activity, *Evaluate UX* focuses on the evaluation of the prototype created previously.

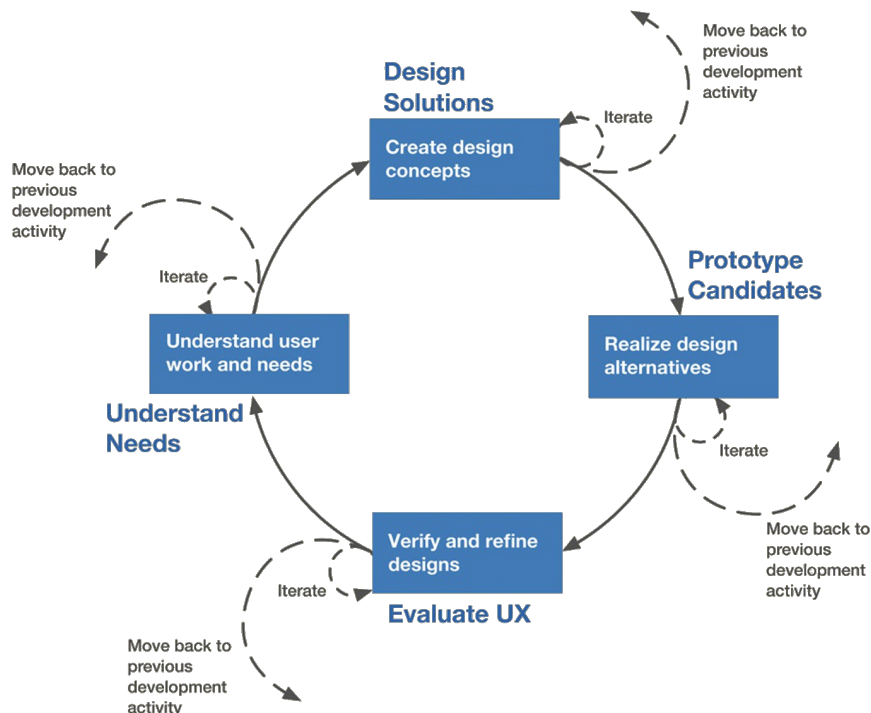


Figure 1.2.: *The Wheel UX Lifecycle* [8]

The whole lifecycle is inherently iterative, so completing the evaluation activity would usually result in new data to start with the first step again. *The Wheel* expands the iterative nature of the lifecycle to the single activities and their sub activities. Findings from the *Prototype Candidates* activity may prompt another iteration of the design phase or another iteration of the *Prototype Candidates* activity itself.

### 1.4. Outline

This thesis follows the structure of the *UX Lifecycle* as modeled by *The Wheel* (see figure 1.3). After the introduction in this chapter, which contains the motivation and the solution approach, the next chapter is *Understanding the Context*. This chapter focuses on the *Understand Needs* activity and starts with of an overview of the environment in which wire harnesses are assembled at *Engeser*. It also consists of the contextual inquiry as well as the analysis and modeling of the data gained from it. The chapter closes with establishing the requirements for *Augmented Laying Board*. In Chapter 3 the theoretical background as well as the related work are examined. Chapter 4 first describes the *Design* activity, with the design concept for the system as result. Its second part consists of the *Prototype* activity, which describes the implementation of the design in the form of a prototype. After that, Chapter 5 covers the *Evaluate UX* activity and deals with the "in-the-wild" study conducted at *Engeser* and its findings. Chapter 6 presents ideas how *Augmented Laying Board* could be modified and extended based on these findings. And lastly, Chapter 7 provides a summary of this work.

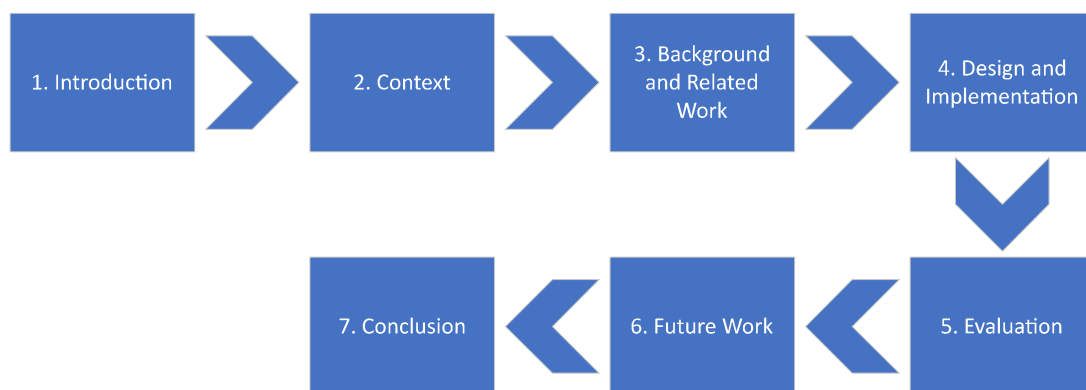


Figure 1.3.: Outline of this thesis

## 2. Understanding the Context

In this chapter, the first activity in the *UX Lifecycle*, the *Understand needs* activity is applied. For this purpose, with Section 2.1 this chapter first provides a short overview of the work environment that *Augmented Laying Board* is supposed to be deployed in. The next section, Section 2.2, covers the elicitation of usage data, which is analyzed and modeled in Section 2.3. In Section 2.4 the collected information is used to establish requirements for the development of *ALB*.

### 2.1. The Work Environment

The current setup for assembling wire harnesses at *Engeser* consists of three main parts: a so-called **(1) Laying Board (Verlegebrett)** on which the cables are laid out, **(2) Assembly Instructions** printed on paper as well as a **(3) Cable Cart** with brackets holding the cables needed to assemble the current wire harness (see figure 2.1).



Figure 2.1.: Laying Board stations at Engeser with the laying board (1), the assembly instructions (2) and the cable cart (3) [1]

## 2. Understanding the Context

1. **The Laying Board** is the central structure where the assembly of the wire harness takes place. It is a rectangular wooden board that is elevated and mounted in a slight angle away from the user to ensure good accessibility of the whole assembly space. Mountings attached to the board can hold plastic housings into which the cable ends are plugged in during the assembly process. For each of these mountings, a unique identifier is printed next to it on the board (see figure 2.2a for a closeup). Additionally, the board also sports markings for the routes along which the cables are supposed to be routed, as well as plastic fasteners that ensure that the cables stay fixated.
2. **The Assembly Instructions** are printed in a table format on paper and attached to the board via a clipboard (see figure 2.2b). They contain a list of all the cables used for a specific wire harness. This includes both the identifiers for the housings the cables are supposed to be plugged into as well as details about the cables themselves, like cables' cross sections, their color or their length. The cables are listed as rows with an housing id denoting where the cable start should be plugged in (written in the "Von" column) and one or multiple housing ids for a cable's ends (written in the "Nach" column).
3. **The Cable Cart** holds all the cables required for the assembly of a wire harness. The cables are clipped into comb-like brackets with the cable end corresponding to the "Von" column on the assembly instructions facing up. This allows an easy removal of the cables from the cart. As an identification measure, the identifiers corresponding to the mountings for a cable's ends are also printed in regular intervals along a cable (see figure 2.2c).



22-8733, Verdrahtungsliste "DrahteGrundaufbau Vorm." (MU-4007)

Nr	12er-Nummer	Anschlag	Quer	Farbe	Lange	Von	Nach
2		<3> v	*2.5Q	WH	1590	=D+S-X400.2	=D+S-AF403.X2.3
3	12-9645W4, 12-3634W4	39.797	*2.5Q	WH	1570	=D+S-X400.2	=D+S-AF403.X2.4
4		<5> v	*2.5Q	WH	1530	=D+S-X400.2	=D+S-AF405.X2.3
5	12-9645W4	39	*2.5Q	WH	1510	=D+S-X400.2	=D+S-AF405.X2.4
6		<7> v	*2.5Q	WH	1570	=D+S-X400.2	=D+S-AF403.X2.4
7	12-9645W4, 12-3634W4	39.797	*2.5Q	WH	1510	=D+S-X400.2	=D+S-AF405.X2.4
9		<10> v	*2.5Q	WH	1680	=D+S-X400.4	=D+S-AF401.X2.3
10	12-9645W4, 12-3634W4	39.797	*2.5Q	WH	1670	=D+S-X400.4	=D+S-AF401.X2.4

(a) Housings on the laying board with their IDs (b) List of steps, entries with a duplicate "Von" values indicating that the cable splits up and has multiple ends



(c) Cable going from housing X400, slot 2 to housing row AF403, second housing, slot 4

Figure 2.2.: Overview housings and their IDs, the labels printed on the cables and the assembly instructions

## 2.2. Contextual Inquiry

After getting an overview of the working environment *ALB* should be employed in, the next step was to gather information about how this environment is being used by the workers. Usually the contextual inquiry is done via a combination of different techniques such as interviews directly with the users or *shadowing* the users during their work to observe their work routine. However, these techniques have not been possible for this project. For one, communication with *Engeser* was difficult to establish and slow, as the contact at the company had recently taken on a new leadership role. A personal visit to the *Engeser* factory in Schramberg could only be arranged at a rather late date, about halfway into the development of the prototype, and unfortunately during the visit none of the actual users were present.

For this reason, the contextual inquiry was mostly conducted with stand-ins or *user proxies*. The first and main source of information was Simon Butscher, the postdoctoral research that offered this master topic. This topic had been subject of a student project for a course in an earlier semester, which unfortunately did not yield any results. Therefore, he was familiar with the general process that is employed at *Engeser*. The second source was Steffen Engeser, the contact for the project at *Engeser*. He was also familiar with the work itself and could offer a few more details during the visit at the *Engeser* factory. However he did not have any deep insight into the work routine of the actual users as well.

## 2.3. Contextual Analysis and Modeling

From the information provided by these sources different models were created to help inform the design of the application. This includes a *Work Role Model* and a *Task Sequence Model*, two kinds of models that were presented in the *UX Book* in chapter 9 [8].

A *Work Role Model* consists of different *User Work Roles* that define a set of users by their responsibilities and functions, for example "worker" or "supervisor". Different *User Classes* are associated with a work role and characterize the potential types of user that could perform this role on the basis of for example skill, experience or demographics.

A *Task Sequence Model* acts as a graphical description of how users perform a specific task, in this case the assembly of wire harnesses.

From the gathered usage data, one main as well as two supporting *User Work Roles* have been generated (see figure 2.3).

The main work role is the *Assembly Worker*. This work role is responsible for the actual assembly of the wire harnesses using the provided tools.

The supporting roles are the *Assembly Supervisor*, whose task is to support especially inexperienced assembly workers during their training, and the *Assembly Process Engineer* who is responsible for creating the assembly instructions for the wire harnesses before their production starts.

## 2. Understanding the Context

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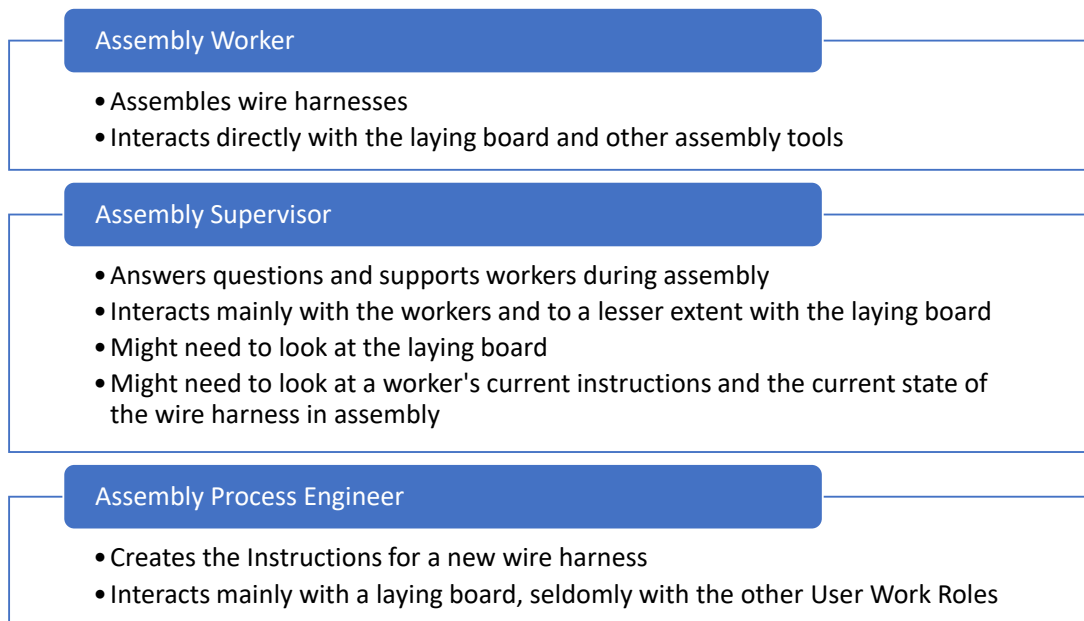


Figure 2.3.: The three User Work Roles for the assembly process.

**The Assembly Worker** is the *User Work Roles* whose responsibility is the actual assembly of wire harnesses. For this, the worker interacts directly with the laying board, the cables and other assembly equipment.

**The Assembly Supervisor** is the first of the support roles. He rarely interacts directly with the assembly equipment, but is instead responsible for answering questions and in general helping and overseeing the actual assembly workers. For this he might have to be able to view the laying board and might need access to a worker's current instructions and the current assembly state of the wire harness a worker is working on.

**The Assembly Process Engineer** is mainly responsible for the authoring of assembly instructions for new types of wire harness. As such, he does not have much contact with the other roles as most of his work needs to be done before the production of a new type of wire harness can start.

The *Assembly Supervisor* and *Assembly Process Engineer* are important roles for employing a system in production. However, adding support for supervision and authoring would have probably been beyond the scope for this work. The decision was made to focus on providing assistance during the assembly task itself in this thesis and forego adding support for the surrounding tasks. For this reason, this work will mainly focus on the *Assembly Worker User Work Role*. To extend the *Assembly Worker* role, two *User Classes* were defined for it (see figure 2.4).



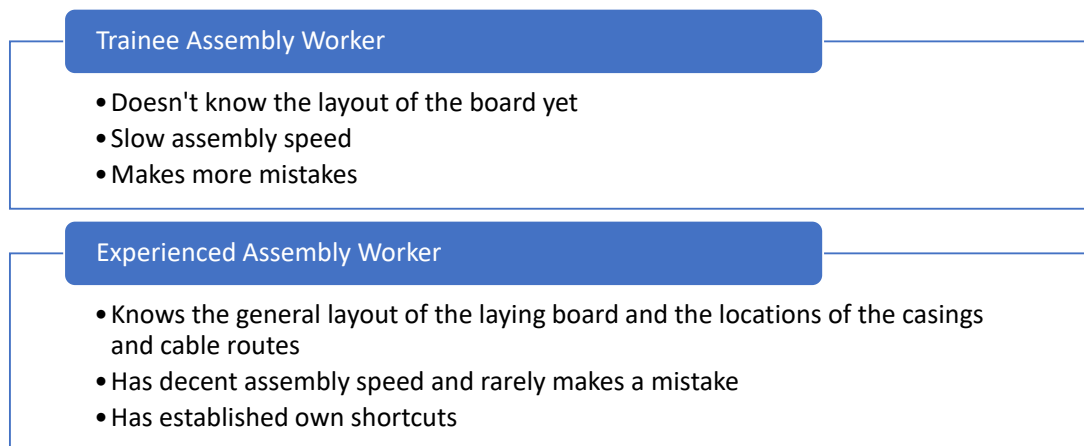


Figure 2.4.: The two User Classes of the Assembly Worker role.

**The Trainee Assembly Worker** interacts directly with the laying board, the cables and other assembly equipment. As a trainee, he does not know the layout of the board and the locations of the cable housings very well yet. Therefore, he still is quite slow at assembling a wire harness and makes the occasional mistake.

**The Experienced Assembly Worker** also interacts directly with the laying board and other assembly equipment. Unlike the *Trainee* class however, the experienced worker already knows the layout of the board and the locations of the cable housings by heart. His speed at assembling the cables is high and the errors he makes are few. He also has established his own shortcuts and method of operation.

The second artifact of the *Usage Data Modeling* activity is a *Task Sequence Model* of the main assembly task (see figure 2.5). It describes the workflow of this task by breaking it down into its *task steps*, their sequential order and potential *task barriers*. These *barriers* represent difficulties or interruptions of the workflow that can occur during a specific *task step*. They are especially interesting as they present particular opportunities for improvement.

During the visit at the *Engeser* factory, it became apparent that the originally modeled task sequence was not entirely accurate. Their engineers too have identified the *barriers* for *Task Step 1a & 2a* and improved the process by prearranging the cables in the correct order. This way, a worker only ever has to take the next cable and read the id printed on it to start a new assembly step and can work completely without the printed instruction sheets. The changes are reflected in the model by *Task Steps 1b & 2b*.

## 2. Understanding the Context

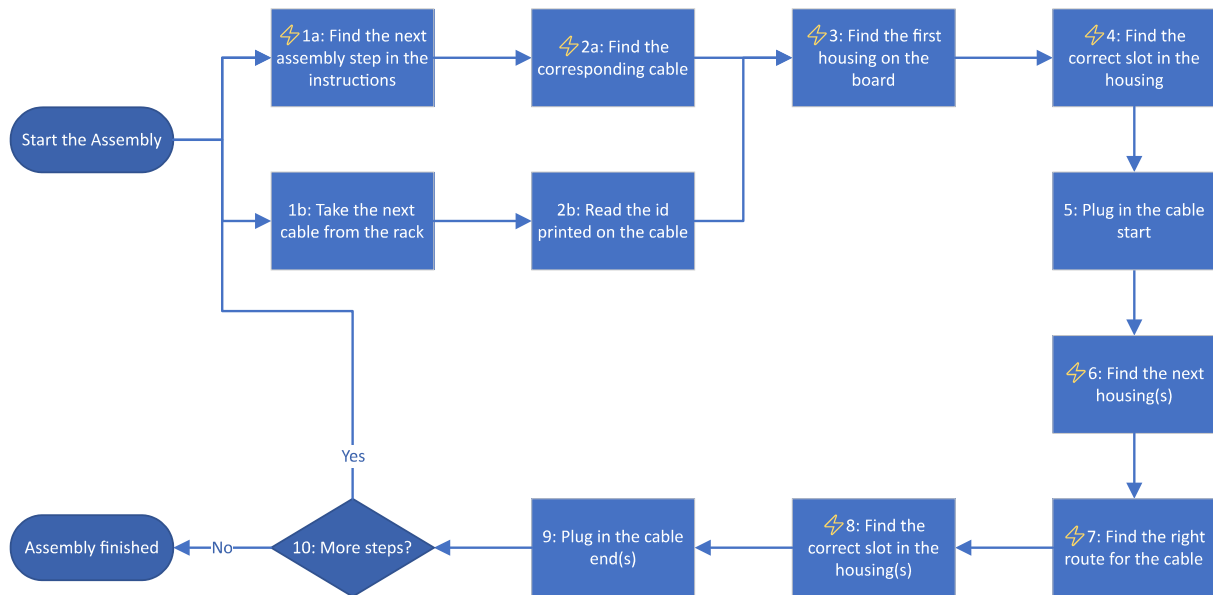


Figure 2.5.: The Task Sequence Model for the main assembly task. The lightning symbol denotes a task step with a barrier.

**Task Name:** Assembling a wire harness.

**Task Goal:** The successful assembly of a wire harness without errors.

**Task Step 1a:** Take the printed instructions and find the entry for the next cable for the assembly.

*Barrier:* To find the next step, the worker needs to search the correct entry in the list for the next instruction. Problems can include mix-ups due to similar cable ids as well as missing a row in the table.

