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Model based operator instructions using AR-technology

MASTER THESIS WORK

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Abstract

Augmented reality or (AR) is defined as a technology that provides a reality-based interface where users can interact with the real environment augmented with computer-generated images. The purpose of this report is to investigate the possibility of using AR in a specific assembly process of a product and to evaluate how it could be used in presenting information for operators at the assembly line. The project aims to provide an AR solution with a full analysis of the assembly process by testing, analyzing, and evaluating the proposed solution.

The assembly process that is investigated in this report is an assembly of a drone. By using Vuforia Studio, an AR software computer-generated as an instruction for the assembly process. 12 participants were chosen to assemble the drone by using two different platforms. Microsoft Hololens, AR 3D eyewear device, and an Android Tablet were used as two distinctively different platforms in this experiment. The assembly process was analyzed and evaluated through observations and questionnaire provided to the participants.

The experiment illustrated that AR can be used as a helpful instruction tool where all participants were able to fully assemble the drone. The Android Tablet platform participants showed slightly better performance due to familiarity with the device. During the experiment, different aspects of AR were explored including advantages, disadvantages, and limitations.

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1. Introduction

In the introduction part of the report background description of Augmented Reality (AR) is presented. Some challenges of modern production systems are specified focusing on AR in assembly operations. The purpose and goal of this thesis project are stated. Several research questions are considered, and project delimitations are identified.

1.1 Background

The fast development of modern technologies influences customer's requirements on the products that are demanded on the market (Danielsson, 2018). These products are often more complex than the respective ones several years ago. It puts pressure on companies that produce these items. Employees must not only design but also build or produce complicated products with a high level of quality, smaller tolerances and during a shorter period. They should adapt to handling an increasing number of variants and agile ways of working (ibid.).

To support operators a lot of operations are automated nowadays (Yuan, 2008). However, there are a lot of tasks that require human assistance. 2D and text-based instructions are widely spread. It means that an operator must constantly share his/her attention between instructions and actual production. It can lead to time losses, stress by the fulfillment of work tasks, fatigue, attention weakening and as result errors and quality issues (ibid.). Another issue here is that every significant change in a process requires updating of these instructions (Agrawala, 2003). Also, high product variants in assembly operations can require a lot of effort to provide detailed instruction. Due to globalization, these instructions must as well be translated into different languages, which is a time and resource-consuming task (ibid.).

Another challenge is the aging population and newly employed people who need effective training and who should be able to fulfill complex tasks at an assembly line within short periods (Farrell, 2018). Larger responsibility that operators will have in the future will require an information system for support (Danielsson, 2018). The time required for training should be decreased as well.

Augmented reality (AR), might be able to provide such support and increase the quality level even if the assembly is carried out by inexperienced operators. This support can be provided in the form of virtual objects combined with the real-world environment (Yuan, 2008). It will help to save time and to avoid eventual distractions. The operator can receive all the information necessary directly on demand without making unnecessary movements or filtering the provided information (ibid.).

1.2 Purpose

The purpose of this thesis work is to investigate how different AR devices and interaction designs in AR can influence the effectiveness and efficiency of AR support in assembly tasks.

1.3 Goal

The goal of this project is to identify appropriate interaction design approaches for a given assembly task supported by AR, as well as analyze why AR is not widely spread in assembly processes although it has now been investigated for some time.

1.4 Research questions

Three questions were raised during the thesis work execution:

- How the application of different AR-devices influences the effectiveness of the assembly process?
- How should AR interaction design be modeled to increase the effectiveness of the assembly process?
- What can be the positive and negative sides of AR when using it in assembly support purposes?

Answers on these three questions can provide an explanation to the reason why AR is not widely used in assembly operations hand-held although it has been investigated for several years?

1.5 Delimitations

AR instructions will not be tested on a product that is currently in mass production it will be limited to a 3d-printed drone manufactured by Stena Industrial Laboratory, Gothenburg, Sweden. Assembly tasks will not be carried out on the whole product a part of the assembly sequence will be included.

Test assembly will not be carried out by experienced operators or people with a high level of assembly skills, operators are chosen randomly. Fully manual tasks will be considered during this project. No detailed ergonomic analysis will be carried out. However, the solutions should be plausible from an ergonomic perspective.

2. Related Studies

The theoretical chapter of the report embraces the literature study part of this thesis work. Several existing case studies are described and analyzed. Human perception mechanisms are considered to distinguish possible guidelines for the design of instructions. The definition of augmented reality is given. A brief description of the Vuforia platform is presented and liable challenges are mentioned.

2.1 AR definition

Augmented Reality (AR) is a technology that provides a “reality-based interface” (Krevelen, 2010). Real and virtual objects are coexisting in the same reality. Virtual objects can be 3D models, text, images, sounds. All of them are aligned in real-time in three dimensions (ibid.). Virtual modalities are added to the real environment (Yuan, 2008). Different senses (hearing, haptics, sense of smell) can be set in motion by AR technology. This is to provide a feeling of reality-based experience (ibid.). However, mainly the visual application of AR is spread nowadays (Kipper, 2012).

2.1.1Three Categories of AR

Augmented reality can be implemented in three ways: head-attached, hand-held, spatial (Danielsson, 2018).

Head-attached AR is often referred to as such devices as AR glasses (Krevelen, 2010). Nothing limits the movements of operators, both hands are free. At the same time, this type of glasses is known for being heavy and uncomfortable for the users. The Graphic resolution of the augmented components in the glasses is often criticized as well. The visual field is also criticized to be too narrow. The hand-held category does not have the same issue with resolution nor weight. However, the operator might be limited in movements while using hand-held devices. It means that the amount of operations is narrowed to the ones that are possible to carry out with one hand. The spatial category eliminates the above-named difficulties connected to head-attached and hand-held devices. On the other hand, large screens necessary in this case require a lot of space which is often a critical factor at an assembly line (ibid.). However, it should be mentioned that technology keeps being developed. For example, so-called “smart glasses” are getting lighter and the technical specification level is increasing constantly (Syberfeldt, 2015). If challenges with AR glasses are solved it might open a lot of potentialities for implementation of AR in training, education, assembly line, etc.

2.1.2 AR systems

There are three main parts in the structure of an augmented reality system: **“tracking and registration, display technology, real-time rendering”** that influence the experience of a user (Mekni, 2019). It should be possible to track and register an object or surface in order to trigger an action in the AR system. Camera and display technology play an important role when physical and virtual objects should be aligned. In the case of a user who changes the position, every movement should be tracked continuously. This is to avoid a feeling that the object is moving although according to the user's knowledge and experience of reality it should be fixed (ibid.). The development of AR system technology is crucial to minimize such limitations as view angles, ergonomic limitations (for example, the weight of the Hololens) (Krevelen, 2010). Display resolution plays an important role in the level of user experience. The technology can be sensitive to the surrounding environment. For example, light or humidity conditions can be limited to indoor use (ibid.).

2.2 AR Application in Assembly

Although AR technology has been investigated for a long time, it is still not widely used in different areas. Several reasons for this fact can be listed. One of these reasons is privacy (Kipper, 2012). People do not trust the system that includes cameras and sensors that are monitoring every step. Another reason is safety since humans can get distracted when using AR- glasses or Hololens. The field of view is quite narrow which limits the ability to control the surrounding environment (ibid.).

A fact that should be considered is that people of different ages and with different backgrounds or levels of experience can be working at an assembly line. It means that instructions should be suitable for different groups of users. **User acceptance** is one of the factors that many studies focus on.

To investigate user acceptance of AR technology an experiment was conducted at the engine factory for Volvo Car Corporation (Danielsson, 2018). The same operator participates in every step of the assembly process. Currently, every station has a fixed monitor that gives information about the time needed and left for an operation, it gives feedback on quality as well (in this case, if a torque on the screw is correct). Operators at the factory were interested in AR-technology and did not show any resistance to testing it on the assembly line. Operators were supposed to follow the color markers to place different parts together and every time when quality issues took place, they received feedback in a form of red highlighting. All the information was presented in colors and design the operators were used to from their previous experience at the station. After the experiment, all people involved expressed positive feelings about AR-technology. They pointed out that it gave necessary information when needed - screwing torque, assembly time and quality issues (ibid.). Clearly, it can be stated that to create intuitive interfaces it is important to state what information can be required by operators.