**Task Step 2a:** Find the cable corresponding to the selected assembly step.

*Barrier:* The worker needs to find the right one among the available cables. This can be time-consuming and error-inducing, for example due to similar cable ids.

**Task Step 1b:** Take the next cable from the cable rack.

**Task Step 2b:** Read the id printed on the cable.

**Task Step 3:** Find the housing on the board that corresponds to the first part of the id printed on the cable and the id in the "Von" column of the current assembly step.

*Barrier:* The worker needs to have a general idea where to look for the housing or else has to look over the whole board to find it. In addition, housings of the same type that are in close proximity generally have similar names, often differing only in one or two digits. This can cause errors or slow down the assembly speed by requiring to re-read instructions or the id printed on the cable.

**Task Step 4:** Find the correct slot in the housing.

*Barrier:* The Worker needs to find the correct slot in the housing for the cable. Slot numbers are partially etched into the housing, but getting the exact one requires experience or counting of the slots. Rotated housings might complicate this even further.

**Task Step 5:** Plug in cable start.

**Task Step 6:** Find the next housings on the board that correspond to the last parts of the ids printed on the cable ends and in the *Nach* column of the current assembly step.

*Barrier:* Same barrier as for *Task Step 3*.

**Task Step 7:** Find the right route for the cable from the housing found in *Task Step 3* to the housings found in *Task Step 6*.

*Barrier:* While some guidelines for general cable routes are etched into the board and the position of the cable fasteners help, there are no printed instructions on where to thread the cable. Therefore this step relies at least partially on experience. Additionally, if the assembly is in an advanced state, already assembled cables might complicate the visual identification of the guide lines on the board.

**Task Step 8:** Find the correct slot in the housing(s) from *Task Step 6*.

*Barrier:* Same barrier as for *Task Step 4*.

**Task Step 9:** Plug in cable end(s).

**Task Step 10:** If there are still uncompleted assembly steps, repeat from Step 1.

## 2.4. Requirements

With the usage data gathered, analyzed and modeled in the previous section, the next step was to translate this data into requirements or *user goals* that the design for *Augmented Laying Board* has to meet. In the *Wheel* life cycle this is the last step of the *Understand* activity. The first three of the gathered requirements are intended to directly address the *barriers* identified in the *Task Sequence Model* from the last section (see figure 2.5).

### **R1: Visualize Locations of Cable Housings**

*Augmented Laying Board* should provide the user with the locations of the cable housings into which the ends of the current cable should be plugged into. The user should be able to differentiate between which ends of a cable should be plugged into which housing shown by the system.

*Addresses barrier of Task Step 3*

### **R2: Visualize Housing Slot Assignment**

After being shown the position of a target housing, the user needs to know into which slot

of the housing he should plug in the cable. *Augmented Laying Board* should provide the user with a map or visualization to determine this slot.

*Addresses barrier of Task Step 4*

### **R3: Visualize Cable Route**

*Augmented Laying Board* should visualize the route a cable has to be laid along on the board, including the fasteners through which the cable should be threaded through.

*Addresses barrier of Task Step 7*

### **R4: Integrate into the Work Process**

*Augmented Laying Board* should integrate as seamlessly as possible into the existing work process. For this, the system should allow at least for partially hands-free operation, as the assembly ideally requires the use of both hands. In addition to that, the system should provide a view on the physical laying board with as little distortion and latency as possible as the assembly process can require a fairly high precision, especially at *Task Step 5 & 9*, where the cables are plugged in and *Augmented Laying Board*.

### **R5: Integrate into the Work Environment**

*ALB* should integrate into the current work environment with as little modifications as possible. Larger changes to the environment or procedures at *Engeser* may not be generally feasible. In addition to that a good integration facilitates the later evaluation of *ALB*, as every modification would have to be applied at *Engeser* for the duration of the evaluation as well.

### 3. Theoretical Background and Related Work

This chapter gives a short summary of the theoretical background of *Augmented Reality* and then provides an overview of its applications in manufacturing. In Section 3.1 the term of *Augmented Reality* and the closely related *Mixed Reality* and *Virtual Reality* are introduced. After that, Section 3.2 covers the previous work for the topic of utilizing *Augmented Reality* in manufacturing in more detail and focuses especially on the application for assisting in the assembly of wire harnesses.

#### 3.1. Augmented, Mixed and Virtual Reality

The term *Augmented Reality* was coined by Caudell et al. [2] in 1992. They proposed a headset with a transparent "see-thru" display that could "augment" a worker's visual field of view with digital content. In 1994, Milgram and Kishino then picked up the term and expanded it by including any device that allows to primarily view the real world with superimposed virtual data [9, 10]. They created a taxonomy which they called "Reality-Virtuality Continuum" or just "Virtuality Continuum". This continuum maps the concepts on spectrum between *Reality* and *Virtuality*, defined as the real, unmodified world and total virtual immersion.

On the continuum, Milgram and Kishino place *AR* more towards the real environment, meaning that its emphasis is on displaying the real world with added elements from virtual environments to augment it. *VR* on the other hand lies on the opposite side. Different concepts of *VR* can be placed all along the continuum on the *Virtuality* side, right up to the extreme point of total virtual immersion (see figure 3.1). And last, *Mixed Reality (MR)* was defined by them as any environment where both real and virtual objects are displayed together by a single device. It spans the complete space between *Reality* and *Virtuality* with the exception of the extreme points themselves.

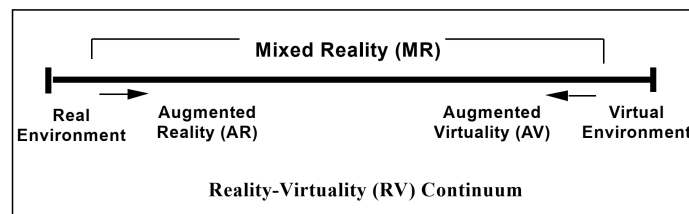


Figure 3.1: The Reality-Virtuality Continuum by Milgram and Kishino [9]

However, Milgram and Kishino were categorizing *AR* and *MR* based mostly on the visual aspect. Azuma tried in 1997 to also include interactivity in his definition for *AR*. He defined three characteristics, that are critical for *AR systems* [11]:

1. Combines real and virtual
2. Is interactive in real time
3. Is registered in three dimensions

With these characteristics, he tried to narrow down the defining aspects of *AR* while also trying to de-emphasize the reliance on *head-mounted displays* as characteristic of *AR*, similar to Milgram and Kishino. His definition was also an attempt at differentiating between "true" *AR* and for example simple digital 2D overlays.

## 3.2. *Augmented Reality* in Manufacturing

From its inception on, *AR* has been utilized to create a wide range of systems that support various manufacturing tasks. Only a handful of them focus on the topic of wire harness assembly though. The next part of this thesis takes a look at some of these systems, which were either research projects or are commercial applications.

### 3.2.1. *Augmented Reality: An Application of Heads-Up Display Technology to Manual Manufacturing Processes* (1992)

As mentioned above, this paper by Caudell et al. coined the term *Augmented Reality* and was one of the first works that explored potential practical applications for this kind of technology at Boeing [2]. Their aim was to improve the various manufacturing processes involved in the assembly of the company's planes like the 747. They developed a prototype *AR* device called *HUDset*, that was able to project simple wire frames, outlines, designators and text into the field of vision of its wearer. Unlike modern *AR* headsets however, this prototype was not working with a true see-through display. The overlay effect was achieved by using a single display over one eye to show the digital content and letting the wearers brain fuse both images together. The hardware was radically different and its capabilities not really comparable to the state of the art today. Despite this, the authors identified many issues of *AR* in general, for example how important accurate registration of both the environment and the objects with virtual overlays or a sufficient field of view are.

The authors identified four scenarios, for practical applications of *AR* in manufacturing (see figure 3.2).

The first scenario is, incidentally, a wiring form board with pegs where wires have to be laid out across to assemble wire harnesses. At Boeing, the instructions were glued onto the board as a computer generated plot, which resulted in them being difficult to read as the harness grew.

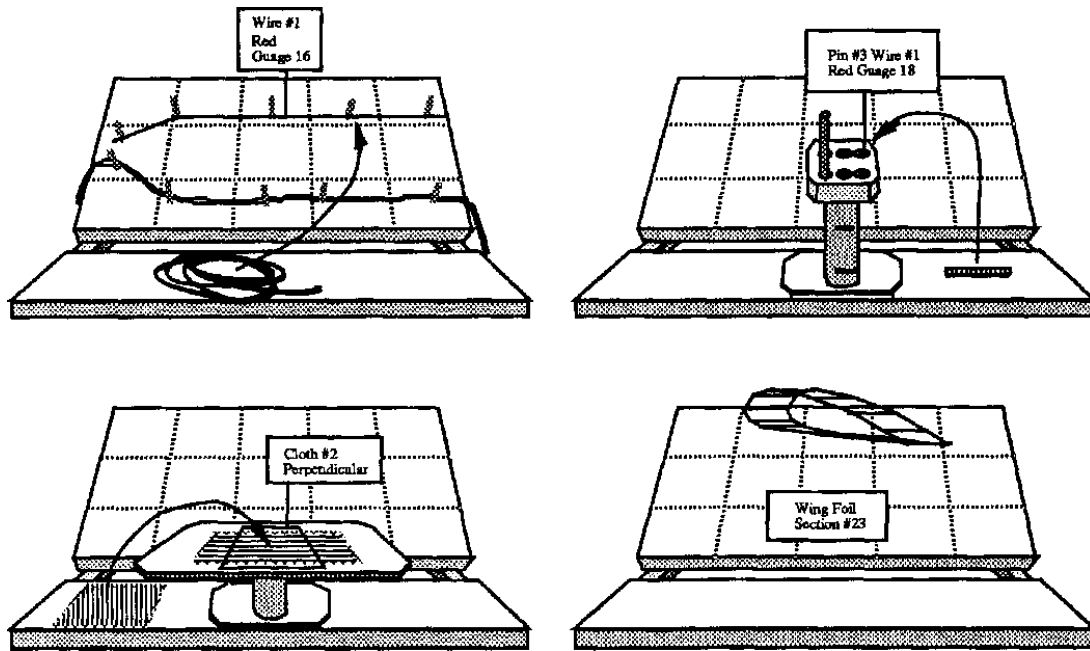


Figure 3.2.: The four applications for AR as envisioned by Caudell et al. Clockwise from the top-left: laying board, wiring up a housing, composite cloth assembly and wire frame display. [2]

The *HUDset* was then used to display the pegs for the current assembly task and sequentially display the paths of individual wires.

The second scenario is also the next step in the assembly of a wire harness. After the wires were bundled, their ends, or leads, had to be inserted into housings. Workers usually used a paper map that showed what wire needs to go into which pin. With *HUDset*, they were shown a red line protruding at the location of the slot for the current wire and a text window with the current wire's number and description.

The next scenario is the manufacturing of composite structures. Here, precut sheets of sticky fabric had to be laid on top of another with an exact orientation and position. Workers were using a physical template and a grease pencil to mark where sheets had to be laid out. With *HUDset*, a red outline was projected directly onto the work piece to show them where to lay the next sheet.

The last scenario are general maintenance and assembly tasks. Here, *HUDset* was employed to display wire frames superimposed on a structure to show workers how it should be assembled or where a part that had to be serviced was located. In addition to that, animations were used to visualize individual assembly or disassembly instructions.

As this project is almost 30 years old, of course it has its fair share of disadvantages. The hardware itself was in its infancy and while Caudell et al. created designs for headsets with true *optical see-through* capabilities, their prototype was severely limited. It restricted its users ability to perceive depth, as the user could only see the real world with one eye and the digital display used had a quite low resolution. To accurately overlay digital content over the real

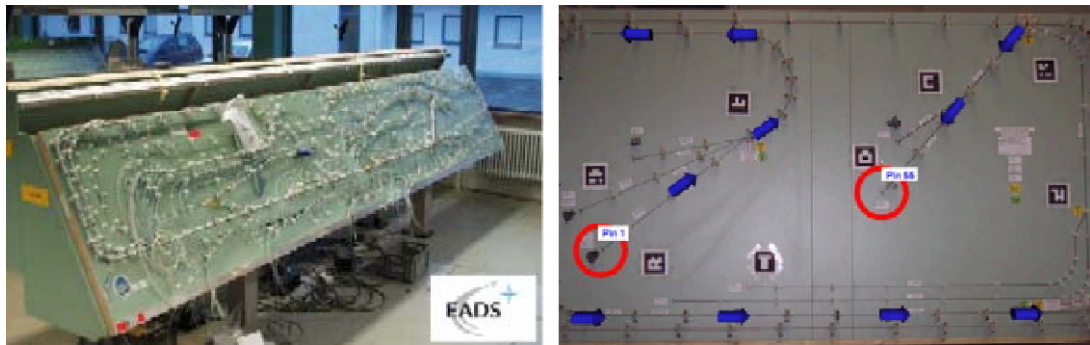


Figure 3.3.: Laying board at EADS (l) and visualizations of ARVIKA for assembling a wire harness (r) [12]

world, it required careful calibration to the users eye positions and regular recalibration as the headset could move too much on the users head. The tracking of the work pieces, for example the form board, was quite limited as well, as the project used multiple "magnetic transmitting units" to estimate the user position. It was state that this gave them "medium accuracy" for positional tracking. All in all, the *HUDset* probably didn't work very well, especially compared to the hardware available today. Despite this, the identified issues for *AR* as well as the developed use-cases have proven to be groundbreaking

#### 3.2.2. ARVIKA - Augmented Reality for Development, Production and Service (2002)

*ARVIKA* was a pilot project sponsored by the German ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) for mobile industrial *AR* at *EADS* [12]. *ARVIKA*'s goals were to support workflows in design, production and maintenance with a focus on automotive and aircraft equipment. Several different scenarios regarding these workflows and how to apply *AR* to them were developed as part of this project.

The chosen use-case for a design scenario was to compare simulated results of a crash test with the actual deformation resulting from a physical test. *AR* was used to display an overlay with a representation of an undamaged section of a car over the real section of the "crashed" car. The aim was to support detection of the actual damage and the comparison between it and the simulated results.

The production of wire harnesses for the Eurofighter was chosen as a use-case for the production and assembly scenario (see figure 3.3). A system was developed, where the assembly worker receives the routing schedule steps depending on his position in front of the laying board. The *AR* headset shows the starting point of the wire assembly as red circle and routing directions that indicate where the cable should be laid along as blue arrows. Marker-based tracking was utilized to register the position of the laying board with the *AR* application. Via speech recognition, a worker was able to request further information.

The use-case for a service and maintenance scenario was to assist in troubleshooting and the maintenance of production machines in the field. The system granted access to documents



about a machine to repair or provide direct interaction with a technician from the service center.

The main focus points for *ARVIKA* were *reliable tracking* of the user to display virtual information correctly within the real environment, *information provisioning* to enable the access of already existing data by users and *interaction* via different input and output devices with a focus on speech input and output that supports hands-free interaction.

### 3.2.3. Using augmented reality in AIRBUS A400M shop floor assembly work instructions (2012)

Of course Boeing's main competitor Airbus has also experimented with utilizing *AR* to improve their assembly tasks. This paper from Serván et al is a more recent example of practical applications for *AR* that were developed as part of *Project MOON (assembly Oriented authoring augmented reality)* [13]. The project attempted to fully integrate *AR* into a digital workflow from the Instruction Authoring phase to the Assembly phase to the Maintenance phase. The assembly and routing of a wire harness in a frame of the A400 transport plane has been chosen as a use-case for the Assembly phase. The assembly itself consisted of installing fittings on a laying board through which wires had to be routed. A tablet PC equipped with a webcam was used as a *video see-through AR device* to display the schematics of the wire harness as an overlay over the assembly board (see figure 3.4). Markers attached to the assembly board were used to enable the tablet PC to recognize the position of the board.



Figure 3.4.: Project Moon Workshop Testing [13].

### 3.2.4. ProjectionWorks Harness (2016-Now)

Unlike the previous works, *Harness* by ProjectionWorks is an application of *AR* for manufacturing that is commercially available [6]. The system uses projectors to project images onto surfaces and *ProjectionWorks* offers different solutions to support assembly tasks, painting tasks or the assembly of wire harnesses (see figure 3.5). As it relies on projectors and can only produce 2D images, it does not strictly support "true AR" as defined by Azuma. However because this system shows that a 3D image is not absolutely necessary for this task, it has nevertheless been included.

To recognize the target surface for the projection, the system projects a special calibration pattern onto the surface and utilizes a camera to recognize it. For the wire harness assembly, a tablet PC or a mobile PC workstation is for configuration and interaction with the system.

### 3. Theoretical Background and Related Work

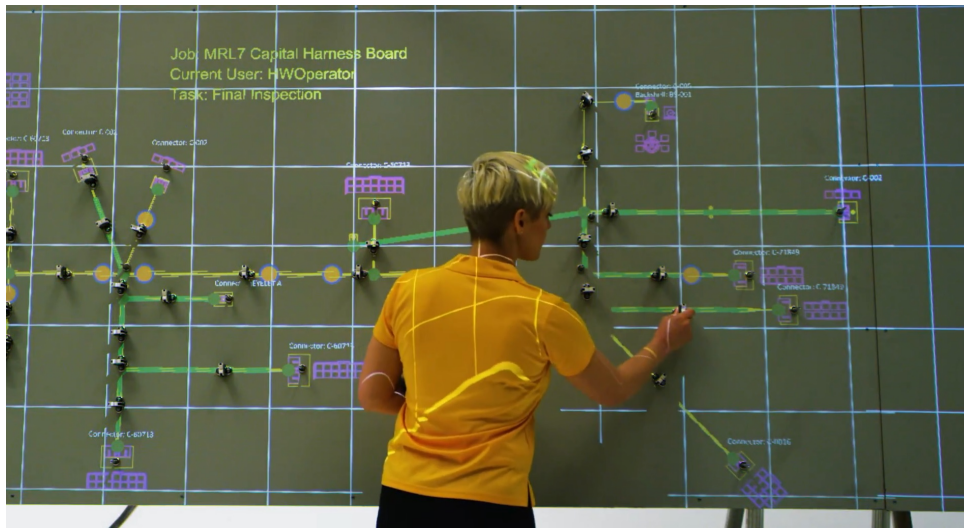


Figure 3.5.: The Harness system in use to assemble a wire harness [6]

A bar code reader that is similar to the ones used at cash registers is used to identify the cables. After a cable has been identified by the system, the start and endpoints for the cable are projected onto the board. Additionally, the route between them and a visual representation of the housings at either ends are shown. The system also supports the integration into an electrical test system. It can test if a cable has been connected correctly and contains a verification mode that shows incorrectly connected cables on the connected tablet or workstation PC.

#### 3.2.5. Upskill Skylight (2011-Now)

The second, currently available commercial application of AR in manufacturing is the *Skylight* system by *Upskill* [14]. *Upskill* started out as a company that provided the hardware and software for a smart glasses project of the US Army. After that, the company started to develop a more general software solution for AR. With the advent of the *Google Glass* and other AR devices, the company eventually abandoned producing their own hardware and expanded their *Skylight* software to work on a multitude of devices. Today it can be deployed on devices with different form factors, from smart glasses like the *Google Glass*, to mobile devices like tablets and smartphones, and to head-mounted AR devices like the *HoloLens 2* from Microsoft. The system also has a much broader scope than *Harness*. In the white paper for *Skylight*, different areas of application are listed, for example the usage by warehouse workers to navigate and pick orders or field technicians that employ it to access work orders, instructions or schematics and are able to access live data from network diagnostics and contact experts at a remote operations center [15]. Another use-case is the support of workers in factories at assembling wire harnesses. The system replaces physical wiring schematics and instead displays them digitally. These digital schematics and instructions can be accessed step-by-

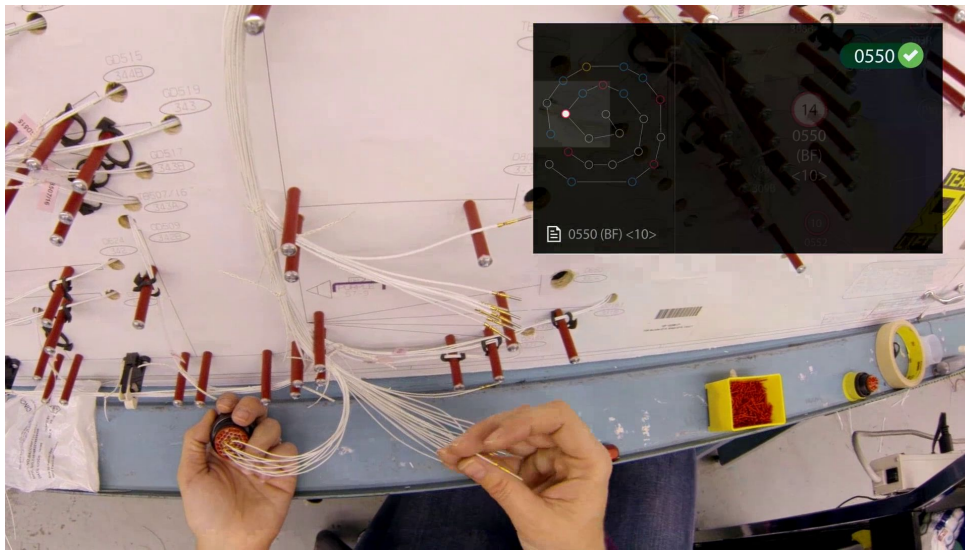


Figure 3.6.: Wire harness assembly at Boeing using ProjectionWorks Skylight [16]

step in a hands-free manner, either via voice commands or gestures. Unlike the *Harness* system however, *Skylight* does not project visualizations onto the laying board. It just renders instructions as 2D window in the field of vision of the worker.

### 3.2.6. Summary

The presented systems have shown that from the beginning of AR on, there has been interest in applying it to the manufacturing of wire harnesses. These systems also show a clear progression of the hardware used to display the digital content and the methods of tracking the work pieces. However, the most interesting aspect for this work is what kind of visualizations they employed to support the assembly process. Weibel et al. introduced a categorization scheme for AR visualizations for manufacturing tasks that divides them into three groups, *direct visual aids*, *indirect visual aids* and *adaptive visual aids* [17].

**Indirect Visual Aids** contain information that is displayed in a static form and are not registered with the environment. They act as "virtual Post-Its" and provide a user with contextual information without pointing at a specific location. This approach is employed by *Skylight*. Users can request information about a specific subject, which is then rendered in their field of view, as can be seen in figure 3.6.

**Direct Visual Aids** represent visualizations who are directly superimposed onto specific parts of the real world. The visualizations of *HUDset*, *ARVIKA*, *Project MOON* and *Harness* belong in this category. These systems use the positions of their visualizations to directly communicate to the user where a specific action has to take place, for example where a cable has to be plugged in. An example is how *ARVIKA* and *HARNESS* project the information about

where a cable should be laid out directly onto the laying board as can be seen in figure 3.3 and figure 3.5.

*Indirect aids* are useful, as they can provide information without having to know much about a users environment. *Direct visual aids* however are a big part of what makes AR so interesting for manufacturing, as they allow to actually enrich the real world with information. There are indications that *direct visual aids* or *in-situ instructions* can be very beneficial for task completion time and task errors compared to *indirect visual aids* and conventional instructions for maintenance and assembly tasks [18–23]. Yet they also have disadvantages. 3D models projected over a physical object can occlude a users view of said object and complicate interactions with it [24, 25]. *Direct visual aids* also require a fairly high accuracy of registration with the real world, depending on the model and task [25]. They can even be detrimental to user performance if this requirement is not fulfilled [25, 26].

As a compromise, Webel et al. introduced **adaptive visual aids** [25, 27]. These visualizations primarily display contextual information, similar to *indirect visual aids*. They are also linked to a specific location in the real world via a pointer object that is rendered over a physical object, like a *direct visual aid*. With this combination, complex information can be displayed for specific spatial contexts without the drawbacks of *direct visual aids*.

For *Augmented Laying Board*, all three kinds of visual aids could be utilized to display the assembly instructions, depending on the context and the information that should be conveyed to the user.

## 4. Design and Implementation

The next steps according to the *UX Lifecycle* are the *Design* step and the *Prototype* or *Implementation* step. As the design depends on the capabilities of the hardware platform used for the system, we are going to take a look at the available hardware platforms first in Section 4.1. Following up, in Section 4.2 a selection of interaction techniques is presented that might be suitable for our system. The design concept itself is elaborated in Section 4.3. This section contains the choice of hardware and interaction techniques as well as the design of the visualizations that should be employed for the system. In the last part of this chapter, Section 4.4, an overview of the implementation of this design concept is shown in the form of the prototype *Augmented Laying Board*.

### 4.1. Hardware Options

Only a few years ago off-the-shelf hardware for *Augmented Reality (AR)* basically did not exist. Researchers and companies aiming to make use of the technology had to either simulate the needed hardware or have it custom built. Nowadays a wide range of devices for *AR* is commercially available. Although they all support *AR* experiences to some degree, the differences between form factor, display capabilities and input modalities are big enough to require a careful evaluation to determine which solution fits *ALB* and its requirements best. In this section a range of different types of devices is presented along with their advantages and disadvantages.

#### 4.1.1. Mobile Devices

The most readily available class of *AR* devices are *mobile devices*, consisting of *smartphones* and *tablets*. They can be used for *Virtual Reality* or, with their cameras, as *video see-through* devices for *AR* (see figure 4.1). These devices usually rely on *inside-out tracking*. They use built-in gyroscopes or sometimes even depth cameras and extensive processing of the normal video image captured by their cameras. This technology is already quite advanced and works well most of the time, however the devices' form factor and the available input modalities have drawbacks, especially for manufacturing tasks. Tablets and especially smartphones only offer a small field of view due to the relatively small displays and their hand-held nature. In addition to that, they need to be held by the user, which may conflict with a user's other tasks. The input modalities usable with them are limited. Due to this, most systems utilizing

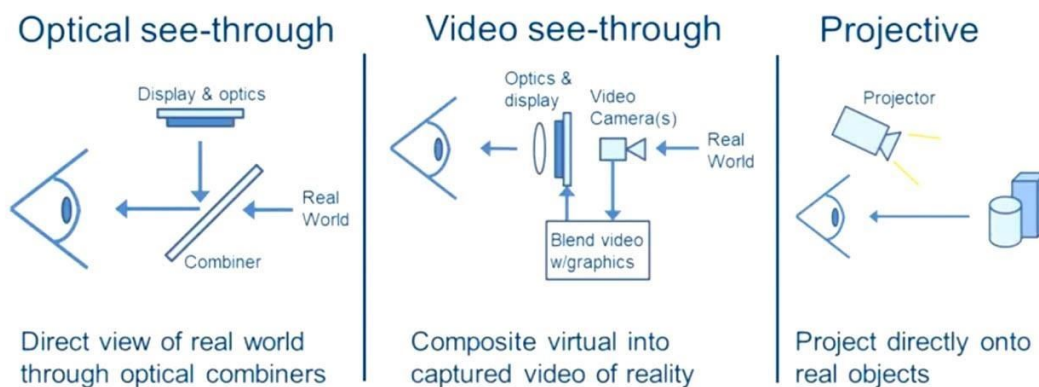


Figure 4.1.: Illustrations of the ideas behind AR via optical see-through, video see-through or Projection-based devices [28].

these devices solely rely on 2D touch input provided by the devices' touchscreens and voice commands.

*Project Moon* that was presented in the previous chapter is an example of a system using this kind of hardware for AR. In addition to that, *Upskill Skylight* can utilize an *Apple Ipad* for AR.

#### 4.1.2. Projector-Based AR

*Projector Based AR Devices* are not as widely used as the other classes of AR devices. A projector is employed to project an image onto a surface and augment it with virtual content (see figure 4.2 and figure 4.1). This class of devices posses several advantages. They don't require a user to hold or wear any hardware. It also does not need any special sensing hardware for the image generation and the hardware itself is widely available and tried and tested. With modern projectors the image quality is at least decent and for our use-case there are no limitations regarding the field of view. Their main disadvantages are that such a device just generates a flat image and does not allow for any 3D visualizations. And while there are no limitations regarding input modalities, these devices also do not provide any tracking of the users out-of-the-box. In addition to that it has several drawbacks due to the nature of the projector used for it. It has a limited mobility and requires a special environment that provides a projection area and potentially a bigger space. Additionally, in most configurations the user stands between the projector and the projection surface. This causes the user to occlude parts of the projector image and creates shadows. This can be circumvented with a special projector that can be mounted above the projection area, which minimizes shadow creation, but requires a more complicated projector mounting.

One of the few systems using this kind of hardware for AR is the *ProjectionWorks Harness* system.



Figure 4.2.: Example of a Projector-Based System for Wire Harness Assembly [29]

### 4.1.3. Head-mounted Displays

*head-mounted display (HMD)* devices can be generally divided into two different sub classes: devices that provide an image via *video see-through (VST)* and *optical see-through (OST)* devices (see figure 4.1). The primary difference between those two classes is their method of displaying the real world and the virtual augmentations. *Video see-through* devices like the *Oculus Rift* typically rely on normal displays that simply render the image of cameras with additional, digital objects. *Optical see-through* devices like the *Microsoft HoloLens* on the other hand feature transparent displays that allow an unobstructed view of the real world and just render the additional objects themselves [9, 30].

**Video See-Through Headsets** are usually *Virtual Reality* headsets that support a VST mode, for example the so-called passthrough mode of the *Oculus Rift and Quest*. Originally this feature was intended to allow a headset to provide a slight, shadowy, visualization of the real world to users to enable awareness of the physical boundaries and obstacles even while users are completely immersed in a virtual world. Some of the latest headsets also support displaying the real world in a non-shadowy way and thereby essentially provide *augmented reality* via *video see-through* [31, 32]. In this mode, the device uses its cameras to capture images of the real world, merges them and combines the resulting image with virtual objects. The combined image is then displayed on the device's screens. Headsets with more advanced

software are also trying to digitally correct camera artifacts and aberrations, for example from wide angle cameras, before adding in the virtual objects.

These devices offer an increased field of view, very good image quality and platforms that are similar to the ones of mobile devices with regard to robustness and maturity. Their form factor is also a big advantage, as it imposes few limits on the user in terms of mobility, input modalities and interactions with the real world. However, these devices also have disadvantages.

First, users are always only seeing a camera feed of the real world. The final image and the correction of both distortions and aberrations introduced by the cameras and the display system depend heavily on two factors: the cameras and their placement, and the software processing capabilities of the headset itself. In addition to that, both the virtual and real parts of the image are influenced by the device's display resolution and refresh rate, as well as the latency between camera and display [30]. At the current time, the different *VST* modes are still in an experimental stage. While they are already quite impressive and generally work well, smaller distortions and other processing artifacts can still occur regularly if the conditions are not ideal.

The second major disadvantage of these *VR* headsets are the available input modalities. At the time of the implementation most headsets only supported hand-held controllers as a direct input method. And while some of those can be quite accurate and intuitive for manipulating 3D objects, they limit what other tasks a user can execute with his hands. Notable exceptions of this were the *Oculus Quest* and the *HTC Vive*, which have introduced hand tracking. However for both devices this feature is still in an early, experimental state.

The second sub class of *HMDs* consists of **Optical See-Through Headsets** that are used as dedicated *Augmented Reality* devices. This type of device has only recently become commercially available for a wider audience. The earliest one was the *Microsoft HoloLens 1* released in 2015. At the moment, buyable devices of this category are the *HoloLens 1 & 2* [33], the *Meta 2* [34] and the *Magic Leap One* [35]. These devices all have a transparent display in common. This allows a user to see the real world directly while at the same time enables the device to render digital object over it. As a result, most of the factors having a negative impact on image quality plaguing *VST* devices either just affect the digital objects or have no effect at all. All different *AR* headsets support predefined hand gestures and head tracking. The headsets are all standalone units, which means they don't require any additional hardware to work. The *HoloLens 2* even supports hand tracking similar to the *Oculus Quest*. The biggest disadvantage of this device class is almost uniformly their limited field of view and the inferior image quality of the virtual content compared to the *VR* devices. In addition to that, the fact that the devices are standalone also means that their usage duration is limited by their batteries and they might require frequent recharges.

The *HUDset* by Caudell et al. can be assigned to this category, however it fits neither really into the *OST* nor into the *VST* category. *Upskill Skylight* can be primarily used with different headsets that support *OST*, like the *HoloLens* or *Google Glass*.



## 4.2. Interaction Techniques

This section concentrates on providing an overview of interaction techniques compatible with the *Augmented Reality* hardware presented above. The techniques are presented briefly along with their advantages and disadvantages.

### 4.2.1. Gestures

One of the most natural methods for us humans to interact with our environment is using our hands. It is no surprise that there is a lot of research into how we can utilize them to interact with virtual environments as well. Quek et al. have categorized such interactions broadly into *Manipulative Gestures* or *Semaphoric Gestures* [36].

**Manipulative Gestures** are generally used to control objects. They are employed for direct interaction, where every action usually invokes a related reaction on the controlled object. Most interactions between humans and their environment that are performed with hands fall into this category. They are typically aided by visual, tactile or force-feedback from the manipulated object. Research into this kind of gestural interaction has been going on for a long time, for example with “Put-That-There” by Bolt et al. from 1980 [37] or the *Holodesk* by Hilliges et al. [38].

**Semaphoric Gestures**, the second category, are defined as gestures that follow a predefined set of hand movements which are interpreted as signals. Gestures that fall into this category are mostly used for communication and don't require any direct feedback like *manipulative gestures* do. Unlike *manipulative gestures* the predefined sets of movements can differ between persons and cultures. Therefore while *manipulative gestures* can be intuitively understood, *semaphoric gestures* have to be taught first.

On the technical side there are a couple of ways to track hand movements for recognizing both types of gestures. The big VR platforms, like *Oculus Rift-Series*, the *SteamVR* headsets or *Windows Mixed Reality* headsets ship with a set of handheld controllers that enable tracking hand positions and allow input via buttons on the controllers. However, these controllers support neither the tracking of individual fingers and therefore more complex manipulation gestures like grabbing nor do they offer anything beyond vibration-based feedback. They also have the distinct disadvantage that they too require to be held in hands, similar to the disadvantage of *AR based on mobile devices*.

As an alternative, several companies have sprung up to develop more complex haptic controllers that promise to support both finger tracking and more haptic feedback for interacting with virtual objects [39, 40]. While they enable the almost full usage of a user's hands and might offer tactile and haptic feedback, they are still in an early stage and not widely available.

The last method to track hand movements is via optical tracking. The *Holodesk* for example has utilized a *Microsoft Kinect* camera but there also exist ready-made solutions specifically

for hand gestures like the *Leap Motion*[41] or the integrated tracking of the *Microsoft HoloLens 2*.

The main advantage of hand gestures is that, if implemented properly, they offer a very intuitive and direct way of interaction. A trade-off has to be made between hardware that supports hands-free interaction, for example optical tracking, and hardware that allows for a high interaction precision, like handheld controllers. The biggest disadvantage all methods have in common is that they are more physically demanding than many other interaction techniques. They require more planning regarding accessibility and physical stress. In addition to that, *semaphoric gestures* and, to a lesser extent, *manipulative gestures* require that a system communicates to the user which gestures are supported, where they are supported and what effects they have.

### 4.2.2. Eye and Gaze Tracking

While eye tracking is mainly used as a tool for researchers to track a user's attention, it has also been deployed as an interaction technique in various research projects like *Still Looking* by Stellmach et al [42]. At first glance tracking a person's focus seems like a great approach for selection and manipulation tasks due to it being very intuitive and not requiring any handheld devices. The latter point also results in it not being prone to associated problems like causing overt physical stress.

However with those advantages there are unique challenges in the eye tracking for interaction. One of the biggest of those challenges is that eye tracking is inherently inaccurate. Most modern eye trackers require careful calibration before each use to reach decent tracking quality. They are therefore sensitive to movement which can throw off the calibration. Additionally, the so-called *saccades* make using the eye direction as interaction complicated. They are the jittery movements we make with our eyes subconsciously, which leads to our eyes not always pointing at what we want to focus. This can be counteracted by smoothing algorithms and other more context-aware techniques. Preventing or designing around bigger jumps however, for example induced by external stimuli, is much harder. These jumps, along with conscious eye movements that are not meant as interaction, are called the *Midas Touch Problem* [43]. Designing around this problem is one of the prime challenges of employing eye tracking as input method.

An alternative to eye tracking has been developed by Microsoft as the primary interaction method for their *HoloLens 1*. The method dubbed *Gaze Tracking* simply uses the direction of your head and a separate method of simulating clicks. These clicks can be triggered either with a *semaphoric hand gesture* or a dedicated clicking tool, which neatly side-steps the *Midas Touch Problem*.

### 4.2.3. Speech Recognition

With the advent of smartphones and their voice assistants, speech recognition have gotten a big boost in accessibility. Through machine learning and other improvements, modern speech recognition systems, like Siri [44], no longer need to be trained for individual users and have become very good at recognizing separate words. Those systems are also much better at recognizing whole utterances and reasoning about them, thus enabling a much more natural interaction between user and their devices compared to earlier systems.

There are a lot of challenges with using speech for interaction with computers, some of which pertain to characteristics of language itself. Ambiguity and imprecision inherent in human language present a problem to computers. Using contextual clues in our speech presents computers with a similar problem that has not yet been fully solved. With “Put - that - there” [37] Bolt et al. already recognized in 1980 that terms like *that* or *there*, while they are constantly used and mostly understood by us, are not processable for computers without additional help. Similar to how we try to resolve such imprecision if we do not understand them, Bolt et al. proposed to mix speech with other input modalities like pointing gestures to make the context of such spatial terms more accessible to computers.

Another disadvantage of speech commands is their *discoverability*. Physical interaction methods usually have physical constraints that can guide a user and help him understand how he can and cannot interact with a system. With speech input there are no such guiding constraints. A user has no way to know intuitively which commands a system may understand, what effects these commands have and if it can understand whole sentences or even process contextual information. This is a similar disadvantage *semaphoric gestures* possess. Speech recognition is also susceptible for noise and accidental input, for example from other people near the user or if the user or from conversations the user has, similar to the *Midas Touch Problem*.

The advantages of speech recognition as interaction method on the other hand are evident. Once the user understands the available commands and the capabilities of a system, voice commands are quick and easy to use and can be combined freely with most other interaction techniques.