A question of acceptance of the AR-technology was raised during another experiment User acceptance is mentioned by D.W.F. van Krevelen and R. Poelman. It is pointed out that one of the critical limitations for AR-technology to be implemented is social acceptance (Krevelen, 2010). People have different types of concerns, for example, appearance (when wearing AR glasses) or video recording. Airbus CIMPA is given as an example of a company where employees are rejecting this technology (ibid.).

Another experiment connected to user acceptance was described by Syberfeldt et al. Twelve participants were chosen randomly to assemble a three-dimensional puzzle (Syberfeldt, 2015). A simple task was chosen to analyze user acceptance of technology, not effectiveness. A comparison was made between paper instructions and instructions provided by AR technology. The result of the experiment showed that mistakes were completely avoided by the group that used AR instructions, while the group with paper instructions showed the worse quality results. As for the time of the task completion, the group with traditional instructions succeeded better. It took significantly more time for the group with AR instructions. The authors of the experiment explain it with the fact that this group had to learn the technology while carrying out the task and participants' ability to get used to the technology. The experiment showed that AR technology can be good security against mistakes in assembly processes. However, a lot of operators needed some kind of confirmation that the task was carried out in a correct way (ibid.). It makes **quality assurance** to one of the key requirements needed for the creation of an intuitive interface for AR instructions.

Another point mentioned by Syberfeldt et al. was that the **task should be complex enough** to make an operator use AR technology. Some studies lift the question of **product complexity** as well. Radkowski et al. assumed that AR might show high performance in comparison to paper-based instructions (used 2D colored images) if products are more complicated. The result showed that even although the AR interface performed better, the difference was not remarkable (Radkowski, 2015). However, an important observation was made. It turned out that operators felt more confident when using AR-based instructions. They were able to learn faster and had no problems in understanding how different parts should be aligned (ibid.). Product complexity should be considered when the instruction interface is designed.

Most investigations that were carried out **compared paper-based and AR-based instructions**.

It should be considered that the AR system is a complex system (Kipper, 2012). It consists of several components (sensors, cameras, displays, etc.) that need to cooperate and coexist in the framework of the same system for better functionality. Since the development of each component is ongoing and there are still some issues existing (for example, sensor accuracy), it influences the whole system. Sometimes it does not work in a way that is good enough for users to trust it (ibid.). Several studies were focused on creating algorithms that could help to improve the level of **accuracy of recognition**. However, these investigations are not included in the scope of this thesis work. Technical limitations can be pointed out as one of the reasons why AR technology is not widely spread nowadays.

Grasset et al. worked at developing a hand-held display that could be user-friendly. To provide **an ergonomic solution** that suited the requirements of people, several prototypes were created (Grasset, 2007). The focus was put on low weight and cost, comfortable solution, simplicity of using the device, the possibility to choose when AR should be used or not. The results and reviews were positive by that time (ibid.). The article was published in 2007.

Orit Shaer talks about **"tangible augmented reality"** that makes communication between humans and computers similar to real-world communication. The input in a real physical world is reflected in the virtual world (Shaer, 2009). Sometimes a human can manipulate virtual targets using physical objects. For example, a manipulation of an object on the screen using real physical lever (ibid.). In this case, both "body awareness & skills" and "environment awareness & skills" provide a feeling resembling the real-world experience (Jacob, 2008).

Using **a physical object as an interactive tool** for manipulating the virtual objects was tested by Yuan M.L. et al. To assemble a toy-train a pen tracked by the system was used (Yuan, 2008). The pen could activate virtual buttons that triggered all necessary information for a particular assembly step. Information was shown in a corner of the screen. The user had to confirm that the task was performed and that he/she was ready to move forward. The system explained how to proceed using text. The overall system was evaluated as a good guidance level. The importance of layout design optimization was indicated. Videos were suggested as one of the possible solutions in future work. An idea to use voice command as a type of interactive tool was expressed (ibid.).

Several investigations of AR applications were performed in training processes. One of these studies was carried out at the chassis plant of a car manufacturer (Quandt, 2018). AR technology was applied in the training process for welders. Welding arcs and beads were simulated. Virtual changes in metal structures and reactions could be observed as well. Focus on such factors as cost, accuracy, ergonomics, etc. was made. Since the level of accuracy was not high enough, it turned out that experienced welders had fewer issues when using AR instructions than inexperienced ones. Employees were open-minded and were ready to accept the technology. The main drawback was the **lack of realistic threats**. Potential dangers connected with the welding process were not experienced, which made the training process incomplete (ibid.).

A similar issue was raised by Ong S.K. et al. Focus was put on creating an interface that could be as realistic as possible (Kalantari, 2018). In the experiment, traditional manipulation devices were substituted by real hands that could be recognized by a camera fixed on the AR device. Virtual objects were manipulated by real hands. When a hand came in contact with a virtual object, it was marked by small virtual circles giving necessary feedback to the user. The system could as well give feedback on the correctness of assembly. Although the overall experience of the experiment was positive, lack of sense of reality (such as force feeling) was recognized (ibid.).

The outcomes from the above-mentioned case studies were taken into consideration when the interface for this master thesis was created.

2.3 Complexity in Assembly Operations

Due to the constantly increasing number of variants of products it is getting more difficult to perform assembly tasks (Mattsson, 2018). This fact puts a lot of pressure on operators working at the assembly line. To avoid stress environment leading to quality mistakes in assembly operations the complexity level of different products should be considered. Instruction designers should keep in mind human cognitive processes, limitations and individual differences (ibid.). The complexity of a product or operation can be defined as the amount of effort that needs to be spent to perform the task (Radkowski, 2015).

Falck et al. distinguished sixteen criteria for the assessment of product complexity. Interviews with experienced employees of several companies working close to production were carried out (Falck, 2016). The result of these interviews or all sixteen criteria will not be enumerated in this report. However, several examples will be given. Tasks that are time-consuming or tasks that require precision can be reckoned among high complexity tasks (HC). While tasks that do not include additional adjustments or do not need a special order in assembly to be followed can be called for low complexity tasks (LC) (ibid.).

2.4 User-Centered Design Interface

According to the case studies described in the chapter “AR application. Case studies” user acceptance of the AR technique is an important factor that will influence the performance of an operator at an assembly line. An operator who is working with an assembly of a complicated product should not struggle with finding his/her way to instructions. To simplify this process “intuitive user interfaces” should be created (Danielsson, 2018). It means that the design of layout and information presentation are of significant meaning in this case.

Good knowledge of human psychology and the fast development of computer technologies helped to move forward with the concept of “Reality-based interaction” (Jacob, 2008). Based on this concept the interface can be created in such a way that the computer interaction will resemble the human interaction with the real, non-digital world as much as it is possible and practically needed. Human skills and knowledge that are a part of everyday life can help to make the collaboration more intuitive. For example, in everyday life, people know that to move forward and reach a certain destination they need to walk. To lift an object, one needs to grip it first. Based on this principle four different themes were distinguished:

- Naive physics. Humans have knowledge of laws of nature, such as gravity or inertia. Applying illusion that creates an experience similar to the non-digital world can improve the understanding of interface;

- Body awareness and skills. Using such natural skills as walking to reach a certain destination, turning ahead to get a better view, gripping objects can help to avoid additional steps in an explanation on what should be done next;
- Environment awareness and skills. If the system recognizes or copies the environment around it will be easier for the user to perceive the situation;
- Social awareness and skills. Human ability to communicate and collaborate with individuals around can be used when creating AR interfaces (ibid.).

The above-mentioned themes could help to avoid long educational periods for new operators, minimize the need to refresh the knowledge after a long break period. A tight connection to the real world can increase user acceptance as well.

Information can be presented in several ways. Two of them are; a structural diagram and an action diagram (Agrawala, 2003). A structural diagram shows the part that is being assembled attached to the parts that have been assembled earlier. It means that an operator has to compare the state before and after in order to understand which part should be used and how it should be placed. When the action diagram is being used the part that should be assembled during a particular step is separated from the rest of the unit. Guidelines (for example, arrows) are sometimes used between parts. This is to show where the piece should be placed. Normally the new part should be situated as long as possible from the unit. It is necessary to avoid interference that can make an operator uncertain (ibid.).