### 4.2.4. Proxemic Interaction

The idea of *Proxemic Interaction* goes back to the theory of *proxemics* and *proxemic zones*, terms coined by Edward Hall in 1966 [45] In his work, Hall identified four different zones of proximity that characterize how a person perceives interaction with other people and their environments: *intimate*, *personal*, *social* and *public* zone. To each of these zones Hall attributed different modes of interaction. As a general rule he postulates that the closer the zone is to the person, the higher the expected engagement and intimacy. An example is a greeting between two people: in the outer zone, the *public zone*, this may consist of a simple hand waving or maybe a shouted greeting. In the *personal zone* the greeting could be a handshake and in the

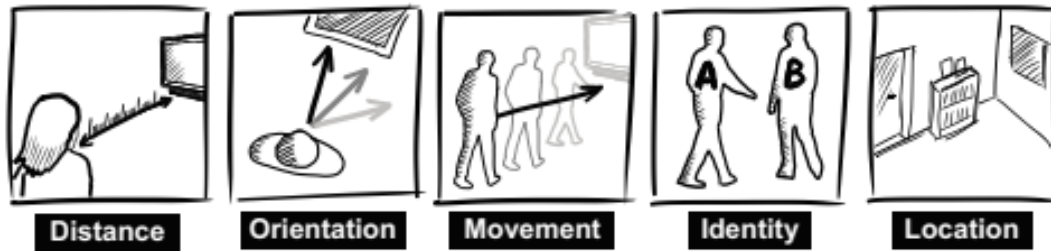


Figure 4.3.: The five proxemic dimensions (from [47])

closest zone, the *intimate zone*, it could be an embrace. In addition to that, Hall described how *fixed features*, like doors or windows, and *semi-fixed features*, like furniture, influence human interaction.

Ballendat, Greenberg and Marquardt [46, 47] then merged the theory of *proxemics* with the concept of *ubiquitous computing* by Weiser et al. [48]. *Ubiquitous computing* describes computer devices so integrated into our everyday-life that they become practically invisible or *ubiquitous*. This resulted in the interaction technique of *Proxemic Interaction*. Ballendat et al. identified five different dimensions that can be utilized to implement *proxemic interaction* for *ubiquitous computing* (see figure 4.3):

- The *Distance* between two entities
- The *Orientation* of an entity in relation to another
- The *Identity* that describes different properties of an entity
- The *Movement* as *Distance* or *Orientation* of an entity over time
- The *Location* of an entity as absolute position of where the interaction takes place

These dimensions can be used as triggers for different context dependent actions, e.g. to reveal interaction possibilities or to provide feedback. In the case of this project, this could take the form of displaying a progress overview if a user steps away from the laying board as an example. The advantage of *Proxemic Interaction* is that, if used well, it can provide another layer of intuitive and natural interaction and enhance the user experience of other techniques. The risk is however that such interactions can be hard to discover and might even be confusing if a user is unable to discern what exactly triggered an action.

### 4.3. Design Concept

After an overview of the available hardware and interaction techniques that could be used for *ALB*, the next step was to select a suitable hardware platform and matching interaction techniques. These were then combined with the insights into the application context that were gathered in Chapter 2 and the insights from the related work of Chapter 3. Based on

this, a design concept for *ALB* has been developed which is presented in the last part of this section.

As described by the *Wheel UX Lifecycle*, the design and implementation activities were iterative processes. During the design and the implementation of the prototype, insights were gathered regularly as to which parts of the design might or might not work out. Some of these insights triggered further iterations of the prototype or even of the design activity when it was deemed necessary.

#### 4.3.1. Hardware

The biggest advantages of *AR* based on *mobile devices* are their good image quality and the mature and readily available hardware. For this use-case however, they have several drawbacks.

Due to their size and the way they are usually held at a distance, their field of view is quite small. They need to constantly be held by at least one or even both hands, which is physically demanding and a problem for our use-case, as it might require the use of both hands. In addition to that, mobile devices only offer *VST*. Both disadvantages present a conflict with requirement R4 (*Integration into the Work Process*).

*Projector-based AR* offers slightly inferior, but still decent image quality. Unlike mobile devices, they don't impose any restrictions on the user regarding interaction techniques or hand usage. And as long as the projection size covers the whole laying board, field of view is not an issue. However, the problem of users occluding a part of the projection and the potential extensive setup needed to mount the projectors are definitely an issue. Especially the mounting conflicts with R5, *Integration into the Work Environment*. In addition to that, utilizing a projector for *AR* would require additional devices for user interaction and environment registration. And unlike for example with *AR* for mobile devices, where official extensive SDKs exist that are widely used, many basic functions for *AR* would have to be implemented for projectors, for example environment registration.

*VR* headsets that act as *VST AR* devices have the advantages of a good field of view and a generally very good image quality. However the devices that were available to develop this system offered only limited hands-free interaction methods. These devices were also all tethered and require additional cabling and a *PC* to use. These headsets also only offer *AR* as *VST*, which conflicts with requirement R4 (*Integration into the Work Process*), similar to mobile devices.

Unlike *VST* devices, headsets that support *OST* and are primarily designed for *AR* prioritize the real world over digital images. This has the advantage that the real world is always visible clearly and without distortions. Together with the support of several hands-free interaction methods these devices offer, they are a good match for requirement R4 (*Integration into the Work Process*). As these devices are also self-contained units, they don't require any larger modifications to the laying board, which satisfies R5, *Integration into the Work Environment*.

The only drawbacks of these devices are the dependency on batteries and the comparatively low image quality and field of view of the display.

In the end, the class of *VST* devices was chosen for this project. These devices meet both requirement R4 (*Integration into the Work Process*) and R5, *Integration into the Work Environment*. They possess a few disadvantages, but the effects of the low image quality and the small field of view can be mitigated by the design of the system. As actual device, the *Microsoft HoloLens* was selected, as it offered the best software support.

#### 4.3.2. Interaction

Both *voice commands* and the combination of *gaze tracking* and *semaphoric gestures* were the strongest contenders for the main interaction technique. Voice commands support completely hands-free interaction and are quick and intuitive to use. However, the assembly workstations for the wire harnesses are in close proximity to each other and situated in a big assembly together with other workstations. Therefore, interference from background noise and other workers cannot be ruled out. *Gaze tracking and semaphoric gestures* only support partial hands-free interaction, as they require one hand to perform the triggering gesture. However this can be mitigated by designing interaction to take place when the user can afford to free one hand.

Using *manipulative gestures* and *eye tracking* were initially ruled out, as they are not supported by the *HoloLens 1*. With the switch to the *HoloLens 2*, employing both became possible. *Manipulative gestures* in combination with virtual buttons became the new system standard for interaction. As these gestures provided a more natural way of interaction, the interaction design was changed to use them instead of the combination of gaze and semaphoric gestures.

*Proxemic Interaction* is an interesting concept that most likely meshes well with spatial applications in AR. It could be employed in *ALB* as an additional interaction method to switch between different levels of detail or activate separate parts of the system depending on the user position and orientation. The final iteration of the design in this work does not contain it, as the design has no actual use for it. However, one of the ideas for future work makes use of it.

Another interaction between the user and the system is the scanning of a cable to load the assembly instructions for this cable. The initial idea was to use the *HoloLens'* camera in combination with *OCR* to read the ids printed onto the cables. However, tests with an early prototype showed that this kind of detection was not reliable enough. *Bar codes* or *QR codes* were investigated as an alternative. As *QR codes* provided a better and faster detection, they were chosen for this task.

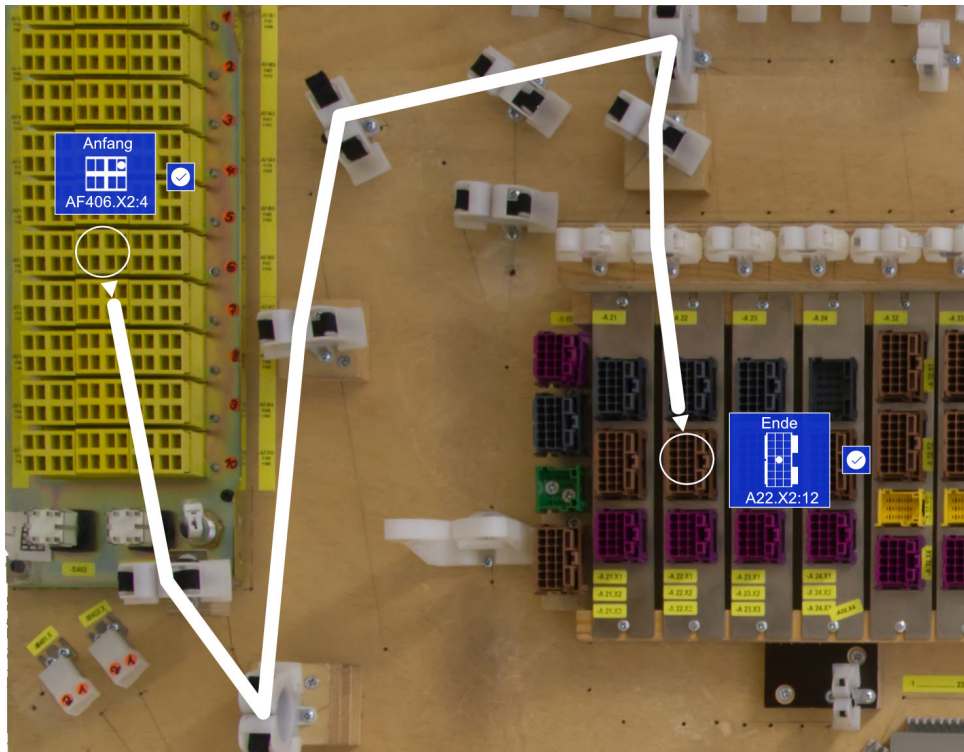


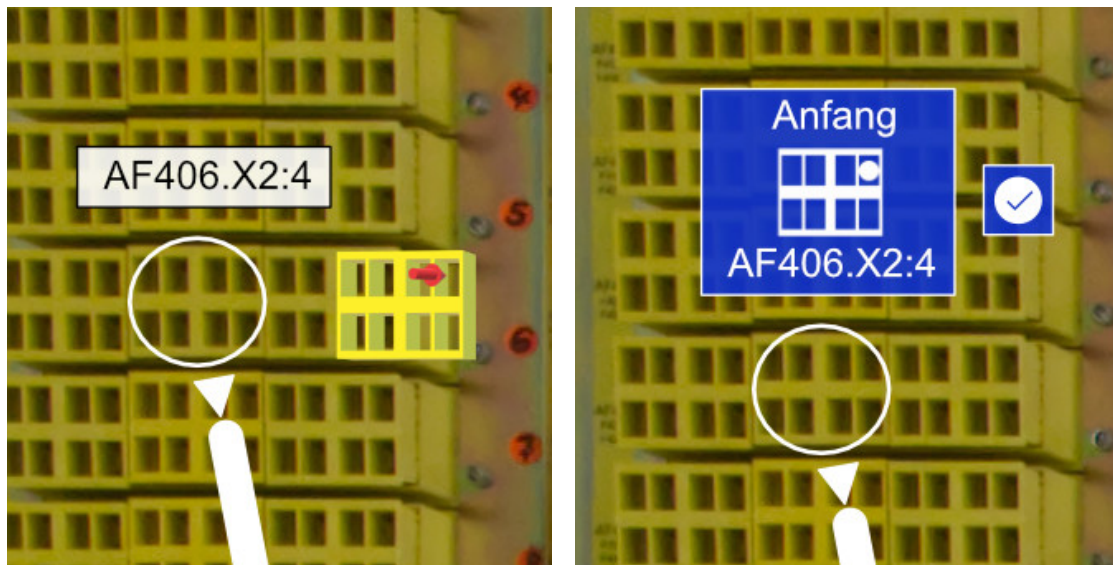
Figure 4.4: Sketch of the final design for ALB

### 4.3.3. Assembly Instruction Visualization

The requirements R1 (*Visualize Locations of Cable Housings*), R2 (*Visualize Housing Slot Assignment*) and R3 (*Visualize Cable Route*) require that *ALB* is able to display the assembly instructions for the current assembly step. These instructions contain information about the housing for the cable start and for the one or multiple housings for the cable ends. This information consists of the housing's position, shape and the slot into which the cable has to be plugged. It also consists of the individual positions of the cable's route between the housings.

The summary of Section 3.2 presented different kinds of visual aids and how they are used by other systems to support the assembly of wire harnesses. As mentioned there, these kinds of visualizations have different requirements regarding the accuracy of the environment tracking. Early tests with the *HoloLens* revealed that its tracking capabilities are good, but not perfect. For our use-case this means that the tracking is good enough to display the housing positions and the cable route. It is unfortunately not good enough to distinguish between the different slots of a housing, which can be as small as 2mm.

For these reasons, the design of *ALB* stipulates *direct visual aids* for the position of a cable's start and end points and the cable's route and *adaptive visual aids* for the slot assignment of the cable housings. The positions of the housings where the cable ends should be plugged



(a) Initial Design of the position indicator and the 3D slot indicator for a housing. (b) Refined Design with a 2D representation for the slot indicator and a confirmation button.

Figure 4.5.: First and second iteration of the Housing Visualization with Slot Indicator and the Info Window

into are indicated by a slim white circle. A circle allows the system to denote the position of a housing even with less than perfect accuracy. It also limits the possibility of the visualization occluding the section of the housing that is important for the current assembly step [24] (see figure 4.4). The cable route is visualized by a simple 3D line that leads through the loops of the fittings where the cables are supposed to be threaded through (figure 4.4). Between the indicator for the housings and the start of the route line, arrowheads pointing either away from or towards the housing signify whether a cable's start or ends should be plugged in.

The slot position for a housing is indicated by the system by highlighting the correct slot in a visual model of the housing. Studies have shown that depictive, image-based instructions offer a clear benefit for spatial tasks compared to descriptive, textual ones [49, 50]. The initial design called for a 3D model of the housing and a 3D arrow pointing to the correct slot for this. However during initial tests it soon became apparent that with unlucky placing, these slot indicators could still be mistaken for direct overlays. This mix up could result in the user trying to plug the cable into a wrong housing (see figure 4.5a). In addition to that it turned out that the visibility of the 3D models was sub optimal and it was hard to perceive the slot at which the 3D arrow was supposed to point at. With the next iteration, the depth of the 3D models were shrunk to make them more abstract depictions of the housings and the arrow was replaced by a simple circle that filled the correct slot. To improve visibility and further prevent the association with a *direct visual aid*, the model was put before a background and combined with the display of the housing's id (see figure 4.5b).

Further tests showed that the visualizations denoting whether a cable start or end should be plugged into a housing were not intuitive enough. For this reason, in another iteration the



labels *Anfang* and *Ende* were added above the housing slot visualization. In the final iteration, buttons were added to the housing positions for a user to click on when the cable has been plugged in at this location (see figure 4.5b). These buttons act as a way to tell the system that a user can continue with the next cable when all housing locations have been confirmed, as well as an aid that ensures the user plugs in all cable ends.

As the users often work close to the laying board, during the test of an early prototype, the small field of view of the *HoloLens* became very apparent. While the *HoloLens 2* is a quite big improvement over its predecessor in this regard, its field of view is still quite small with 52°. For this reason *off-screen visualizations* for the housing positions were added to the design. The purpose of these visualizations is to provide a user with the information where on the board the housing positions are, even if they are outside of the field of view.

## 4.4. Implementation

This section provides an overview of *ALB*, the prototype implemented based on the design that was proposed in Section 4.3. First, the hardware that was used, the *Microsoft HoloLens*, and its specifications are presented. The second part gives a brief summary over the software used to create the system. After that, Section 4.4.3 provides a walk-through of the system itself and the last part covers the limitations of the prototype. As the technical details of the implementation are not the focus of this work, a more thorough elaboration of the system and its technical structure can be found in the master project report on the USB drive attached to this document.

A short video walk-through of the prototype has also been included on the USB drive. The video was shot shortly after the development of the prototype was completed. Unfortunately, the digital "holograms" in this video appear to be offset due to the way the *HoloLens* recorded videos at that time. The main camera that is used to record videos sits centered on the forehead. The rendered images of the digital content however were taken from the display for the right eye and laid over this video, which caused the offset.

### 4.4.1. Hardware

Originally, the *HoloLens 1* was chosen as main device for this project. However, during the *Prototype* activity, some previously ordered *HoloLens 2* units were delivered. As the transition to the newer hardware was very easy, the development was continued using the *HoloLens 2*. The *HoloLens 2* is a standalone headset that provides *AR* of the *optical see-through* type via a pair of transparent displays using *waveguides*. The displays offer a resolution of 2048x1080 pixels per eye and a combined field of view of 52° for both eyes. The device uses inside-out tracking to track the head position and orientation of a user through 4 cameras, an accelerometer, a gyroscope and a magnetometer, which allows 6 degrees of freedom tracking. In addition to that, the device supports depth tracking via a dedicated depth camera and



Figure 4.6.: The HoloLens 2 HMD

utilizes that to continuously generate a 3D mesh of its environment, named *spatial mapping* by Microsoft. Users can interact with the device through gaze tracking, eye tracking via two dedicated IR cameras, voice commands and hand tracking, where the *HoloLens 2* supports tracking individual fingers. The display of the device is hinged, so it can be worn over glasses. Its battery and processing unit is located in a box on the back of the device, balancing out the weight of the display unit in front. The *HoloLens 2*'s battery allows for around 2-3 hours of active use.

#### 4.4.2. Software

The choice of software platform was mainly dictated by the choice of the *HoloLens* as hardware platform. Microsoft offers the ability to use either *Unity3D*[51], *Unreal Engine*[52] as development environment or *DirectX* as a low level option. Since *Unity* is the most beginner-friendly of those options and offers a broad spectrum of resources to draw upon, *Unity 2019* was chosen as main development platform. This also allowed the usage of the *MixedRealityToolkit for Unity*[53] provided by Microsoft that offers easy access to many *HoloLens* features. This toolkit provides a library of UI elements in the *HoloLens* system style that work out-of-the-box with the gaze and hand tracking of the *HoloLens 2*. In addition to that, *Unity3D* comes with the integration of the *Vuforia SDK* [54]. This SDK offers the capability to track positions in the physical world via camera and printed markers. To detect and read QR codes, *ALB* uses the *ZXing.Net* library [55].



(a) The overlay that shows the current process of the calibration  
 (b) After calibration has been completed, the user sees a pulsing overlay over the whole board that visualizes the calibration result

Figure 4.7.: The user interface for the laying board calibration

### 4.4.3. Augmented Laying Board

This passage gives an overview of implemented prototype of *Augmented Laying Board*. Its first part provides a short "walk-through" of the system from a user perspective. This is followed up with more detailed descriptions of important aspects of the prototype: The calibration process involving the physical laying board, the method for recognizing the cables, the visualization of the instruction data and the interaction with the system.

#### Walk-Through

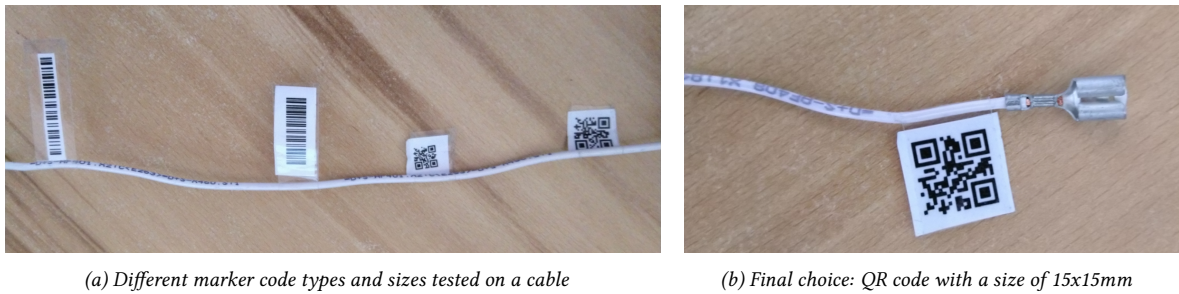
After a user starts *ALB*, the first step that has to be performed is to calibrate the position of the physical laying board used in the assembly process. At the start of the calibration process, a message is displayed to direct the user's attention to the laying board's calibration marker. Once the system picks up the marker, this message is replaced by an overlay over the marker itself that shows the process of the calibration (see figure 4.7a). After the calibration is finished, an overlay is displayed that renders a repeated pulse over the laying board. This overlay shows the position and orientation the system detected for the board (see figure 4.7b). With the help of this, the user can check if the calibration is good enough. The user can chose to continue if it is or restart the calibration process if it is not.