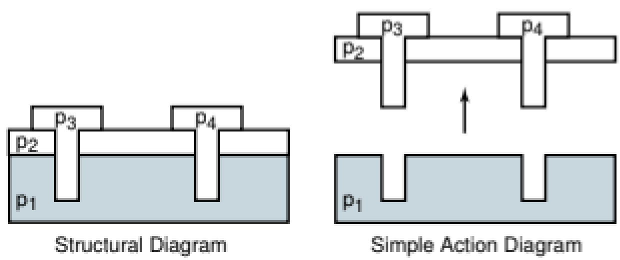

Figure 1. *Picture of structural and action diagrams from Agrawala, M. et al. (2003) Designing effective step-by-step assembly instructions, ACM Digital Library, July 2003*

2.5 AR-technology and Vuforia platform

Vuforia platform developed by PTC Vision is applied to fulfill the goals of this master thesis. It can be used for Android, iOS and Unity Editor (Sural, 2019). It supports the recognition of objects, text documents, and environments (ibid.). Videos, instructions in 2D can be created using the Vuforia platform (Vuforia Studio, 2019). Information will be given to an operator in real-time and on-demand. The update process is supposed to be simple, without long development periods and not resource-consuming (ibid.).

There are several ways of initiating the AR experience or so-called tracking methods (Vuforia Developer Library, 2019):

- Spatial Target - tracking based on the surface for an object to be placed on, not on the object itself or its 3D model.
- Model Target - a method of tracking a physical object by comparing its 3D model with a physical object in real-time.
- Image Target - a method where an image is used for tracking.
- ThingMark - a mark used to closely align physical objects and its 3D model (ibid.).

When using the Vuforia platform there are different ways of navigating the system: moving forward and backward in the process, getting a generalized picture, receiving comments, declining help, etc.

3. Methodology

In the chapter "Methodology" a detailed description of project steps is shown. The design of the experiment, hypothesis, corresponding reasoning for chosen and rejected scenarios are presented.

3.1 Pre-study

The literature study was carried out at the beginning of the project. A lot of focus was put on the definition of Augmented Reality (AR) and three categories of AR. Possible applications of AR in production systems were investigated using several case studies conducted in earlier projects. A short description of those case studies is included in the theoretical part of the report. Outcomes from the investigations were used to design the experiment for this project.

Information about research on the design of instruction creation was investigated. This is to get an insight into human perception mechanisms. Among others, the concept that includes "reality-based interaction" was applied for the creation of intuitive interfaces. A short description of the concept is provided in the theoretical part of the report.

An acquaintance with the Vuforia platform was conducted at this project step. Possibilities and options of this platform were studied in order to understand what resources and capabilities were available.

3.2 Experiment

Several outcomes from case studies were taken into consideration when designing the interface for the information presented in this master thesis.

- User Acceptance;

- Reality-Based Interface;

- Quality Assurance needs;

- Product Complexity;

- Technology Limitations.

3.2.1 Experiment purpose and goal

The following questions are expected to be answered during the thesis work:

- How the application of different AR-devices influences the effectiveness of the assembly process?
- How should interaction design be modeled to increase the effectiveness of the assembly process?

- What can be the positive and negative sides of AR when using it in assembly support purposes?

The purpose of the experiment is the need to collect information that can be useful for answering the questions above. The goal of the experiment is to compare performance when HoloLens and Tablet are used, as well as the influence of interface design. Another goal is to list the points that can affect user acceptance of the technology.

3.2.2 Test Environment

The experiment was carried out in a quiet controlled laboratory environment at Lindholmen in Gothenburg for tablet and in a quiet conference room at an office of a certain company also in Gothenburg for HoloLens. No special light or noise level adjustments were made. No special light or noise disturbances were registered.

3.2.3 Test Equipment

Several categories of AR technology could be used during the project: head-attached, handheld or spatial. Both head-attached and spatial variants allow a user to conduct operations with two hands, while hand-held devices have limitations in this case. Head-attached units are known for being heavy and not very comfortable from the ergonomic point of view. Spacial (tablets/displays place in a fixed position) devices can be too bulky and require additional space that assembly areas usually have lacked.

Since the project is not carried out in a real production environment and shortage of space is not as critical, the limitation of spacial AR can be partially ignored. The technology of head-attached devices is developing fast and ergonomic risks will with high probability be minimized or eliminated completely in the future. This is the reason why this factor is not rated as one of the most crucial ones for this project.

The clarification above explains the reasons why during this project only two types of AR technology were applied: **head-attached** (Microsoft Hololens) and **spatial** (a tablet in a fixed position). It was decided not to apply a hand-held device. The reason for it was to get a situation that would be the most equitable. When HoloLens or fixed Tablet are utilized both hands are free which means that the same type of operations can be conducted, and the assembly sequence does not have to be adjusted to a certain category of AR.

3.2.4 Experiment Scenarios

Since most of the studies conducted before compared paper-based instructions and AR-based instructions, it was decided not to focus on a similar comparison. Instead, two different AR-devices were compared.

Several scenarios were suitable for both head-attached and spatial devices were proposed and analyzed. **ThingMark** was used for all scenarios and devices.

Text-based 2D instructions were discussed as one of the possibilities. Yet, this scenario was declined due to the following hypothesis. Several languages might be needed to provide good support for people who do not have the official language as a mother tongue or do not speak the country's official language. Translations are time and resource-consuming, special competence is required. Even if a user has language competence that is good enough, it still can be influenced negatively by fatigue and lack of concentration. It might take a longer time for a tired operator to read and understand 2D instructions. The focus was decided to put on the 3D based instructions.

When scenarios were created the main focus was put on the development of an interface that had a close connection between the physical and virtual world. The AR-experience was supposed to be as similar to real-world knowledge and experience as possible using such themes as "naïve physics, body awareness and skills, environment awareness and skills, social awareness and skills" (Jacob, 2008).

Scenario 1 raises a question on **how each operation should be shown**. It was decided that *scenario 1a* would demonstrate how a part should be handled (a part is lifted, rotated in the same way as the operator should do, aligned with the rest of the parts) just before placing it on a jig. *Scenario 1b* was decided to be a contrast to 1a. The handling of parts was not included. A part appears directly on a jig.

Scenario 2 contains a question on **how parts appear in front of the eyes**. It was decided to place the parts on the table around the fixture. This scenario was valid for both Tablet and HoloLens. Only the number of pieces needed for assembly of one drone was used in every case. This is to reduce the space needed for the experiment and avoid possible distractions when operators are searching for parts.

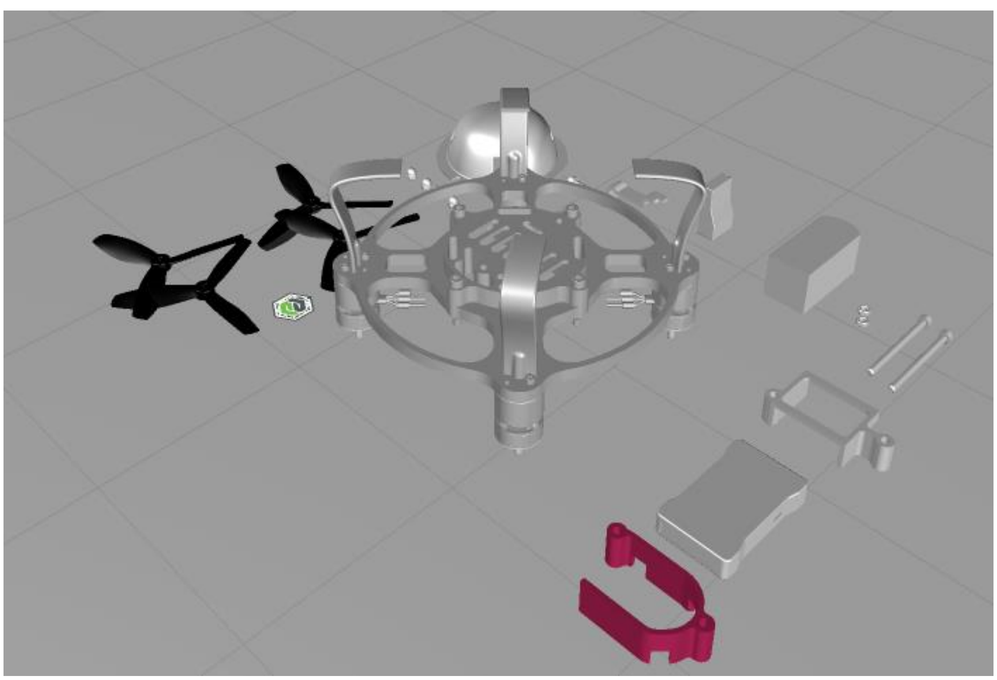

Figure 2. *Vuforia Studio. The layout presented for every participant*

Scenario 3 represents **a way of moving forward or take a step back**. *Scenario 3a* uses arrows shown on the touch screen of the tablet. *Scenario 3b* introduces voice command in English “Next”, “Back”, “Reset” as an interaction tool.

Scenario group number	Scenario index	Scenario group	Scenario description	Type of AR technology
1	1a	How each operation should be shown	Object manipulation is demonstrated	Tablet/Hololens
	1b		Object is placed directly on the jig	Tablet/Hololens
2	2	How parts appear in front of the eyes	Parts are in front of the eyes all the time	Hololens/Tablet
3	3a	How to move forward or back	Touch function	Tablet
	3b		Voice command	Hololens

Table 1. *Scenario description*

3.2.5 Hypothesis

The authors of the thesis work had a hypothesis on which scenario a or b will be preferable, to give better results in questions of training and quality.

3.2.5.1 Scenario 1

According to the authors’ hypothesis, Scenario 1a could provide additional help for the operator showing in what way/direction the part should be assembled. Yet, if too long or complicated manipulation is shown an operator can get stressed and nervous. Scenario 1b could be much easier to create, it is not as time-consuming. However, there might be a risk for misunderstandings because it is not obvious how some parts should be aligned. It could lead to a situation with time losses when an operator must think some additional time to fulfill the operation.

Scenario 1a is expected to be more effective, the mistake rate will probably be reduced. Both Tablet and HoloLens are anticipated to have approximately the same result. However, Tablet could be somewhat better due to a wider view field.

3.2.5.2 Scenario 2

When using scenario 2 an operator does not have to search for parts, watch away or stretch for something. In the authors’ opinion, it can have both positive and negative sides - an operator will avoid additional steps, will probably show a more effective result, but still will need to change his/her body position to avoid getting tired too fast. From the ergonomic point of view, it can be valuable to change a position, look in a more remote direction or stretch to reach an object from time to time. Tablet is expected to get better results due to a wider viewing angle and larger freedom in movements for participants.

3.2.5.3 Scenario 3

Voice command can be an effective and intuitive way of moving forward or back. Using touch function on the tablet is a very usual operation nowadays as well. This is because a lot of people nowadays own a smartphone with a touch screen, a lot of household appliances move towards touch screens as well. A hypothesis is that both scenarios will show high performance.

3.2.6 Components and Operations

The sequence used was set up by 12 different types of components (Components B – M) and 1 component used as a jig (component A).

15 operations in total were created in Vuforia Studio. Operations 2-15 corresponds to the manipulation of parts B-M necessary for assembly. Operation with part M was separated into two. This is since there are 2 types of part M. The part A (drone body) needed to be flipped twice during the sequence. This results in two additional operations.

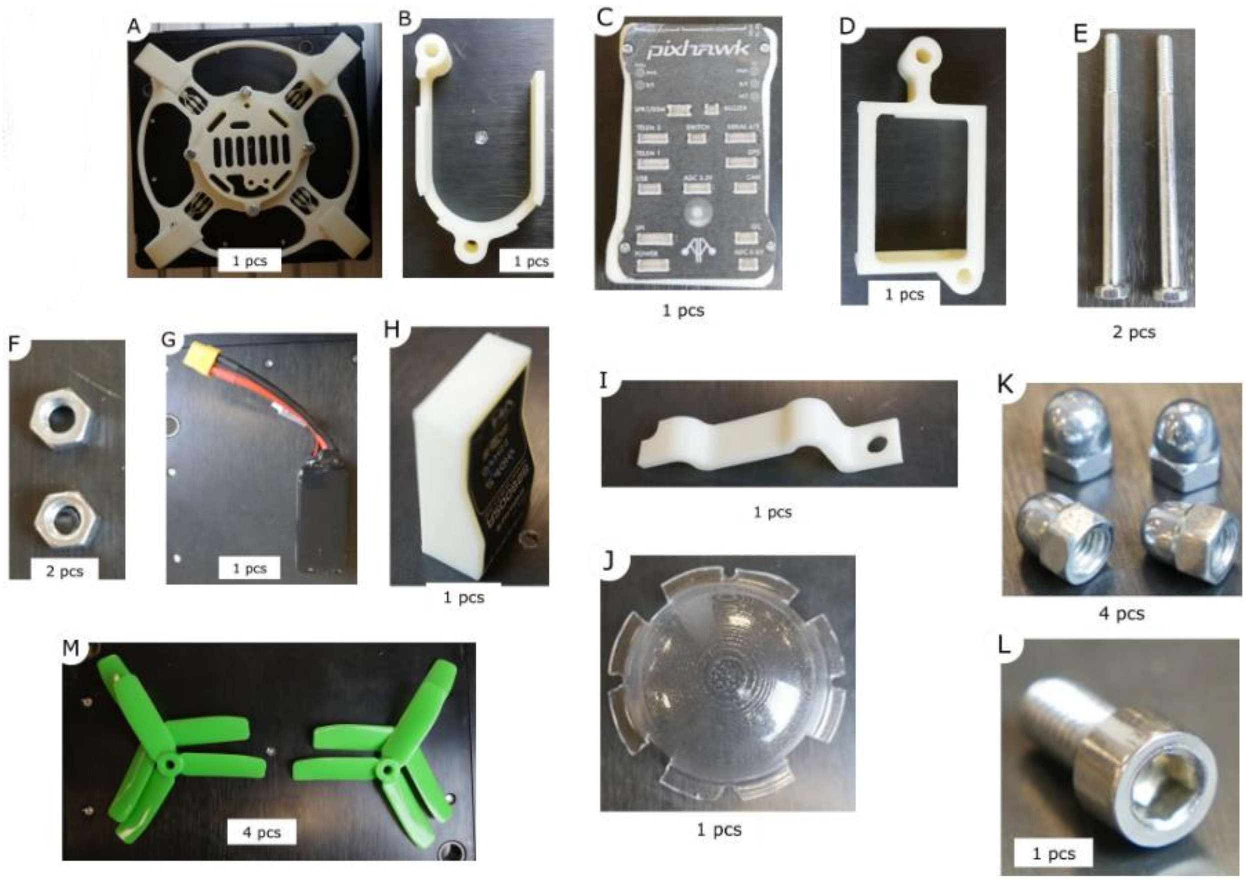

Figure 3. *Drone components.*

3.2.7 Scenario combination

Three scenarios were suggested for testing. Scenarios 1 and 3 were divided into 2 groups with index a or b.

Scenario 1 is supposed to prompt and provide (or not) help for the operator. Since the complexity of different operations varies it was decided to counterbalance and use scenario 1a for more complicated operations (operations 1, 2, 5, etc). Scenario 1b where the parts are placed directly on the correct position was applied for less sophisticated operations (operations 7, 11, 13) or operations where a part could not be mounted in a wrong way (operation 8). However, for some operations that seemed to be equally complex different scenarios (1a and 1b) were used. An example can be operations 1 (1a) and 6 (1b), 2 (1a) and 4 (1b). This is to compare performance for scenario 1a and 1b, with additional help and without.

To get as reliable results as possible it was decided to make counterbalancing and to create equal conditions as possible for every operator. Although the sequence cannot be called complex some operations are more difficult than the others. A short analysis of the complexity of each operation was carried out. Sixteen criteria for the assessment of product complexity mentioned by Falck et al. were applied. Tasks with high complexity levels were marked as HC. Tasks with assessed low complexity levels were marked as LC.

Operation Number	Complexity level
Operation 1	HC
Operation 2	HC
Operation 3	LC
Operation 4	HC
Operation 5	LC
Operation 6	HC
Operation 7	LC
Operation 8	HC
Operation 9	LC
Operation 10	HC
Operation 11	LC
Operation 12	HC
Operation 13	LC
Operation 14	HC
Operation 15	LC

Table 2. *The complexity level of the operation tasks*

Operation 8 was considered to have high complexity. During the creation of supporting animation some difficulties appeared. Instead of a demonstration of handling of the part, it was decided to add a picture that showed clearly how the part needs to be aligned.