With the calibration process completed, a new window is shown. This window contains a list of all available laying board profiles. A profile contains the list of assembly steps and their instructions for a specific wire harness and laying board. The user can load one of the profiles by simply touching its button with his finger.

After the profile is loaded, another prompt is displayed that asks the user to scan the first cable by holding its QR code into the camera. If the cable is recognized, the user is informed by this via a prompt. After that, the visualizations for the assembly instructions are loaded.

## 4. Design and Implementation

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(a) Different marker code types and sizes tested on a cable

(b) Final choice: QR code with a size of 15x15mm

Figure 4.8.: Bar codes and QR codes attached to cables

The system displays the locations of the housings and the route along which the cable should be laid out. Above the housing location, it also displays a visualization of the housing which highlights the slot into which the cable should be plugged. After a cable has been plugged in, the user has to confirm this by pressing a virtual button next to the housing position. Once this confirmation has been performed for all cable ends, the system prompts the user to scan the next cable.

During the assembly, a window with the overall progress of the assembly is rendered on the top left corner of the laying board. This window can also be brought by a user up by holding out the left hand with the palm facing the user's face. In addition to the progress of the assembly, this window provides the user with the ability to go back to the profile menu and to revert the last assembled cable. This feature allows to rescan an already installed cable and display its instructions again in case it was installed incorrectly.

When all cables of a wire harness have been installed, the user is shown a completion message and can chose to return to the profile menu or repeat this assembly.

### Board Calibration

The calibration of the laying board is required so the *HoloLens* can position the board relative to its internal coordinate system and augment it with virtual objects. For the calibration itself, the system employs the *Vuforia SDK* [54].

With the *Vuforia SDK*, registered markers can be tracked by the *HoloLens*' camera and allow the calculation of the position and orientation of the marker relative to the camera position. The initial version of *ALB* also used the *Extended Tracking* feature [56] offered by the *Vuforia SDK*. This allows not only to track the position of visible markers, but also to get an estimation of a marker position after it has moved out of the view of the camera. The SDK relies on *Visual (Inertial) Odometry* [57] to do this. It uses the camera image and sensors like the *HoloLens*' accelerometer and gyroscope to estimate the movement of the device and approximate the new relative position of the tracked marker. A similar method is used by phones without any depth sensing hardware to implement some AR capabilities. However, due to a visible jitter of the object position and noticeable positional drift it was decided that this method

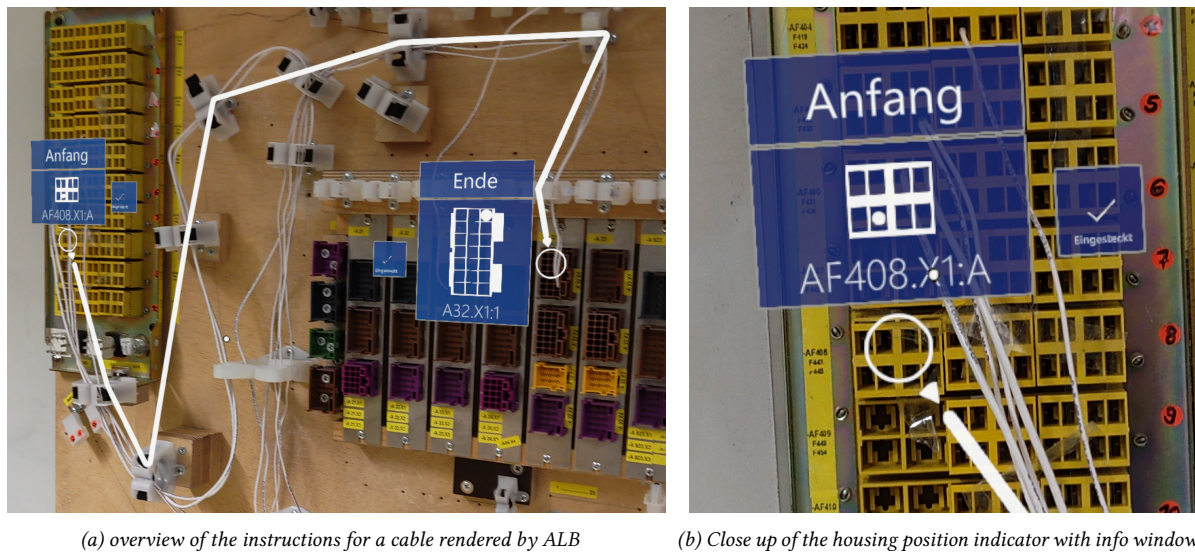


Figure 4.9.: Rendering assembly instructions in ALB

was inadequate. After another iteration of the prototype, the *Vuforia SDK* is now only used to get the initial position of the marker. During the calibration process multiple samples of position and rotation of the marker are collected and averaged to combat jitter. The position is then handed over to the internal tracking of the *HoloLens*. This proved to be a significant improvement, both regarding performance and accuracy.

### Cable Recognition

Initially, *ALB* was supposed to use the labels printed directly on the cables to identify them. However, even with additional preprocessing, the recognition of the labels proved to be not reliable enough. As a replacement, the usage of different sized and configured bar codes and QR codes was evaluated (see figure 4.8a). In the end, QR codes with a size of 15x15mm with an extra level of error correction were chosen as a compromise between detection distance and marker size (see figure 4.8b). The codes were attached to the cables with matte *Scotch Magic Tape*, as the glossy finish of normal transparent tape caused reflections of light which led to recognition problems. To read the ids encoded in the QR markers, the video feed of the *HoloLens*' main camera is processed with *ZXing.net*[55].

### Assembly Instruction Visualization

After a cable has been recognized, the system displays the assembly instructions for it. As figure 4.9a shows, the positions of the start and end housings are indicated by a white circle. The white line connecting them denotes the path the cable should be laid along. Small

arrowheads pointing either from the circle to the line or the other way around indicate whether the location is the start housing or one of the ends.

Next to every housing indicator, an info window is displayed by the system. At the windows top, a label is whether the cable's start or one of its ends should be plugged in at this position. At the bottom, the housing's part of the id printed on the cable is shown, with the housing id and slot position separated by a double point. The central part of the window is a visualization of the housing and the slot position for the cable end. This visualization shows a flattened model of the respective housing and a white circle in the slot where the cable is supposed to be plugged in.

As added to the design, the implementation of *ALB* contains *off-screen visualizations*. When a housing indicator moves out of the *HoloLens*' view port, a visualization in the form of a chevron is displayed that points in the direction of the indicator. The chevrons itself are placed *in-world* on the plane of the laying board and positioned so that they are on the outer edges of the device's view port.

### Interaction

To interact with the system, virtual buttons are displayed that can be pressed by user by "clicking" it with a finger. At the side of the info window is a button labeled with "Plugged in" and a check mark. When a cable has been plugged in by the user, he is supposed to press this button as well to confirm it to the system. Once both sides of a cable have been confirmed to be plugged in, the system marks the cable as completed and shows a prompt that asks the user to scan the next cable.

#### 4.4.4. Limitations

While the prototype of *ALB* meets the requirements established in Section 2.4, some limitations exist. The hardware is still in an early state. The visibility and brightness of the virtual content and the field of view and color accuracy of the displays are in need of improvement. The visibility and brightness issues have been worked around in *ALB* by using colors with high contrast and white as foreground color. For the low field-of-view *off-screen visualizations* have been added. In addition to that, with the laying board provided by *Engeser*, there is no way to reliably detect if a cable has been plugged in correctly or plugged in at all. To remedy this, the design was extended to require the user to manually confirm that the cable has been plugged into a housing.

As mentioned in Section 2.3, the scope of this work has been reduced to providing assistance for the assembly task. For an actual deployment in production at *Engeser*, *ALB* would of course require some authoring capabilities. The assembly instructions for the demo and study have been created by hand, as adding a separate authoring solution or integrating it into the system itself would have been out of scope for this thesis.

## 5. Evaluation

After implementing the created design in a prototype, the fourth activity of the *Wheel* life cycle is *Evaluate UX*. For *Augmented Laying Board*, this was done via a "in-the-wild" study directly at one of *Engeser's* factories with domain experts as participants. Section 5.1, describes the study design, starting with an overview of the *DECIDE* framework that was used to devise the study. It also provides some information about the participants from *Engeser*, a short outline of how the study was conducted and how the data gained from the study has been processed. Section 5.2 presents the results yielded by the study, which are discussed in Section 5.3. The last section, 5.4, concludes this chapter by covering the limitations of the study and its results.

### 5.1. Study Design

This section presents how the user study was designed using the *DECIDE* framework. After that, a short overview is given over how the user study has been conducted. The last part gives a brief summary over how the data collected during the study was analyzed.

#### 5.1.1. The DECIDE Framework

The *DECIDE* framework is a checklist to guide UX designers through the conception of an evaluation study, introduced by *Preece, Rogers and Sharp* in their book *Interaction Design: Beyond Human-Computer Interaction* [58]. The framework consists of six steps that are modeled after the main issues that need to be considered for the evaluation of a user experience.

#### **Determine the Goals**

The first step of *DECIDE* is to identify the main goals of the evaluation. As stated in Section 1.1, the overarching goal of this thesis is the following:

Determine how to design a system that supports workers during the assembly of wire harnesses.

However to formulate the evaluation goals, the primary and secondary goals of *Engeser* should also be taken into account. This leads us to the following **evaluation goals (EG)**:

### **EG1: General User Experience**

Determine how users perceive the general user experience of *Augmented Laying Board*. **EG2: Suitability for Experienced Workers**

Investigate if users consider *Augmented Laying Board* a suitable tool for experienced workers to use for wire harness assembly in general. **EG3: Suitability for Training Inexperienced Workers**

Investigate if users consider *Augmented Laying Board* a suitable tool to train inexperienced workers for wire harness assembly.

## **E**xplore the Questions

The evaluation goals formulated in the first step can be refined into more precise **evaluation questions (EQ)**. These in turn can be further broken down into sub questions as well to gain more detailed insights during the evaluation.

### **EQ1: Does *Augmented Laying Board* provide a good User Experience?**

- EQ1.1: Is the operation of the system intuitive for a user?
- EQ1.2: How difficult is it to operate the system with no or minimal prior experience with *Augmented Reality* or *Virtual Reality* devices?
- EQ1.3: Are the visualizations for the housings and routes easy to understand?
- EQ1.4: Is the 2D visualization of the housing with the slot assignment easy to understand and is it helpful?
- EQ1.5: Are the off-screen visualizations for the housing positions helpful? Is the field of view of the HoloLens enough or are they needed?
- EQ1.6: Is the interaction via direct hand gestures a good fit for the tasks and working well?
- EQ1.7: Is the recognition of the cables working well and fast enough?
- EQ1.8: Are the ergonomics for the HoloLens well suited for this task?

### **EQ2: Is *Augmented Laying Board* considered helpful by experienced workers for the assembly of wire harnesses in general?**

- EQ2.1: How does *Augmented Laying Board* compare to the existing tools and support for wire harness assembly?
- EQ2.2: Could *Augmented Laying Board* be used in the day-to-day work?
- EQ2.3: Did *Augmented Laying Board* restrict the usual way of working?



- EQ2.4: Have the users perceived a change in assembly speed or errors made during assembly compared to their normal work environment without *Augmented Laying Board*?
- EQ2.5: Do they have suggestions to improve how *Augmented Laying Board* integrates into their current work environment?
- EQ2.6: In their opinion, are there any important features missing from *Augmented Laying Board*?

### **EQ3: Do non-expert workers consider *Augmented Laying Board* helpful to train wire harness assembly?**

- EQ3.1: How does *Augmented Laying Board* compare to the current training process for the wire harness assembly?
- EQ3.2: Does *Augmented Laying Board* pose any impediments that could hamper the learning process?
- EQ3.3: Are there any specific changes that could be made to *Augmented Laying Board* to improve the training of new laying boards?

## **Choose the Evaluation Methods**

After identifying the research questions for the evaluation, the next step was to choose which methods and techniques to use for the evaluation and how to collect the data. Ideally, multiple studies would be conducted for the evaluation of *Augmented Laying Board*:

**1. Usability Test** This study would be conducted with a larger pool of random participants to assess the general usability of the system and uncover any usability problems, addressing mainly *EQ1*. This includes for example how easily understandable the interaction with the system is or if the visualizations are both understandable and easy to see.

**2. Qualitative Field Study with Domain Experts** The second study would be a field study conducted with domain experts "*in-the-wild*" at the *Engeser* factory in Schramberg. In this study the participants would use the system over a certain period of time while going about their actual work. Here, the goal would be to evaluate how well the system integrates into the work environment and how well it fits the mental models and work flows of experienced workers, addressing *EQ1* and *EQ2*.

**3. Comparative Field Study with Domain Experts** To evaluate especially the impact of the system on the performance of experienced workers, a comparative field study with domain experts would be needed. The participants would be divided into an experimental group and a control group and given identical assembly tasks to work on. The study would measure mainly

quantitative data, like the time to task completion or the amount and type of errors made and would mainly address *EQ2.3* and *EQ2.4*.

**4. Comparative Field Study with Non-Experts** The last study would be a comparative study with non-expert participants. The aim here would be to measure the impact of the system on the learning progress and retention of the learned assembly process. This would again require an experimental and a control group and the usage of the system over a longer time period. Similar to the third study, the interesting data would be the time to task completion and the amount and type of errors made. It would be also interesting to analyze the change of these values over time both during the usage of the system and after some time without it. This study would address *EQ3* and its sub questions.

To collect the data during these studies, several methods are suitable. Questionnaires are a useful and well-established data gathering method to collect demographic data and the opinions of participants. Well-designed and standardized questionnaires have already been developed specifically for usability evaluation, such as the *System Usability Scale* by Brooke [59]. This questionnaire contains 10 questions using a *Likert scale* to assess the usability of the system in question. In addition to that, semi-structured interviews can be used to clarify and follow up on answers given in the questionnaires. Observing participants during their operation of the system, as well as recordings through external cameras or through the *HoloLens* can be used as a more objective data gathering method. These recordings, in combination with log files from the system can be used to reconstruct and examine critical incidents that happened during the study.

### Identify Practical Issues

Conducting all these studies would unfortunately have gone beyond the scope of this thesis. It would have required an exceptional amount of willingness on the part of *Engeser* to invest an not insignificant amount of time and provide the participants as well as the study environment. In addition to that, due to the current circumstances of the Corona pandemic a study with non-experts at the University was not feasible as well. Despite these issues, it was fortunately possible to arrange for a small field study at *Engeser*. As this is most likely the only study that can be conducted, it was decided to chose the proposed study 2 as template and modify it.

The goal of the second study would have been to focus on *evaluation questions EQ1* and *EQ2*, concerning the general usability of the system and its suitability for experienced workers. As the participants at *Engeser* are most likely already experienced workers, the study had to be adapted to address all three research questions. For this, questions were added to the concluding interview on how well the participants imagine the system to be for training inexperienced workers.

For a study directly at *Engeser* there are several practical issues that need to be addressed. First of all, an early coordination with them is required regarding participants, the study setting as well as the timetable. As the study will probably be conducted directly on the factory floor,

a disruption of other workers has to be avoided. The study laying board profile has been created for the laying board located at the university. Therefore, either a similar board has to be provided by *Engeser* or transportation has to be organized for the board at the university.

No bigger issues are foreseen for most of the data collection methods. For both the questionnaires and the interviews, some quiet space with a desk and chairs will be required. External video recordings however are probably little help, as they are unable to record what the user sees. Recording video through the *HoloLens* is theoretically possible, however while recording it limits the frames per second of the device to 30 which results in a degraded user experience.

### **Decide How to Deal with the Ethical Issues**

Images, recordings, statements and questionnaires of a participant will only be used in the evaluation if they agree by signing a consent form and in an anonymized fashion. The data will only be used for the evaluation and will only be shared with *Engeser* in the form of this thesis. The study will most likely be conducted directly on the factory floor. For this reason, there is the possibility that other employees of *Engeser* will be recorded who do not participate in the study and have not consented to it.

### **Evaluate, Analyze, Interpret, and Present the Data**

The evaluation of the collected data is covered in the following sections. Section 5.1.3 provides a brief overview of how the data collected by the questionnaires and the interviews has been processed and analyzed. Section 5.2 presents the results and findings gained therefrom, which are discussed in Section 5.3.

#### **5.1.2. Procedure**

The "in-the-wild" study was planned to be conducted over the course of one complete day at the *Engeser* factory in Schramberg. This ensured that there was no time pressure even if the schedule prepared in advance could not be met. It also allowed to accommodate the different work shifts the participants were in. During the study, the first step was an introduction where the participants were welcomed and briefed about the purpose of the study. They were also informed about the general procedure as well as what data was collected and what it would and would not be used for. After signing the consent form, they were then asked to fill out the first questionnaire containing questions related to demographics, previous experiences with AR or VR devices and a self-assessment of their experience in assembling wire harnesses. Following this, the participants were allowed to put on the *HoloLens* and eye calibration for the device was performed. The participants then received a brief introduction to the *HoloLens* as well as to *Augmented Laying Board* and how to operate the system. They were then asked to start

## 5. Evaluation

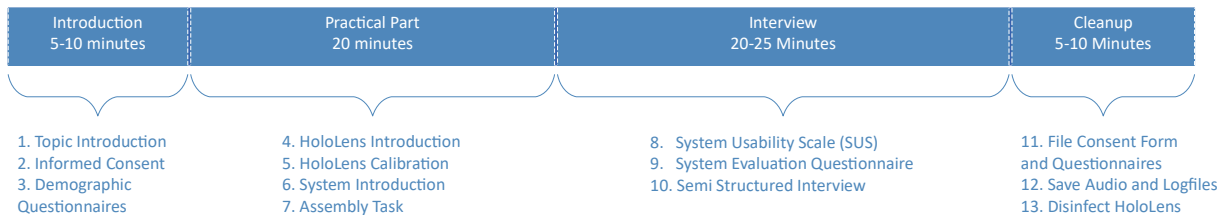


Figure 5.1.: Overview of the study procedure

assembling the wire harness for the current laying board using the support provided by the system. They were given 15-20 minutes to try out the system and get a feeling for it.

After the session with the system, the participants were then asked to fill out the next two questionnaires, the *System Usability Scale* questionnaire and the *system evaluation questionnaire*. The *system evaluation questionnaire* was based on the research questions established in the process of applying the *DECIDE* framework. It can be viewed in Appendix A and is available on the attached USB drive as "*Study\_Documents.pdf*". The last part of the evaluation was a semi-structured interview with a length of about 15-30 minutes. Its questions were mainly derived from the research questions with the intent on elaborating on the answers given in the system evaluation questionnaire.

### 5.1.3. Data Analysis

During the study, both qualitative and quantitative data have been collected in the form of questionnaires and interview recordings. Different methods of analysis are required for each type of data. While the analysis of *Qualitative Data* focuses on patterns or themes, for *Quantitative Data* usually statistical methods are used.

**Quantitative Data** As the amount of participants is relatively low, statistical analysis of the demographic data and system evaluation questionnaires was regarded less useful. Instead, their data was used provide more context to the qualitative data gathered through the interviews with the participants.

The exception to this was the *System Usability Scale*. Because it is a standardized questionnaire, its results can be compared to those of other systems. As such its results have been analyzed according to the scoring system *Brooke* has established for it. Each answer is assigned a numerical score from 1 (strongly disagree) to 5 (strongly agree). Then, the values for each answer are summed up, with the values for the even questions subtracted by 1 and the values for the odd questions subtracted from 5. After that, the sum is multiplied with 2.5 which results in a usability score ranging from 0 to 100.