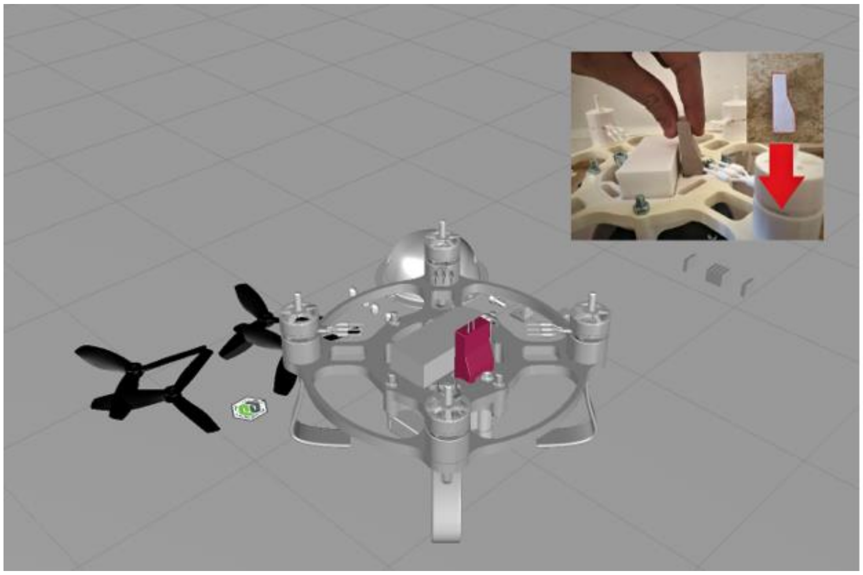

Figure 4. *Vuforia Studio. The layout presented for every participant. Operation 8*

Scenario 2 demonstrates how the parts appear in front of the eyes. This scenario had no indices (a or b) and was used for both Tablet and HoloLens.

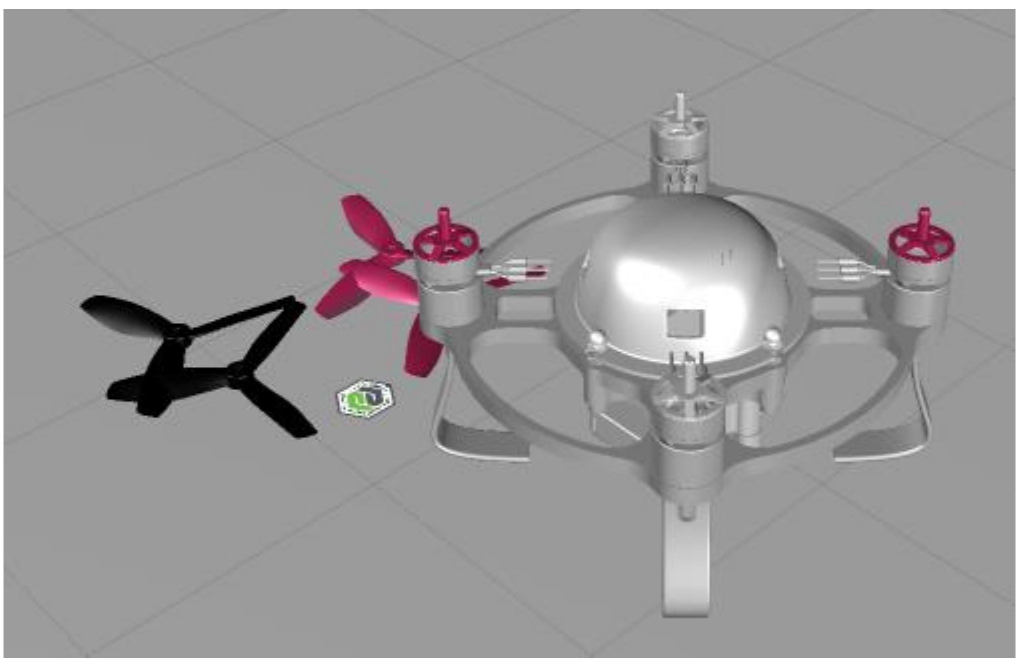

Figure 5. *Vuforia Studio. The layout presented for every participant. Operation 14 and 15*

The authors of this thesis work do not consider that the complexity of the operation plays a significant role in the application of *scenario 3*. However nowadays when people are getting more and more used to using smartphones and other devices, it seems to be an intuitive reality-based scenario. That is the reason for the decision to use a touch function for the Tablet. Since people are aware that to move forward it might be needed to use social skills, a voice command was applied for HoloLens.

	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5	Operation 6	Operation 7	Operation 8	Operation 9	Operation 10	Operation 11	Operation 12	Operation 13	Operation 14	Operation 15
1a	x	x			x			x	x	x		x		x	
1b			x	x		x	x				x		x		x
2	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3a	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3b	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Table 3. *Counterbalancing of operations and scenarios*

3.2.8 Participant Characteristics

12 persons participated in the experiment. All participants were male and had an engineering background – studying or working/worked as engineers. The age varied between 24 and 49 years old. The average age of participants was calculated to 36.

All participants were divided into two groups – 6 persons for the experiment using Tablet and 6 persons for the experiment using HoloLens.

3 persons had previous experience of AR technology, took part in previous experiments or used it on their phones. All 3 participants used Tablet during the experiment.

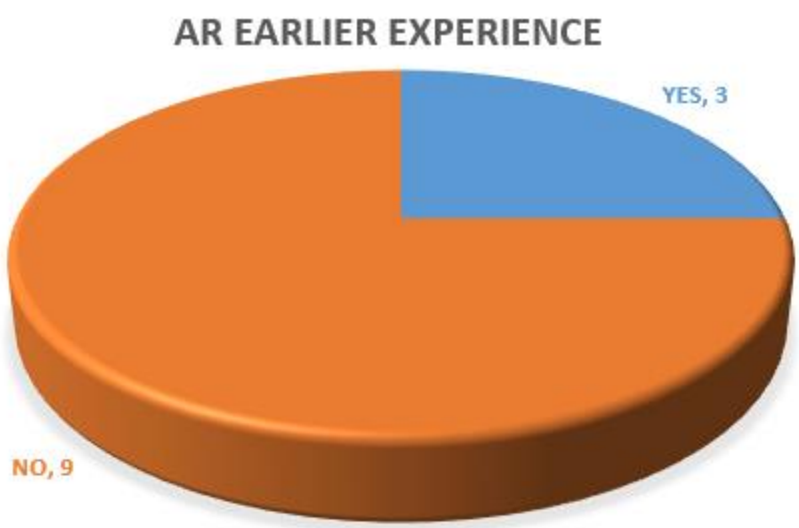

Figure 6. *Information on earlier AR earlier experience of experiment participants*

3.2.9 Introduction to the Experiment

No special introduction on how to use the tablet was performed. A short comment on how to start, move back and forward was made. A similar introduction was performed for the participants in the experiment with HoloLens.

The authors of this thesis work suggested that the most suitable way to get reliable results is to let one person assemble a unit only once. This is due to the low level of assembly sequence complexity. In the best-case scenario, "the operator" should have no knowledge of the product or sequence, should not have time to learn in detail how to use the AR-based instructions. Each person performed the assembly using either a tablet or a HoloLens, not both.

3.2.10 Questions to be answered

- Can profound training in how to use software be minimized or avoided?

- Is there any difference in performance between HoloLens and tablet users?

- How much influence has the interface design on the performance during the assembly process?

- Is feedback on the quality status needed?

- What are the main limitations of using HoloLens and Tablet?

All the questions that were asked to the participants can be seen in the Appendix.

3.2.11 Data to be collected

Both quantitative and qualitative data are expected to be received after the experiment completion.

Quantitative data:

- Completion time for the whole sequence for HoloLens;

- Completion time for the whole sequence for tablet;

- Completion time for operations 1 for HoloLens;

- Completion time for operation 1 for tablet;

- Completion time for operation 6 for HoloLens;

- Completion time for operation 6 for tablet;

- Completion time for operations 2 for HoloLens;

- Completion time for operation 2 for tablet;

- Completion time for operation 4 for HoloLens;

- Completion time for operation 4 for tablet;

- Answers on the questions where the information needed to be ranked.

Qualitative data:

- Subjective data from the participants received from the questionnaire;

- Notes made during unstructured observations during the assembly process;

3.2.12 Data collection

- Each participant of the experiment assembled the unit only one time using either HoloLens or tablet.

- The total time of the assembly process was noted for each person participating in the experiment.

- For operations 1 and 6, 2 and 4 time was noted separately. This is due to the planned comparison of two situations (1a and 1b) within the same scenario (scenario 1). A stop-watch on a smartphone was used.

- During the experiment, unstructured observations on how people react to every situation and scenario were made and notes were taken.

- When operators were finished with assembly tasks they were proposed to fill in a questionnaire. It consisted of 19 questions. Some of the questions demanded answers in the form of ranking on the scale from 1 to 5. For example, “to what extent do you agree with the following expression?” Other questions required more detailed answers and comments. For example, “Is there anything you would like to change?” The questionnaire was anonymous, only age and sex of participants were inquired.

4. Results

The result of the experiment is presented in the form of answers on the questions mentioned in chapter 3 “Methodology” of the report:

Q1. Can profound training in how to use software be minimized or avoided?

Q2. Is there any difference in performance between HoloLens and tablet users?

Q3. How much influence has the interface design on the performance during the assembly process?

Q4. Is feedback on the quality status needed?

Q5. What are the main limitations of using HoloLens and Tablet?

The answers are supported by both quantitative and qualitative data collected during the experiment.

4.1 Can profound training in how to use software be minimized or avoided?

All participants managed to finish the experiment. One of the questions asked was to rank to what extent each participant agreed with the expression “I needed more information on how the system works”.

Quantitative data

The average ranking for Tablet was 1,67 and for the HoloLens – 2,5.

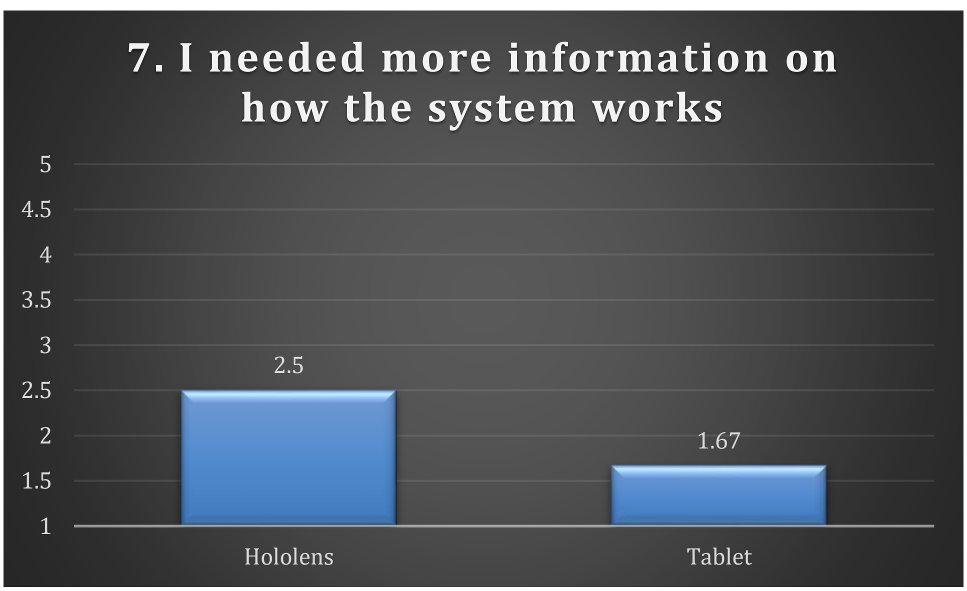

Figure 7. *Answer results for question 7 “I needed more information on how the system works”*

These results can be interpreted as a low necessity of training on how the system works. However, the participants who used Tablet expressed 33,2% less need for training in comparison to the ones using HoloLens. Yet, 3 participants in this group had previous experience of AR-technology.

Qualitative data

Very few qualitative data were obtained regarding this question. One person commented, *"The task was not very clear from the beginning".* No further opinions were received.

4.2 Is there any difference in performance between HoloLens and tablet users?

Time for assembly completion was taken. The recorded time for each operation reflects the time required for the operators to comprehend the instructions. The variation in time duration depends mainly on the operator's interpretation of instructions and the chosen scenario for a certain task.

Quantitative data

On average it took 6 minutes and 53 seconds to finish the assembly using the instructions provided on the tablet and 9 minutes and 15 seconds for HoloLens instructions.

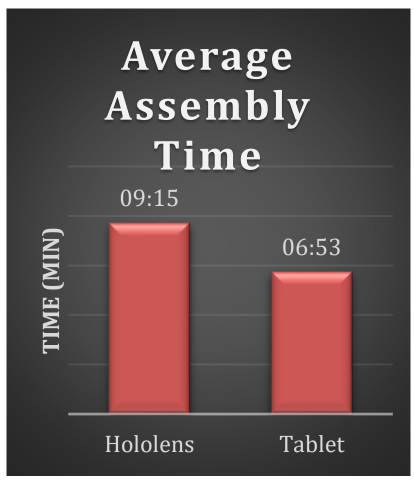

Figure 8. *Average assembly time*

The results showed that the time for Tablet was 25,6% lower than for HoloLens.

Qualitative data

No qualitative data were received. Observations showed that participants who were using HoloLens seemed to be more nervous and stressed.

4.3 How much influence has the interface design on the performance during the assembly process?

Time for completion of task 1&6 and 2&4 was compared to get the information about the experience of scenario 1.

Several questions/expressions in the questionnaire were aimed at the interface design as well:

Q11. It was clear to me how to move to the next step or to take a step back

Q12. I understood directly how every part should be mounted

Q13. I had problems understanding how every single part should be mounted

Question 11 was directed to interface scenario 3 with a touch function for the Tablet and voice command for the HoloLens. Questions 12 and 13 showed a more general experience of the designed interface.

Both quantitative and qualitative data were collected and could be used to answer the question about interface design influence.

4.3.1 Scenario 1

Quantitative data

Time for completion of tasks 1 and 6 was noted and compared. The first task included animation on how to handle the part (scenario 1a), the second task was missing the animation. A similar action was performed with tasks 2 and 4.

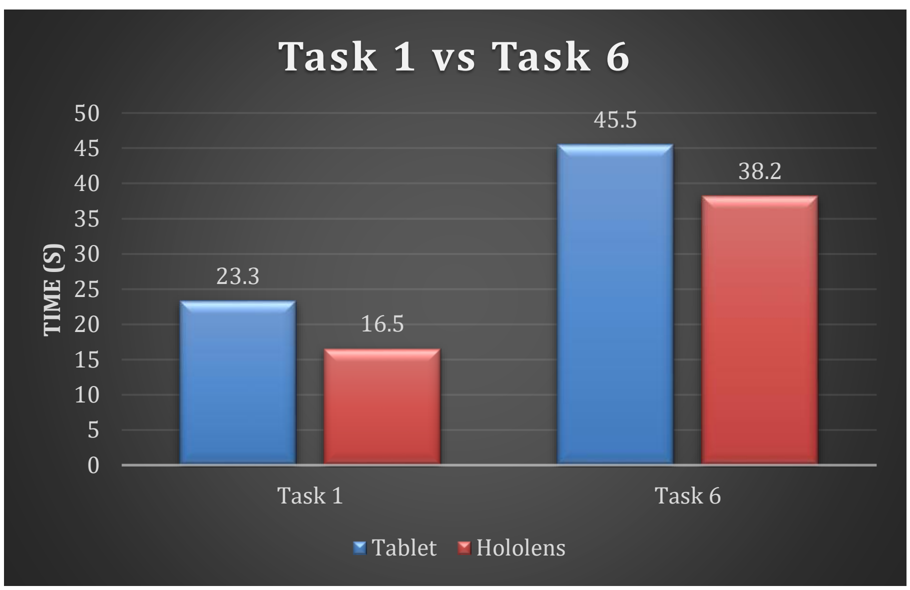

Figure 9. *Comparison of time required for task 1 and task 6*

For both task 1 and task 6, HoloLens showed better results than the tablet. In both cases, the time difference between the two devices was around 7 seconds (6,8 s and 7,3 s). Task 6 (without animation) took almost twice as much time as task 1 (with explanatory animation). Although, the tasks are considered to be very similar. They consist of simply flipping the drone upside down. However, in the first step, the animation was shown illustrating how the drone is supposed to be lifted up, flipped, and then placed back in the jig. In the sixth step, the state of the drone is shown directly in the jig after being flipped upside down.

Tasks 2 and 4 showed a slightly different result.