**Qualitative Data** To identify the themes in the qualitative data from the interviews and questionnaires, the *Affinity Diagram* method was used (see figure 5.2). This method, which was introduced to the field of HCI by *Beyer and Holtzblatt* [60], is used to gather ideas and organize them into groups based commonalities or relationships to identify common themes among them.

The first step is to write down the statements made by participants during the interviews or stated in the questionnaires onto Post-Its and collect them. The second step is to look for two ideas that seem to be related and place them into a group. After this, the goal is to find more ideas that belong to this group and place them together with the original two ideas. This step is repeated until there are no more ideas left that can be used to create a new group or fit into an existing group. The last step is to find fitting headers, or themes, for each group.

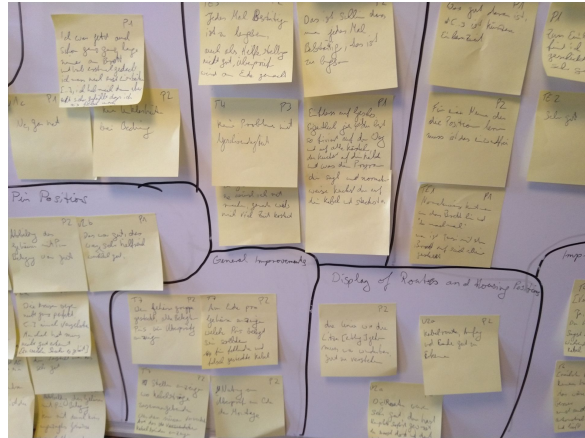


Figure 5.2.: Affinity Diagram of the data collected during the study

## 5.2. Results

This section covers the results of the study at *Engeser*. The first part gives a summary of the participants and the demographic data collected about them. The following parts present an overview of the findings gained from the collected data regarding the evaluation goals established in Section 5.1.1. For this, the findings were categorized into the three evaluation goals, *EG1: General User Experience*, *EG2: Suitability for Experienced Workers* and *EG3: Suitability for Training Inexperienced Workers*.

### 5.2.1. Participants

Unfortunately, due to the current circumstances only three participants could be provided by *Engeser*. All three participants were female, aged 26, 47 and 50. They rated their general knowledge with technical devices such as smartphones or PCs as *bad* to *medium* on a five-point Likert scale (Mean = 2.66, SD = 0.47, 1 = very bad, 5 = very good). Two of the participants already had previous experience with VR or AR. One had previously used *Pokemon Go!* and experienced a ride at the *Europa Park* which utilizes VR headsets, another has used *Samsung Gear VR* with her smartphone. The third participant had no prior experience with either AR nor VR. All of them had prior experience with assembling wire harnesses like the one used for the study and their estimates at their own experience with assembling wire harnesses ranged from 2 - *inexperienced* to 5 - *very experienced* on a five-point Likert scale (Mean = 3.33, SD

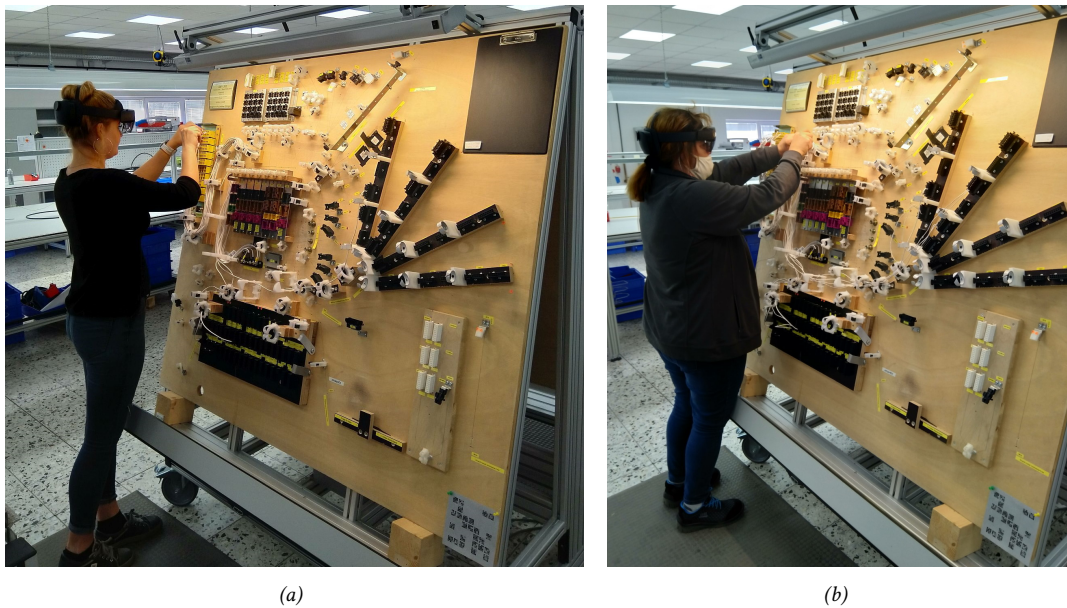


Figure 5.3.: Two of the participants during the study

= 1.24, 1 = very inexperienced, 5 = very experienced). One of them had also experience in training others in the assembly process.

After the formal study with the three participants, short demonstrations were offered to a few other employees of *Engeser*, including the main contact at the company. These demonstrations lasted only for a couple of minutes each and none of them were recorded or followed up with a formal interview, like for the three study participants. However, a few observations and ideas that came up during discussion with those employees were included in the findings below.

### 5.2.2. EG1: General User Experience

The first part of the findings are the ones related to the general user experience of *Augmented Laying Board*, as per EG1.

#### **Finding 1.1: *Augmented Laying Board* was very well received.**

The overall reaction of the participants to *Augmented Laying Board* was very positive. The participants had no major problems with the user experience of the system, with two exceptions which will be discussed further below. All participants reported that it was always clear what the system was telling them and how to proceed. At no point during the sessions were there any confusions or hangups where they did not know how to continue. One of the participants was even very enthusiastic about the system.

”It was a lot of fun. [...] I did not even want to stop in the end.” (P1)

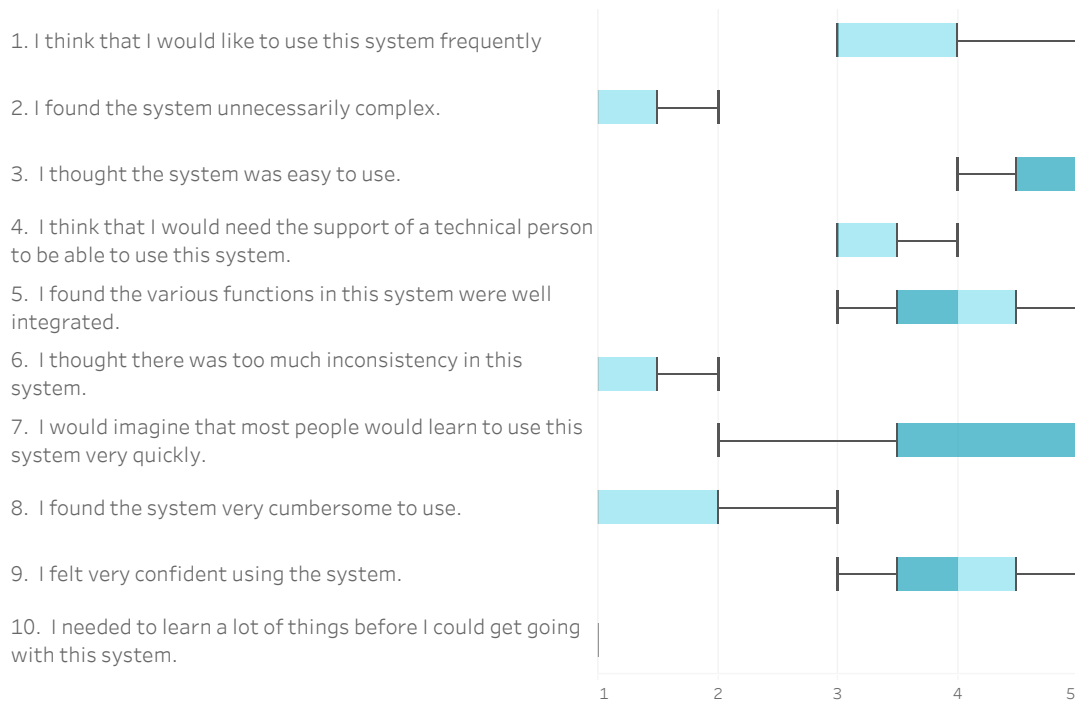


Figure 5.4.: The results of the System Usability Scale questionnaire, with 1 equating strongly disagree and 5 equating strongly agree.

These sentiments are also reflected in the answers to the *System Usability Scale* questionnaire (see figure 5.4). The questionnaires resulted in an average score of 82.5, which can be interpreted as a B grading or *good* [61]. *Augmented Laying Board* was rated well in most questions, with the exception of question 4, regarding whether a person thinks the support of a technical person would be needed to be able to use this system.

The participants also reported that they felt confident both in the operation of *Augmented Laying Board* as well as in the assembly itself thanks to the system. One participant stated that she had concerns because she thought she should have brushed up her knowledge of the assembly process beforehand. With the system however, she felt:

”really confident that I do not do anything wrong [regarding the assembly]” (P1)

### Finding 1.2: The Cable Recognition with QR codes works mostly well

Recognizing the cables via QR codes attached to them proved to be a good alternative to reading the cables’ labels via OCR. No major problems with the recognition were observed during the study and the demos afterwards. The speed at which the system could recognize the cables was sufficient most of the time. One participant noted, that the reliability of the recognition depended strongly on the background captured by the device. When asked about how well the recognition of the cables worked, the participant responded:

”Also well, however it varied depending on the background.” (P1)

She reported that holding the cables in front of a solid, uniformly colored area without much clutter improved the recognition. This is in accordance with the observations made during the development of *Augmented Laying Board*.

### **Finding 1.3: Hand Interaction using the *HoloLens 2* is not reliable enough**

Although the gestural interaction provided by the *HoloLens 2* worked quite well under lab conditions, the study painted a different picture. While one of the participants reported no problems with it, the other two had more issues. Initially, one of them had big issues getting the gestures to register with the *HoloLens* but managed to overcome them. The third participant however had problems with it over the course of the whole session. This was in line with the observations during the demo sessions with the other employees. An estimation of around 30% of the people participating seemed to have persisting issues with getting the *HoloLens* to recognize their hand movements. There was also no clear indication on what set them apart from those who had no issues whatsoever.

### **Finding 1.4: The Visualizations for the Routes and the Housing Positions are helpful and easy to understand**

The participants all reported that the visualization of the cable routes was excellent. According to them, the visualization was easy to understand and the visibility of the white lines was considered very good.

”The line where the cable has to go was wonderful, easy to understand.” (P2)

Similarly, from a visibility standpoint, the housing positions were also liked by the participants.

”Cable routes, start and end [were] good to see.” (P2)

### **Finding 1.5: The Accuracy of the Housing Positions is not good enough**

The accuracy of the circles indicating the housing positions was reported by one participant to be sometimes lacking in accuracy. The inaccuracy was apparently enough to sometimes make it difficult to understand which housing the circle was supposed to indicate.

”The circles were not quite perfect [...] shifted minimally. [...] Sometimes you did not recognize it well [which housing the circle was pointing at].” (P1)

The accuracy of the route positions on the other hand was not reported to be an issue.



**Finding 1.6: The Visualization of the Slot Assignments is helpful and easy to understand**

Another aspect of *Augmented Laying Board* that received praise from the participants was the visualization of the slot assignments.

”You can see which cable you have in your hand, and then you see ok, you have the AF402 and you have to plug it into the 5 and you have the drawing next to it and you see there is the 5 and that’s it.” (P1)

The participants confirmed that finding the correct slot in a housing according to its number is a major pain point during the assembly, especially for inexperienced workers, as described in Section 2.2. One participant reported, that the visualization makes this step much easier to deal with.

**Finding 1.7 The Visualization of the Slot Assignments can be mistaken for the Housing Position**

Besides the hand tracking, one of the biggest UX issues the study brought to light was that confusing the housing slot visualization for the housing position is still a problem. Especially in parts of the board where the housings are close to another, the 2D visualization was still sometimes misunderstood by the participants to depict the position of the housing the cable should be plugged into. This led to wrongly plugged in cables and complaints that the visualization the system showed was ”offset” from the actual housing.

**Finding 1.8: Off-Screen Visualizations were helpful**

All participants regarded the off-screen visualizations as very helpful.

”[The arrows] have pointed at the start and end points, well visible, good to know, in which direction to go.” (P2)

As the participants usually closed up to the board to scan a new cable, one participant noted that the visualizations were very helpful directly afterwards to get an initial feeling for the positions of the start and end points of the cable.

**Finding 1.9: The Ergonomics of the HoloLens are good**

With VR devices there often are some issues related to ergonomics, like the weight of the device, incompatibility with glasses or motion sickness. However, no serious issues regarding the ergonomics of the *HoloLens* were voiced or could be observed during the study. One participant wore glasses, but thanks to the hinge of the device’s display this was not a problem.

”I basically did not even notice it [the HoloLens].” (P1)

Neither the weight nor the display of the *HoloLens* posed any problems for the participants either.

### 5.2.3. EG2: Suitability for Experienced Workers

The following findings pertain to the participants' evaluation of *Augmented Laying Board* for the general use in the assembly process by experienced workers.

#### **Finding 2.1: *Augmented Laying Board* is not yet Ready for General Usage by Experienced Workers**

In the current state, two of the three participants would not use system to support experienced workers during the assembly.

”As boss, I would only use it for learning instead of working with it.” (P1)

Two main reasons were given for this. The first reason were the problems with the confusion between the actual housing position indicated by the system (see Finding 1.7). The second reason was the negative speed impact the system has for experienced workers, as explained in the next finding. However, they also remarked that they could see the system being useful even for experienced workers if those issues were resolved.

One participant also noted that, while she did not feel restricted by the system, she sometimes applies a shortcut that is not supported by *Augmented Laying Board*. For the shortcut, she would take multiple cables that start and end in housings in close proximity and then first plug in all the cable starts, route the cables together in the end plug in the individual cable ends.

#### **Finding 2.2: For Experienced Workers, the System has a Negative Speed Impact**

The least experienced participant did not have the impression that she was slowed down by the system. The other two however felt that the system had a strong negative impact on their working speed. This was apparently caused the need to press a button for each cable end to confirm that it has been plugged in.

”Confirming every time is too slow, also not good as assistance, checking [if the wiring is correct] is done at the end.” (P2)

Finding 1.3 was also a contributing factor that slowed down participants that had the described issue.

**Finding 2.3: The Speed Impact might be Reduced by Changes to Interaction**

The impact on assembly speed was regarded as a major blockade for the usage of the system for experienced workers. Both participants that felt slowed down by the system agreed that they would consider employing *Augmented Laying Board* even for experienced workers if the issue could be resolved or at least improved. One possible solution for this could be the usage of voice commands. In the design for the system, they were rejected in favor of the gestural interaction, however when asked, the participants could imagine them being an improvement over the buttons:

”[When asked about voice commands] Yes, I would like that better. Because then you have laid your cable as the program tells you, you say OK and take the next cable and start again.” (P1)

When they were asked if they could imagine another possible solution for this issue, one of the participants responded that she could also see simply holding the next cable into the camera as a trigger:

”[On using the next cable as trigger] That would be even better. That would even be very good. Because you automatically take the next cable without glasses and read it.” (P1)

Recognizing the next cable would then act as a sort of implicit trigger for the system to mark the currently displayed cable as complete and bring up the visualizations for the next cable.

**Finding 2.4: There are further sub processes of the assembly process that could be assisted by *Augmented Laying Board***

During the interviews, the participants had some ideas how *Augmented Laying Board* could be extended. The ideas revolve around the system providing assistance not only during the assembly but also during the review process and the finalization of the harness after the assembly.

**Assistance during the Review Process** The first idea is to further utilize the slot assignment visualization. After either all the cables have been assembled or all cables for one group of housings have been plugged in, the system could show for each housing which of the pins should have a cable and which ones should not. With this, a worker could more easily identify cables that are either missing or plugged in incorrectly.

**Assistance during the Bundling Process** The second idea is about extending *Augmented Laying Board* to provide assistance during the final bundling process for the harnesses. During this process, the cables have to be tied together with zip-ties at specific locations to create a single harness from the individual cables. This would not only benefit experienced workers, but also inexperienced ones, as apparently also requires experience on where to bind the cables and which zip ties to use, both of which could be displayed by the system.

**Integration into Electrical Verification of Laying Boards** Another idea has been proposed by one of the employees that had the chance to try out *Augmented Laying Board* for a short while after the study. The employee noted that for another type of laying board they have a system that is electrically connected to the housings. This system can then verify the cable connections as soon as a cable has been plugged in and provides information about completed or wrong connections via a separate monitor to the workers. It might be possible to connect this system with *Augmented Laying Board* and use this information to display the connection status via the *HoloLens* or trigger actions based on established and verified connections.

#### 5.2.4. EG3: Suitability for Training Inexperienced Workers

This section lists the findings related to the participant's assessment of the use of the system for training inexperienced workers.

**Finding 3.1: The current training process for the assembly is not very good.**

All three participants report that the current process for training new workers is not very good. The participants are put in front of a laying board and have to struggle to the first few laying boards by themselves until they start to learn the positions of the housings.

"If you're brand new to it, it's really a search, you can really spend 2 days on a harness or even longer." (P1)

"The problem at the beginning are always learning the positions, you always have to search for them." (P2)

"In the beginning it's rather difficult." (P3)

There is no further assistance available to them besides the ids printed on the cables and next to the housings on the board or asking a more experienced co-worker.

**Finding 3.2: *Augmented Laying Board* is well suited to assist inexperienced workers**

As additional assistance for inexperienced workers, *Augmented Laying Board* was considered a good fit by all participants. As Finding 3.1 describes, the current training process for new workers is lacking and all three participants were very positive about using the system as a tool for inexperienced workers.

"For someone new who still has to learn the positions this is great." (P2)

"For someone learning the ropes, this is really clever, I think it's really good." (P1)

### Finding 3.3: Possible Negative Learning Effects

A potential downside of employing *Augmented Laying Board* for inexperienced workers was discovered during the interviews. Two of the participants stated that they were basically only doing what the *HoloLens* showed them to do.

”I only did what the glasses displayed. [...] I first look at what the glasses were showing me, not what was [printed] on the cable.” (P1)

The participants completely disregarded the ids printed on the cables and on the board next to the housings and solely focused on what was displayed by the *HoloLens*. This could indicate that an inexperienced worker might work quite well with the system equipped, but would still have problems with the assembly after the training process is over if the assistance of the system is not available anymore.

## 5.3. Discussion

The findings presented in the previous section helped to gain insight into how the participants experienced *Augmented Laying Board* and how they assess its applicability to different usage scenarios. They also shed some light on issues regarding the system’s user interface and user interaction. These findings are now discussed in this section.

### 5.3.1. EG1: General User Experience

The first goal for the evaluation was concerned with the user experience provided by the system. In general, the system was considered clear and easy to understand by the participants. At no point during the study where there any critical incidents or hangups where the participants did not know how to proceed. Different levels of experience with *AR* and *VR* devices did not seem to make any difference regarding the subjective usability. All participants seemed to have no problems to grasp the visual output of the device and the interactions via hand gestures. These results are also reflected by the good *SUS* score.

As noted in the findings, there was one negative exception to the results of the *SUS* score: Question 4, *I think that I would need the support of a technical person to be able to use this system*. The factors that contributed to this were probably that the UI of the *HoloLens 2* was set to *English* and that at the time of the study the *HoloLens 2* required a new user to calibrate the device via a short task when using it for the first time. The participants were led through this process as part of the introduction for the study, but afterwards voiced concerns that they would not have known what to do if they would have been on their own. With the latest version of the *HoloLens*’ OS, this calibration process is now performed completely automatically and in the background.