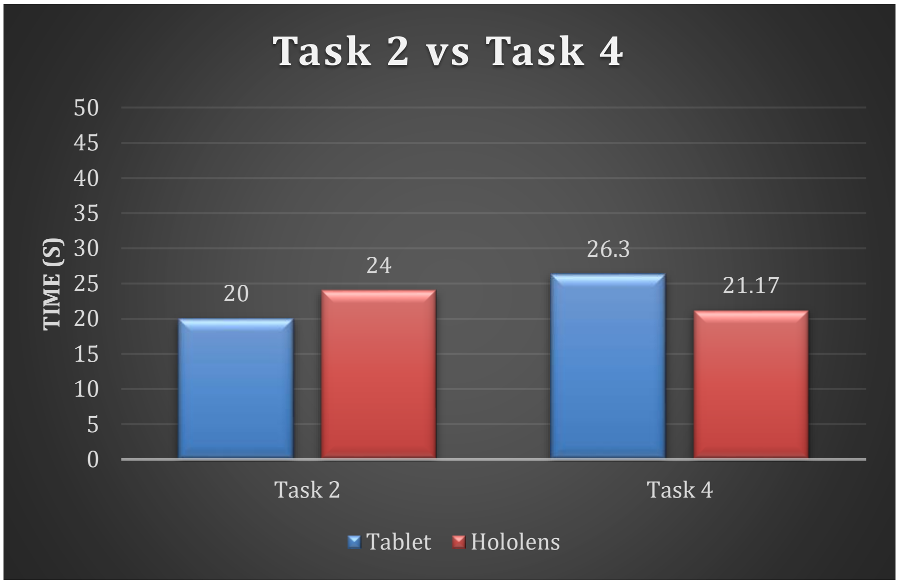

Figure 10. *Comparison of time required for task 2 and task 4*

Tablet showed better results for assembly with animation and performed worse for assembly without animation. For step 2 animation was used as instruction while only parts position as shown in step 4. The animation should be instinctively easier to interpret, but in this case, whereas in step 4 the part D can be easily placed and aligned to the cover bottom and the drone, if the drone, bottom holder, and control unit are placed correctly. Therefore, step 4 is consequently less complex to operators which explains the duration assembly in the result section.

One remark should be made here. The presented information about these four tasks should be used carefully. This is since it was more difficult to note time for every single operation in comparison to the time for the whole sequence. There is a risk that data can be unprecise.

Qualitative data

Some comments about animation were received:

"The second way of instructing (meaning scenario 1b) *was requiring extra focus. Moving sequence preferred".*

"It was difficult to understand that the drone must be flipped…I did not see animation".

"It would be could to have arrows that point".

"If possible – continuously repeat the task".

“Asymmetrical parts were difficult to orient”.

“The propellers did not need that many instruction steps”.

On the tasks where the animation was not included several participants needed to go back to confirm that they did not miss anything or that the alignment was correct.

One point should be noticed about product complexity. Several times when animation was included for simple operations, the instructions were ignored. It sometimes resulted in dropped or missed parts.

4.3.2 Scenario 2

Mainly qualitative data was collected for scenario 2. Participants made comments:

“It went well, especially when it was only one item and I could remember it and implement.”

“Smooth with clear colors.”

4.3.3 Scenario 3

Quantitative data

Expression 11 in the questionnaire was directed on scenario 3. This question had the highest rating for both Tablet and HoloLens in comparison to other questions. However, Tablet showed the highest possible result.

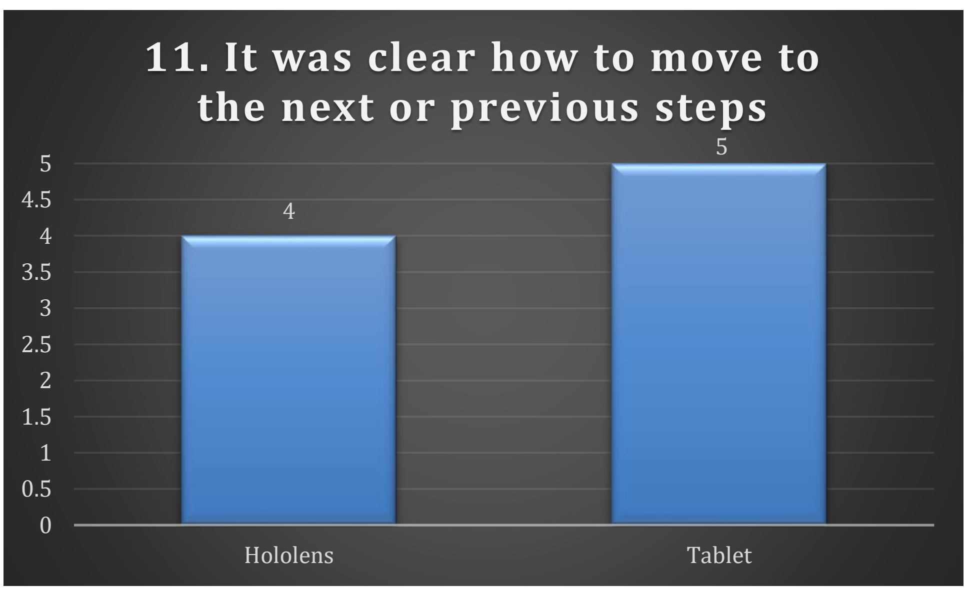

Figure 11. *Comparison of answer results for question 11 “It was clear how to move to the next or previous steps”*

Qualitative data

No comments were received on the touch function on the tablet. Voice command on the HoloLens caused the following reactions:

“Using voice to walk through the steps went smoothly”.

“Comfortable with the voice command”.

However, it should be mentioned that during the observations it was noticed that sometimes participants used the word “PREVIOUS” instead of “BACK”, which caused no reaction from the HoloLens.

4.3.4 General impression on interface design

Quantitative data

Questions 12 and 13 provided quantitative data on how good the impression of the interface design was. These questions ask about the same thing but in a different way to get as reliable results as possible. In both cases, the results were quite even. However, Tablet showed 10 to 17% better results.

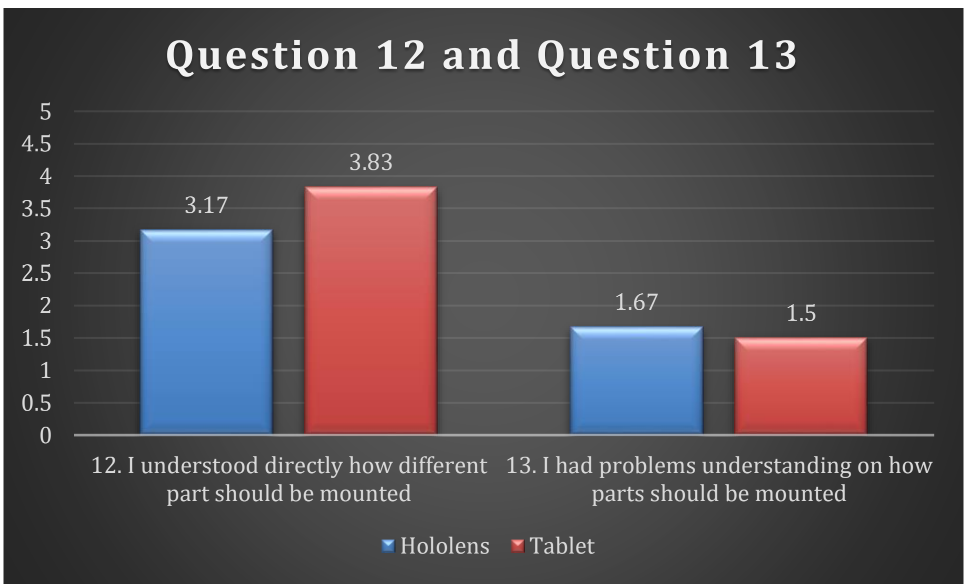

Figure 12. *Comparison of answer results for questions 12 and 13 for the general impression on interface design.*

Qualitative data

A lot of comments on the general impression on interface design were collected:

“It was way better than following some instructions from an instruction manual”.

“Hard to see overlaid graphics”.

“I would rather see the parts/instructions beside the view of the product”.

“With better calculation of position and better viewing angle, it will be perfect”.

4.4 Is feedback on the quality status needed?

Participants were asked direct questions on the necessity of quality assurance.

Quantitative data

The result showed that participants made fewer mistakes when using the tablet. Yet, the difference was not significant. People who used Hololens on average needed more confirmation on the correctness of assembly than people who received instructions on the tablet.