The cable recognition with QR codes worked well most of the time. There were some problems when participants were trying to scan a cable by simply holding the qr code into the air in front of them. However, using a more flat, uniform background solved these issues. One way to improve this might be to provide a dedicated space with good lighting and clean background where the user is supposed to place the cable for scanning. On the technical side, an improvement might be achieved by adjustments to the auto-focus of the *HoloLens*' camera. In addition to that, only a small part of the camera image could be used for recognition. This could be communicated to the user by displaying a camera recticle. It might also be worth it to look into alternatives to the QR codes. This might take the form of a dedicated bar code reader, which would probably be an improvement in both recognition speed and reliability. Another advantage of using bar codes would also be that they can be printed directly onto the cables along the ids instead of having to use tags attached to the cables.

Unlike the cable recognition, the hand recognition proved to be more of a problem. Despite it working very well in the lab, two out of the three participants and at least around 30% of other employees during the demos had problems getting the system to recognize their button presses at some point. As the system is just using the hand interaction API provided by Microsoft, this is unfortunately a black-box whose behavior can not be modified. There are probably only a few ways to determine what is actually the issue and probably even less ways to fix it. Therefore, voice commands might be an alternative which even the participants thought a good idea. A more implicit interaction design might also be worth looking into. However this might be harder to implement since it requires to keep the camera active and "scanning" for cables the whole time. This would be problematic for performance as well as the user experience, as it increases the possibility of accidental scans of other cables. A dedicated space for scanning the cables in combination with the usage of a dedicated device for scanning the cables' codes might be a solution for this problem as well. Such a device could run continuously without impacting the *HoloLens*' battery or performance and could communicate with the system wirelessly.

On the visualization side, the route visualizations were especially appreciated. According to the participants, they were easy to understand and their visibility was very good. The 2D visualizations of the housings with the slot assignment were also well understood and considered helpful by them. The housing positions however proved to have a few problems.

First, the accuracy of the circles showing the housings' positions was not good enough. This might be related to the different board that was used for the study at *Engeser*. While the type of the board is the same as the one used at the university, all the boards are hand built at *Engeser* and may exhibit some slight differences in the positions of the housings. Before the study, a cursory comparison with a photo of the board at the university was done and a few small differences were noted, which lends some credence to this theory.

Another possibility is tracking drift from the *HoloLens*. As the accuracy problem was noted by the very first participant and did not seem to get noticeably worse, this is unlikely to have been a main factor. Issues with the initial calibration accuracy of the board might have been a factor for this as well. The usage of a single marker for the calibration of large areas has downsides,

especially if the marker can not be placed centrally and is situated on the corners. Small inaccuracies in the calibration can accumulate to bigger discrepancies over longer distances. Some inaccuracies of the calibration can be spotted via the shadow of the recognized board that is displayed after the calibration process completes. However it is much harder to spot if there is a discrepancy in the tilt of the board as recognized by the system. This, in combination with a bad perspective on a housing location indicator might also account for some of the offset described by the participants.

However, this would not only affect the housing positions, but also the route positions for which no such issues have been reported. An explanation for this might be that the brackets for the cables are spaced far enough apart, so that the position indicators can still be recognized as belonging to the original brackets by the users. With the housing positions, an inaccuracy of one or two centimeters can already make the indicator be perceived as pointing to another housing.

The second problem is the potential to confuse the visualization for the housing slot assignments with the actual housing positions. Especially in areas where many housings of same type are arranged in a grid, the slot assignment visualization might accidentally be positioned over another housing. The problem was first caught during initial tests at the university and the design was subsequently altered to fix or at least minimize the issue. The main change to design of the slot assignment visualization was to make the depiction of the housing flat and more abstract instead of using a 3D model. In the prototype, manual overrides for the automatic positioning behavior were added so direct overlaps with other housings could be avoided. As it seems that these changes were not enough, the slot assignment visualization needs to be further modified once again address this issue. The most elegant solution would be if the accuracy of the overlay provided by the *HoloLens* could be improved to the point where the slot position could be directly shown via a hologram instead of only showing the housing position. However, this approach is also not without issues on its own. Size and form of such a visualization has to be chosen carefully to not be visually obstructive and complicate the assembly [24].

The off-screen visualizations for the housing positions were noticed by the participants and considered helpful by them. There were no complaints or problems encountered regarding ergonomic problems. Neither the display of the *HoloLens* nor the interaction through direct hand gestures seemed to interfere with the assembly work, which was one of the main reasons why head-mounted hardware and this type of interaction were chosen. However the assembly duration for a single harness is at least several hours. A longer study to evaluate the effects of heat, weight and eye strain caused by the *HoloLens* may be beneficial to estimate if such a system is viable in the long term.

### **Design Recommendations**

- Improve calibration accuracy
- Improve the slot assignment visualization
- Replace hand interaction

### **Further Research & Evaluation Directions**

- Conduct a more extensive User Experience evaluation
- Look into a replacement for QR Code tags on cables
- Investigate accuracy issues for housing positions
- Conduct ergonomics evaluation

### 5.3.2. EG2: Suitability for Experienced Workers

Unfortunately, the participants did not consider *Augmented Laying Board* to be ready for the general usage by experienced workers during the assembly of wire harnesses, mainly because of the issues with accuracy and interaction, which was partly covered above. Additionally, the study findings made clear that while the design of the system is well adjusted to the normal assembly process, shortcuts and other deviations made by individual workers might not be supported. One of the participants explained an example of this, where she would install multiple cables with similar start and end points together to save time. *Augmented Laying Board* already supports assembling the cables in any order, not only the one given by the instructions. It also supports displaying instructions for multiple cables in theory. However, the interactions and user interface were not designed with this in mind. The design would have to be adapted to fully support approaches like this, for example by including aggregating the routes or the locations and slot assignment visualizations to prevent them from overlapping. Here, the lack of direct access to the actual workers for the contextual inquiry becomes apparent. Neither of the sources for information about the assembly process could elaborate on what kind of shortcuts the workers were using.

Another major issue that made the experienced participants dislike the system for general usage was the noticeable negative impact on assembly speed. Due to the design of requiring hand interaction for each cable end to confirm it has been plugged in, the two more experienced participants felt that they were slowed down by a significant amount. A contributing factor were once again the issues surrounding the recognition of hand interaction by the *HoloLens*. Possible solutions for this are similar to the ones that might resolve the problems with hand interaction mentioned above. Voice commands could be employed to simply complete the current step and can be issued by a user at the same time as grabbing



a new cable. For this, their feasibility regarding the noise produced by its usage, as noted in Section 4.3.2, as well as the resistance against the noise already prevalent in the factory would need to be re-evaluated. Implicit interaction might be helpful here as well, removing the explicit need for confirmation would probably remove most of the negative speed impact.

Because of these issues, if *Augmented Laying Board* were to be used as a general tool for all workers in the wire harness assembly, another iteration of the *UX design life cycle* is recommended. This includes another pass of the *Understand* and *Design* activities to get a clearer picture of the need for them and evaluate the possible ways to resolve the issues.

As for the question of features that might be missing from *Augmented Laying Board*, three potential additions were found. It was suggested for the system to support the verification process after the assembly has been completed, as well as the packing process where the cables are bound together to an actual wire harness. Additionally, it might be possible for *Augmented Laying Board* to communicate with the system for electrical verification that is already used at *Engeser* for a different type of laying board. This way, it might be possible to bridge one of *Augmented Laying Board*'s biggest weaknesses, that it has no way to verify if a cable has been plugged in correctly. The system could display error messages for cables that have been plugged into the wrong slot and display information about the final verification results directly on the board where the errors are located. Furthermore, the information that a cable has been plugged in correctly could be used as signal to allow the scanning of the next cable.

#### **Design Recommendations**

- Redesign how to confirm the current cable is completed
- Add support for assembling multiple cables at once
- Add support for the verification sub task
- Add support for the bundling sub task

#### **Further Research & Evaluation Directions**

- Conduct a more thorough usage data elicitation for experienced users
- Research if the data of the verification system used by *Engeser* could be used by *Augmented Laying Board*

### 5.3.3. EG3: Suitability for Training Inexperienced Workers

Contrary to reluctance to use *Augmented Laying Board* for experienced workers, the participants of the study were very enthusiastic about using the system for training new workers. The current training process was described by them as very self-learning oriented

with a minimal amount of introduction. The trainees are put in front of a board and are basically on their own.

Compared to this, according to the participants *Augmented Laying Board* offers much more assistance to newcomers. However, a more thorough study with control and experimental groups would be helpful to quantify the benefits regarding training provided by the system.

In addition to that, the study has also revealed a potential problem with using *Augmented Laying Board* for in-situ training. The reports from two participants hint at the possibility that the system facilitates a certain dependency of the users on itself. This too is something that should be further looked into via a separate study. If it turns out that this is indeed a problem, some changes to the design of *Augmented Laying Board* might be needed to improve the learning experience. This could include adding more information to the board itself, for example by providing an annotated overview of the board that shows the general location of housing groups to reinforce the learning of the housing positions. Another possibility would be a separate *training mode* with extended capabilities of the system's visualizations to provide different guidance levels, as postulated by *Webel et al.* in their later iteration of *adaptive visual aids* [27]. With this, the level of information provided by *Augmented Laying Board* could be reduced step by step, the more experienced a worker becomes. This might prevent or at least weaken the development of any dependency on the system in the long run, while still providing the full capabilities of assistance to workers that are just starting the training.

### **Design Recommendations**

- Redesign the visualizations to provide additional information for inexperienced users
- Add different guidance levels to provide assistance depending on the experience level of a user

### **Further Research & Evaluation Directions**

- Conduct a more thorough usage data elicitation for inexperienced users
- Conduct a study with inexperienced users concentrating on the benefits and drawbacks of *Augmented Laying Board* as a learning tool

## 5.4. Limitations

While the results of the study are encouraging, there are several limitations that need to be considered. The first, and probably strongest, limitation of the study is the small number of participants. Additionally, all three of them had previous experience with assembling wire harnesses, although their experience levels varied. Regarding the user experience of *Augmented Laying Board* this means that the results can be taken as an indication, but a more thorough study would be advisable. For the usage of the system as learning tool, the results are mostly estimations from experienced users. A more extensive study with participants that have little to no prior experience with the assembly process would be recommended, as noted in the discussion above. The participants also only had the chance to use the system for 15-20 minutes, which is a relatively short time compared to the typical assembly time for a wire harness. Therefor the study can make no statement about long term ergonomic issues.



## 6. Future Work

This chapter covers potential future work for *Augmented Laying Board*. The proposals for improvements and further evaluation have been selected from among the issues identified in the previous chapter. In Section 6.1, technical improvements for the system are presented. Section 6.2 gives an overview of the design improvements that could be applied to the system. Section 6.3 details ideas for future studies to further evaluate the effects of *Augmented Laying Board* on the workers and the assembly process itself.

### 6.1. Technical Improvements

In this section, improvements to *Augmented Laying Board* that are purely on the technical side are presented. This includes mainly improvements to the tracking and calibration process for the physical laying boards as well as improvements to the recognition of the cables.

#### 6.1.1. Laying Board Tracking and Calibration

As noted in the previous chapter, the usage of a single marker for calibration and its position on the corner of the laying board pose an issue regarding the magnification of even small inaccuracies in the calibration. A simple improvement to reduce the magnifying effects would be to make space for a marker in the middle of the board. However, this might pose other practical issues. First, depending on the structure of a specific wire harness, it might not be possible to make enough space to place the marker more closely to the center. Second, and more importantly, placing a marker in the middle of the board might also require to adjust the routing of the cables so they don't occlude the marker, in case a recalibration in the middle of an assembly is needed.

Another, more complex improvement would be the usage of multiple markers for calibration. Here, the markers could be attached to the other corners of the board, which should be less of an issue compared to placing markers in the center. Each marker could be scanned individually and its position and orientation could be saved. When all markers have been scanned, the board position and orientation can be calculated from the stored marker values. With two markers, placement in diagonal corners would be optimal to increase the robustness of the rotation values for the x and y axes. With three or more markers, the plane of the board could be constructed with a simple plane equation using only the markers' positions (see [62]).

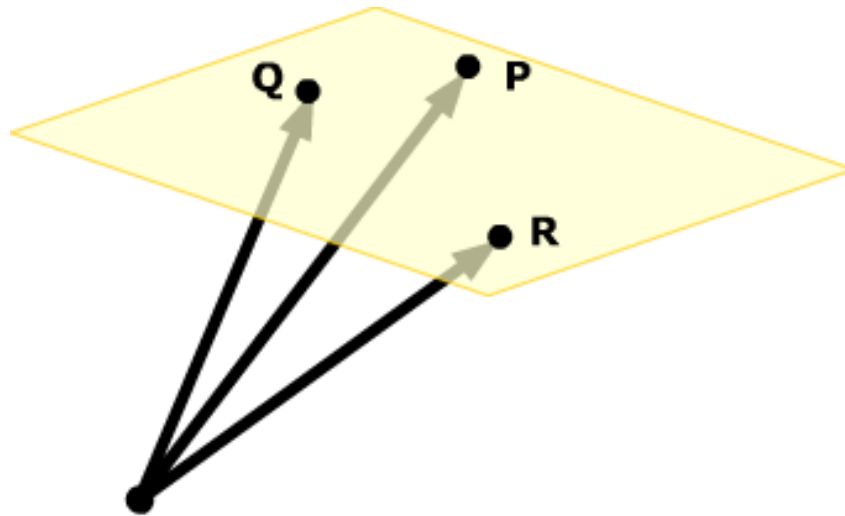


Figure 6.1.: Using the position of three markers to calculate the plane of the laying board. [62]

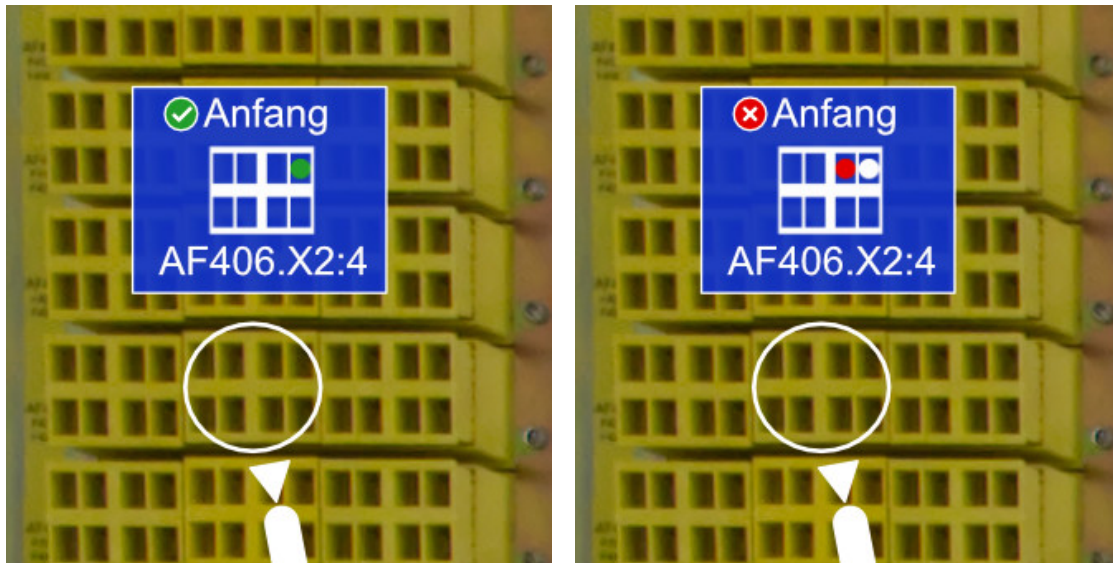
Their orientation data could then be either disregarded completely or used to supplement the calculated values.

### 6.1.2. Cable Recognition

In the current iteration of *Augmented Laying Board*, the decision was made against using an external device to recognize the cables in favor of using the camera integrated into the *HoloLens*. However, the study showed that the recognition of the cables could be improved further and it turned out that it would indeed be possible to print bar codes directly onto the cables. Because of this, a dedicated bar code reader might be a worthwhile addition to the system, as mentioned in Section 5.3. Such a device could be combined with a dedicated area for scanning the cables, for example on the cable rack, which could further improve and speed up the recognition of the cables.

## 6.2. Design Improvements

In addition to the technical improvements, the study unveiled a few areas in the original design of *Augmented Laying Board* that could be improved upon. The first one presented here is an improved interaction concept that doesn't require a user to constantly confirm that a cable has been plugged in. It also replaces the gestural interaction that many users had issues with. After that, the improvements to the pin assignment visualization are introduced. This is followed by a concept of how the integration of the verification and bundling tasks could work with the system. The last design improvements target the user experience for training inexperienced workers and how the system could assist the *User Work Roles* that were omitted in the contextual inquiry.



(a) Info Window when the cable has been plugged into the correct slot.

(b) Info Window when the cable has been incorrectly plugged in, with the correct slot (white) and the slot where the cable has actually been plugged in (red).

Figure 6.2.: First and second iteration of the Pin Assignment Visualization and the Info Window

### 6.2.1. Improved Interaction Design

The interaction by hand gestures as well as the requirement to confirm plugged in cables via a button were not well received. Therefore, in a revisited interaction both aspects would most likely either have been completely replaced or at least modified.

In Section 5.3.2, the idea was presented to integrate *Augmented Laying Board* into an already existing computer system that provides a direct feedback to workers if a cable has been connected correctly. This system is used for a different, but similar, type of laying board, where each housing is electrically connected to a computer integrated into the workplace. When a cable is plugged in at both ends, an electrical contact is made and the computer can see which two pins in a housing have been connected. A monitor next to the board shows a digital version of the paper-based cabling list and also displays, if a cable has been plugged in correctly or not. If this system could be modified to send a message via network if a cable has been connected correctly or incorrectly, it could be utilized by *Augmented Laying Board* via the *HoloLens'* WiFi connection. Our system could then show both the status of the cable connection, as well as display where exactly a cable has been connected incorrectly (see figure 6.2). After a cable has been recognized to be connected correctly, it could then continue with the next step, allowing a user to scan the next cable. The other uses of hand interaction, for example buttons in menus, could be replaced with simple voice commands.

### 6.2.2. Improvements to the Pin Assignment Visualization

Another set of changes that are fairly high priority are improvements to the info window and the pin assignment visualization. The main issue here is that it may happen that the visualization for the pin assignment accidentally lines up with a similar housing. In such a case, the visualization can be mistaken for a direct overlay which signifies that the cable should be plugged into a pin of the housing directly underneath instead of the one indicated by the circle that is the actual housing position indicator. Essentially, the info window and the pin assignment visualization it contains are mistaken for a part of the direct overlay, a *direct visual aid*, instead of an indirect or adaptive one.

The main idea to tackle this issue would be to emphasize the differences between the info window and the other overlay elements more strongly. A promising solution would be first to increase the distance between the info window and the laying board compared to the housing position indicator. In addition to that, a billboard effect could be applied to the info window, so that it is not a static element anymore but rotates to always face the user. And last, a funnel-like visualization could be added between the info window and the housing position indicator, to emphasize that the info window displays additional information for the position that is shown by the latter (see figure 6.3).

### 6.2.3. Support for the Verification and Bundling Tasks

The verification and bundling tasks are performed after the actual assembly and their addition to *Augmented Laying Board* should be pretty straight forward. During verification task, the worker goes from housing to housing and verifies, that pins that should have a cable connected are actually occupied and that only those pins are occupied. For the data on which pins of a housing should be occupied, the system can aggregate the pin assignment data from all cables for any given housing. On the visualization side, the info window and the pin assignment visualization can be reused. The system then only needs to iterate over all housings in the cable data, display the occupied pins for one housing at a time and after the worker confirms the manual verification, e.g. by voice command, it can move on to the next housing (see figure 6.4).

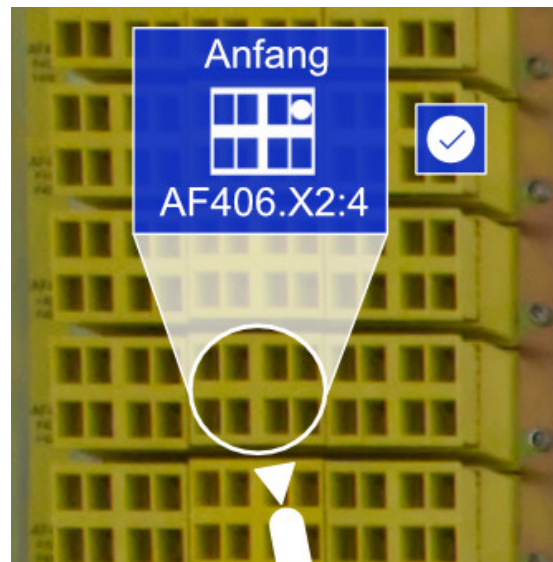


Figure 6.3.: Info Window and Housing Position Indicator connected by a funnel-like visualization.



The bundling task afterwards is the finalization of a wire harness. During this task, the different wires are bound together by cable ties, which allows them to be extracted from the laying board and installed as one piece. To assist a worker with this task, *Augmented Laying Board* would simply have to display indicators at specific, predetermined points together with accompanying descriptions for which type of cable tie to use at which position.

#### 6.2.4. Learning Mode

To further improve *Augmented Laying Board* for the use as training tool for inexperienced workers, a separate learning mode could be implemented. The aim of this mode would be to reduce the assistance provided by *Augmented Laying Board* step-by-step to facilitate the learning of the assembly without the system. This might be especially helpful to accelerate the training of new workers that in the future will be deployed to locations where the assistance of the system will not be available. This feature could be implemented by displaying additional information about the general location of related housing groups, to indicate for example that all housings of the scheme *AF4XX* are located in a specific area. *Proxemic Interaction* could be employed to render this overview when the user steps back from the board and to disable it when a user is close. To step up the training, the indicator for the exact housing position could then be switched off. The user would then have to rely on this housing group indicator as well as their own experience where to search for the specific housing.

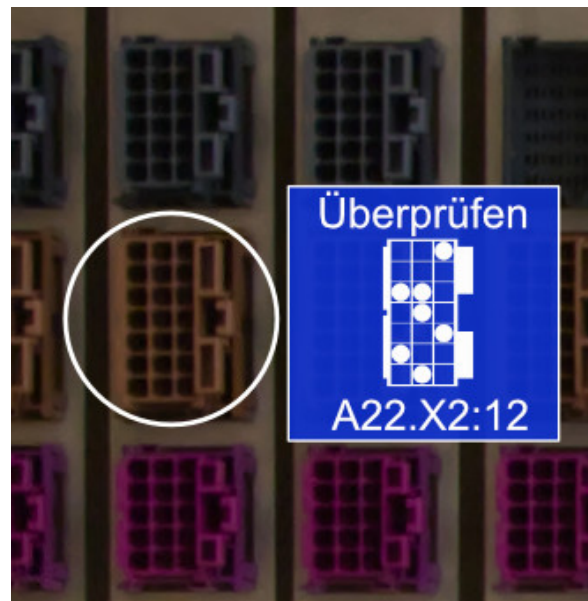


Figure 6.4.: Info Window during verification phase where it shows all slots of a housing that should be occupied.

#### 6.2.5. Support for the Assembly Supervisor Work Role

The work role of the *Assembly Supervisor* was one of the two work roles cut from the contextual inquiry due to the scope of this work. As described in Section 2.3, the supervisor is not directly involved with the assembly process. He is a support role that mainly interacts with the *Assembly Worker* role and to a lesser extent with the laying board itself. In the case of *Engeser*, it might even be that the supervisor is in a completely different factory than the worker.

To support the assembly supervisor, a separate *supervisor mode* could be added to *Augmented Laying Board*. In this mode, the supervisor can remotely connect with the worker. The

system of the assembly worker, which runs in the normal mode, would then communicate the visualizations visible to the worker. The systems of both participants could also exchange the users' position and those of their hands. This way, the supervisor can see what the worker sees and for both users, an avatar of them and their hands could be displayed for each other, similar to techniques used for collaboration in AR or VR [63–65]. The supervisor mode could also offer tools to the users that allow the placement of markers or highlights that are shared to further facilitate communication. Another possibility would be to allow the supervisor to access the video footage of the worker's *HoloLens*.

### 6.2.6. Support for the Assembly Process Engineer

The other work role that was cut was the role of the *Assembly Process Engineer*. This role is responsible for the authoring of assembly instructions. As already mentioned in the limitations of the prototype in Section 4.4.4, this task that precedes the assembly process is not covered by *Augmented Laying Board*. Automatically generating assembly instructions in a format ready for AR is a topic that has received some attention from researchers, for example as part of the previously presented *Project MOON* [13, 66]. However this requires digitized information about the layout of the wire harness or the laying board itself.

In absence of such digital data, *Augmented Laying Board* could be extended with an *authoring mode*, to create these instructions manually. In this mode, the system could offer the ability to place housing position indicators and route points via manipulative gestures. After a housing position indicator has been placed, the correct housing shape and slot could be selected from a list. This way, the instructions for a wire harness could be created step by step in an interactive way.

## 6.3. Further Studies

As described in Section 5.1, there are a quite a few studies that might be conducted to further evaluate *Augmented Laying Board*, besides the one that has already been run at *Engeser*. First and foremost would be the comparative field studies with both the domain experts at *Engeser* and non-experts to quantify the benefits that *Augmented Laying Board* provides to the workers. If *Engeser* would want to focus on the goal to employ *Augmented Laying Board* as a training tool, further evaluation into how well the system already supports this and how strong the learning effect actually is would also be a top priority. Of course, if any of the improvements and changes proposed above were to be implemented, their impact would also have to be confirmed in a follow-up study.

## 7. Conclusion

This work introduced *Augmented Laying Board* as a system to support the assembly of wire harnesses using *Augmented Reality*. It has been conducted with the support of *Engeser GmbH*, a cable and wire harness manufacturer. During the contextual inquiry, major barriers and pain points in the assembly process were investigated and analyzed. From these barriers, requirements were derived for a system that wants to provide assistance during the assembly process. Based on these requirements and the previous work related to the topic of wire harness assembly, a design concept for the system was created. The concept was implemented in the form of *Augmented Laying Board*, a prototype application running on the *Microsoft HoloLens* hardware platform that provides assistance to workers during the assembly in the form of digital overlays.

This prototype was evaluated "in-the-wild" with three employees of *Engeser* with previous experience in wire harness assembly at their factory in Schramberg. The results of this study have shown that the overall response of the participants to the system were very positive. The system was regarded as a great benefit to less experienced workers, especially the ones that are at the start of the training phase. For the more experienced workers, the system was also seen as a potential improvement, however the interaction concept using hand interaction was regarded as too slow and turned out to be unreliable for some users. To remedy this and other issues uncovered by the evaluation, several improvements and ideas have been proposed as potential future work for the system. They range from a reworked interaction concept to a modified experience especially for workers in training to a better integration into the work environment at *Engeser*.



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# A. Study Documents

This appendix contains the documents that were created for the user study at *Engeser*. They include:

- Schedule for the Individual Sessions
- Interview Guide
- Introduction
- Declaration of Consent
- Demographic Questionnaire
- System Usability Scale Questionnaire
- Custom User Experience Questionnaire

# Ablaufplan

## Vorbereitung

<b>1. Anwendung starten &amp; Brett kalibrieren</b>	<5 min
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## Einführung

	5-10 min
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**1. Begrüßung & Einführung**

**2. Einverständniserklärung**

**3. Demographische Daten**

## Studie

	20 min
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**4. HoloLens aufsetzen, anpassen und Kalibrieren**

**5. AugmentedLayingBoard öffnen und kurze Einführung**

**6. Montage durch den Probanden**

**7. Beim „Montage fertig“ Bildschirm HoloLens abnehmen**

## Interview

	20-25 min
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**8. HoloLens laden**

**9. SUS Fragebogen**

**10. Eigener Fragebogen**

**11. Sprachaufnahme einschalten**

**12. Interview**

**13. Sprachaufnahme ausschalten**

## Nachbereitung

	5-10 min
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**14. Einverständniserklärung mit Fragebögen abheften**

**15. Audioaufnahmen sichern**

**16. Logdateien sichern**

**17. HoloLens desinfizieren**

**18. Kabel demontieren**

# Interviewleitfaden

## Usability

1. Wie haben sie die Nutzung von AugmentedLayingBoard empfunden? (1a)
  - a. Gab es Probleme mit der Brille? Z.B. mit der Größe, Passform, dem Gewicht, Sehprobleme, ... (1b)
  - b. Wie empfanden sie die Interaktion mit dem System? (1b)
    - i. War die Bedienung per Hand gut verständlich und benutzbar?
    - ii. Wie gut hat die Erkennung von neuen Kabeln funktioniert?
  - c. Gab es während der Benutzung Unsicherheiten, wo sie nicht wussten sie sie weiterkommen? (1a)
    - i. Haben sie vom System genug Rückmeldung bekommen bei welchem Arbeitsschritt sie gerade sind?
2. Wie gut haben sie die Darstellungen für die Montagepositionen verstanden ...
  - a. ... was die Position der Kabelenden und der Kabelrouten angeht? (1c)
  - b. ... was die 2D Darstellung des Steckers und der Position im Stecker angeht? (1d)
  - c. ... was die Darstellung von Kabelenden außerhalb des Sichtfelds angeht? (1e)

## Tauglichkeit für die generelle Montage von Kabelbäumen

1. Was für positive und was für negative Punkte sind ihnen bei der Benutzung von AugmentedLayingBoard aufgefallen? (2a)
2. Fanden sie das System hilfreich? (2a)
3. Gab es Stellen, an denen das System nicht flexibel genug für ihre normale Vorgehensweise war? (2c)
4. Haben sie während der Benutzung des Systems Änderung in ihrer Geschwindigkeit oder der Anzahl der Fehler, die sie machen im Vergleich zu ihrer normalen Arbeit feststellen können?
  - a. Falls ja, können sie beschreiben wo und warum?
5. Wie würden sie das System im Vergleich zu ihren normalen Werkzeugen einschätzen? Was macht es besser? Was macht es schlechter? (2e)
6. Können sie sich vorstellen das System im Arbeitsalltag regelmäßig einzusetzen? (2b)
  - a. Falls ja, was für Verbesserungsvorschläge gibt es? (2f)
7. Gibt es wichtige Funktionen, die dem System fehlen? (2g)

## Tauglichkeit für das Einarbeiten in neue Verlegebretter/Kabelbäume

1. Wie einfach oder schwer ist der momentane Einarbeitungsprozess für die Montage?
2. Als wie gut würden sie das System für das Einarbeiten neuer Mitarbeiter im Allgemeinen oder bestehende Mitarbeiter in neue Verlegebretter einschätzen? (3)
3. Hat das System Einschränkungen, die diesen Lernprozess behindern könnten? (3a)
4. Gibt es Änderungen oder Funktionen, die den Lernprozess verbessern könnten? (3b)

# Einleitung

Im Folgenden werden noch einmal die grundlegenden Informationen sowie der Ablauf dieser Studie zusammengefasst.

Das Ziel meiner Masterarbeit war es, mit *AugmentedLayingBoard* ein System zu entwickeln, das Arbeiter bei der Montage von Kabelbäumen visuell unterstützt. Dabei soll sowohl die Einarbeitung in neue Verkabelungen und Verlegebretter als auch die generelle Montage unterstützt werden.

Diese Studie dient zur Evaluierung von *AugmentedLayingBoard*. Durch sie möchte ich zum einen herausfinden ob die Anwendung diesen Zielen gerecht wird und zum anderen ob die Anwendung grundsätzlich benutzerfreundlich ist. Dabei soll ausdrücklich *nicht* ihre Leistung als Teilnehmer bewertet werden, sondern nur, wie gut sie von *AugmentedLayingBoard* unterstützt werden und wie die Anwendung in Zukunft verbessert werden könnte.

Im Rahmen dieser Studie würde ich sie zuerst bitten einen kurzen demographischen Fragebogen auszufüllen. Im Anschluss werden sie kurz in das System und die vom System verwendete HoloLens-Brille eingeführt. Anschließend dürfen sie *AugmentedLayingBoard* ausprobieren. Dazu werden sie mit Hilfe des Systems in ca. 15 Minuten einen Teil eines Kabelbaums montieren. Danach bitte ich sie darum, noch zwei weitere Fragebögen auszufüllen und in einem abschließenden Interview einige Fragen zu ihrer Erfahrung und Einschätzung des Systems zu beantworten.

Sie haben jederzeit das Recht die Studie ohne Angabe von Gründen abubrechen. Bitte geben sie mir dazu einfach Bescheid.

Vielen Dank für ihre Mithilfe und sollten sie noch Fragen haben, dann zögern sie bitte nicht diese zu stellen.

# Einverständniserklärung

Über das Ziel, den Inhalt und die Dauer der Studie wurde ich informiert.

Im Rahmen dieser Studie werden durch Audioaufnahmen, Fragebögen, Notizen, Speicherung der Interaktionen mit der Anwendung (Logging), Videos und Fotos Daten erhoben.

Hiermit bin ich darüber aufgeklärt, dass diese Daten pseudonymisiert analysiert und vertraulich behandelt werden. Die Daten werden ausschließlich für die Auswertung verwendet und für die Analyse, Dokumentation, Präsentation und Publikation von wissenschaftlichen Arbeiten genutzt.

Abseits der genannten Zwecke werden die Daten nicht an Dritte weitergegeben.

Ich wurde ebenso darauf aufmerksam gemacht, dass ich meine Einwilligung jederzeit widerrufen kann. Weiterhin wurde mir mitgeteilt, dass ein Widerruf nicht mehr möglich ist, falls bereits mit der Auswertung der erhobenen Daten begonnen wurde. Pseudonymisierte Daten, welche in wissenschaftliche Arbeiten eingeflossen sind, können nicht mehr gelöscht werden.

Hiermit erkläre ich mich mit den oben genannten Punkten einverstanden:

\_\_\_\_\_  
(Name, Druckbuchstaben)

\_\_\_\_\_  
(Ort, Datum)

\_\_\_\_\_  
(Unterschrift)

Hiermit verpflichtet sich der Befragende, sämtliche der gewonnenen Daten lediglich wie oben beschrieben zu verwenden:

\_\_\_\_\_  
(Name, Druckbuchstaben)

\_\_\_\_\_  
(Ort, Datum)

\_\_\_\_\_  
(Unterschrift)

# Demographische Daten

Alter

---

Geschlecht

Männlich

Weiblich

Sehstörungen oder Körperliche  
Einschränkungen (falls vorhanden)

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---

Wie gut schätzen sie ihre  
Kenntnisse im Umgang mit  
Computern, Smartphones oder  
ähnlichen Geräten ein?

Sehr  
schlecht

Sehr  
gut

Haben sie bereits Erfahrung mit  
Virtual Reality oder Augmented  
Reality gemacht?

Ja

Nein

Falls ja, womit?  
(Z.B. Pokemon Go!, VR Brille, ...)

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Wie erfahren schätzen sie sich bei  
der Montage von Kabelbäumen  
ein?

Sehr  
unerfahren

Sehr  
erfahren

Haben sie bereits Erfahrung mit  
anderen digitalen Hilfsmitteln für  
die Montage von Kabelbäumen?

Ja

Nein

# System Usability Scale

Ich denke, dass ich das System gerne häufig benutzen würde.

Stimme überhaupt nicht zu Stimme voll zu

Ich fand das System unnötig komplex.

Stimme überhaupt nicht zu Stimme voll zu

Ich fand das System einfach zu benutzen.

Stimme überhaupt nicht zu Stimme voll zu

Ich glaube, ich würde die Hilfe einer technisch versierten Person benötigen, um das System benutzen zu können.

Stimme überhaupt nicht zu Stimme voll zu

Ich fand, die verschiedenen Funktionen in diesem System waren gut integriert.

Stimme überhaupt nicht zu Stimme voll zu

Ich denke, das System enthielt zu viele Inkonsistenzen.

Stimme überhaupt nicht zu Stimme voll zu

Ich kann mir vorstellen, dass die meisten Menschen den Umgang mit diesem System sehr schnell lernen.

Stimme überhaupt nicht zu Stimme voll zu



Ich fand das System sehr umständlich zu nutzen.

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stimme überhaupt nicht zu				Stimme voll zu

Ich fühlte mich bei der Benutzung des Systems sehr sicher.

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stimme überhaupt nicht zu				Stimme voll zu

Ich musste eine Menge lernen, bevor ich anfangen konnte das System zu verwenden.

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Stimme überhaupt nicht zu				Stimme voll zu

# Fragebogen

## Nutzererfahrung

Haben sie die Benutzung von AugmentedLayingBoard als schwer empfunden?

Ja

Nein

Falls ja, weshalb?

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Hatten sie Probleme, die Darstellung für die Kabelenden und Kabelrouten zu verstehen?

Ja

Nein

Haben sie die 2D-Darstellung der Stecker neben den Kabelenden als hilfreich empfunden?

Ja

Nein

## Allgemeine Nutzung

Wie hilfreich schätzen sie AugmentedLayingBoard für die Montage von Kabelbäumen ein?

Wenig  
hilfreich

Sehr  
hilfreich

Können sie sich vorstellen AugmentedLayingBoard in ihrem Arbeitsalltag einzusetzen?

Ja

Nein

Falls nein, weshalb?

---

---

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---

Haben sie sich durch  
AugmentedLayingBoard in ihrer  
normalen Vorgehensweise in  
irgendeiner Form eingeschränkt  
gefühlt?

Ja

Nein

Falls ja, weshalb?

---

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Haben sie während der  
Benutzung von  
AugmentedLayingBoard eine  
Veränderung ihrer  
Arbeitsgeschwindigkeit oder der  
Anzahl der Fehler, die sie  
gemacht haben im Vergleich zu  
vorher festgestellt?

Ja

Nein

Auf welche Hilfsmittel können sie  
momentan bei der Montage von  
Kabelbäumen zurückgreifen?

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Als wie gut würden sie diese  
Hilfsmittel bewerten?

Sehr  
schlecht

Sehr  
gut

Als wie gut würden sie  
AugmentedLayingBoard im  
Vergleich zu diesen Hilfsmitteln  
bewerten?

Sehr  
schlecht

Sehr  
gut

## Nutzung zur Einarbeitung

Wie hilfreich schätzen sie  
AugmentedLayingBoard beim  
Einarbeiten in neue  
Verlegebretter ein?

Wenig  
hilfreich

Sehr  
hilfreich

Gibt es etwas, was  
AugmentedLayingBoard für  
diesen Einsatz besonders gut  
oder schlecht macht?

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Haben sie eine Vorstellung, was  
man an AugmentedLayingBoard  
im Hinblick auf das Einarbeiten in  
neue Verlegebretter verbessern  
könnte?

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## B. USB Drive Contents

The attached USB drive contains:

- A Digital Copy of This Thesis
- The Documents Used for the User Study
- The Report of the Master Project for *Augmented Laying Board*
- A Short Video Demonstration of *Augmented Laying Board*