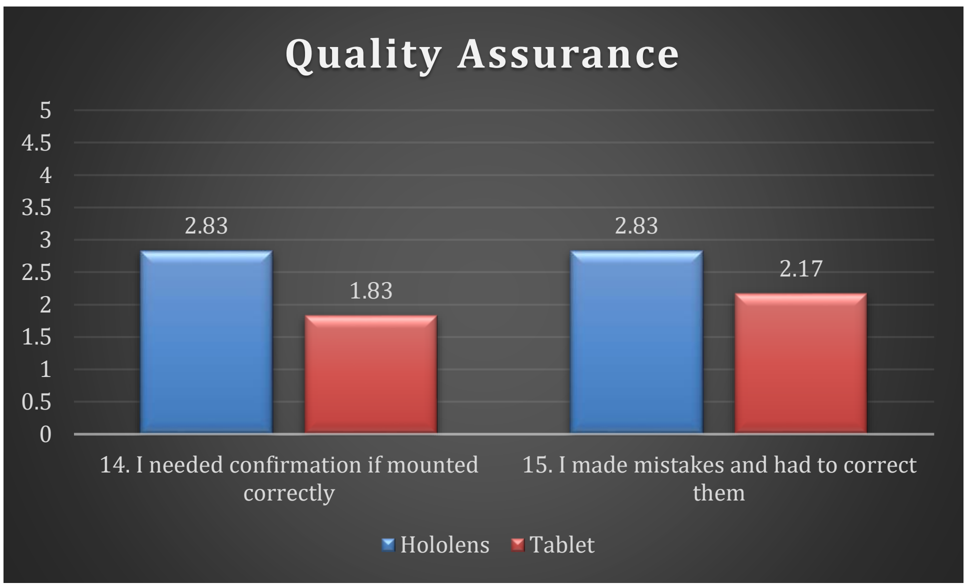

Figure 13. *Comparison of answer results for question about quality assurance.*

Many answers were very clearly pointing out the need for quality assurance. Participants mentioned that they made mistakes and that they needed help to avoid them otherwise.

Several answers suggested that although no mistakes were made, it still would simplify the assembly process if some kind of quality confirmation was present.

One participant gave answers contradicting to each other. He mentioned that he made mistakes and had to correct them. However, he did not think that he needed confirmation that a part was assembled in a correct way.

Qualitative data

Although the qualitative data shows average values on the need for quality assurance, observations show a different result. Almost every participant asked a question *“Is it correct?”* at least once during task performance. At some points, participants had to get back to the previous step in order to confirm if they did exactly the same action as was shown in the animation.

4.5 What are the main limitations of using HoloLens and Tablet?

To answer the question about limitations in using Hololens and tablet mainly qualitative data were collected. Below several comments that were made are demonstrated:

"Constraint position for tablet"

About the tablet: *"I think the unit should be more agile, but still not too small"*

"The tablet method seemed to be a little bit inconvenient"

"AR helmet felt uncomfortable, difficult with my glasses".

The last comment came several times in different variations since several participants wear glasses on an everyday basis.

4.6 Summary of results

An overview of quantitative data can be seen in the diagram below.

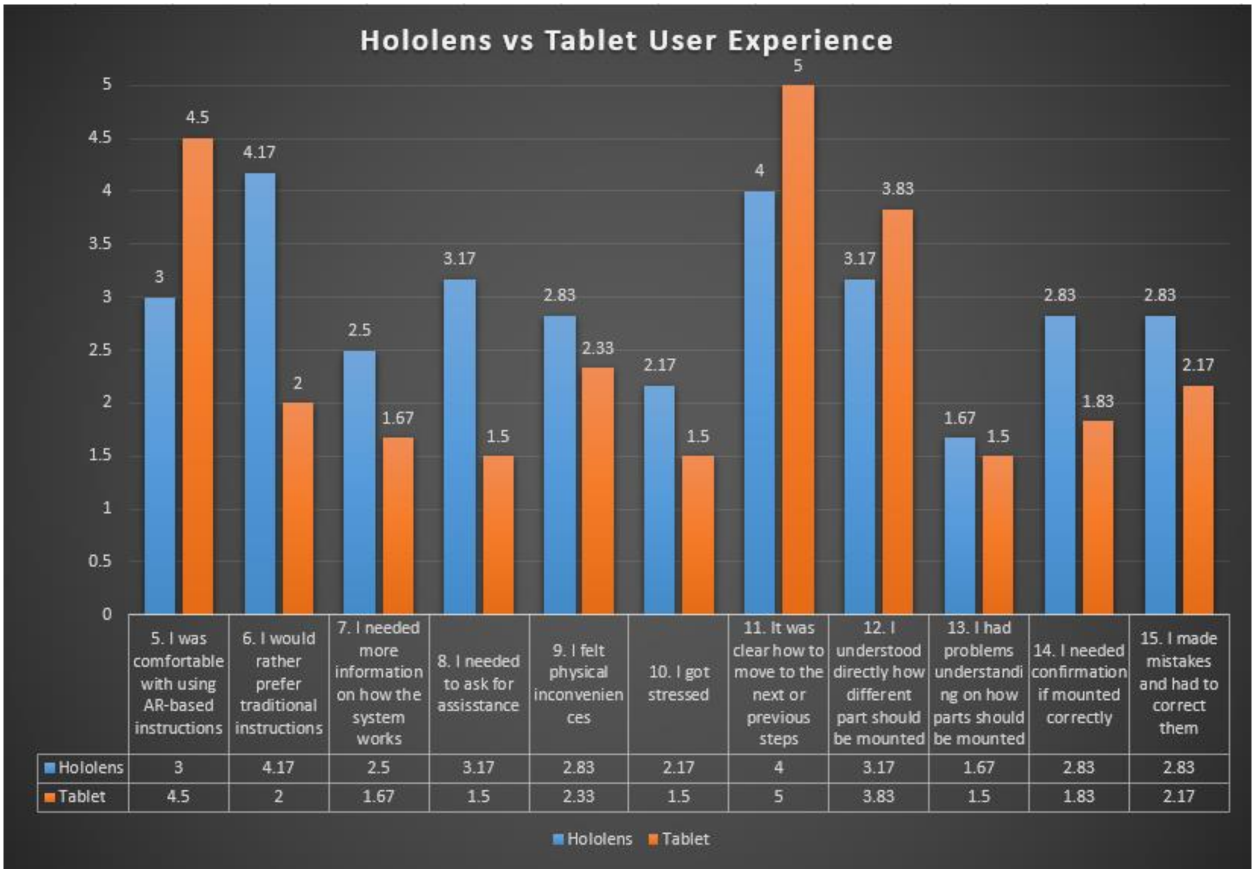

Figure 14. *Summary of the questionnaire results*

To summarize the results, several points can be mentioned:

- Participants were more comfortable with using AR-instructions provided on the tablet;
- Performance level was higher by participants who used tablet (both when it comes to completion time and mistake amount);
- Users accepted tablet technology much more than the Hololens;
- In both cases participants needed quality assurance;
- A lot of participants did not like to have the Hololens on due to such reasons as eyesight corrective glasses or very narrow viewing angle;
- Several participants suggested that the fixation position of the tablet was not smooth enough and needed to be reconsidered;
- All participants were very positive towards the scenario 1 when animations were included;
- No one made any comments or complains about scenario 2 where the parts were presented in front of the eyes;
- Both scenarios (scenario 3a and 3b) for moving back and forward were accepted by users;
- No text was expected or required by users. Moreover, as soon as language was needed (to say “NEXT” or “BACK”) confusion appeared;
- All participants understood fast how to use the system.

5. Discussion

During the thesis work focus was put on the following questions:

- How the application of different AR-devices influences the effectiveness of the assembly process?
- How should AR interaction design be modeled to increase the effectiveness of the assembly process?
- What can be the positive and negative sides of AR when using it in assembly support purposes?

All three questions are connected to each other and might help to clarify why the AR technology that has been investigated for several years still is limited to the main entertainment areas.

When the results of the experiment were compiled it turned out that Tablet showed the best results at every point. Some results varied slightly between two devices. For example, when it came to questions about interface design or physical inconvenience. Tablet's slightly better performance here can be explained by the fact that users could separate themselves from the AR interface when they felt for it. They did not have to have it in front of the eyes all the time and could decide when they apply it or not.

In general, results confirm the authors' hypothesis on AR-devices performance. Tablet was expected to achieve better results. **User acceptance** can be a reason for it. Mobile phones and tablets are part of modern everyday life. Almost every household has at least one smartphone with touch functions and satisfactory display quality. Most users know or can easily guess how to interact with phones/tablets even if a completely new device is in front of them. There is a great number of models and price categories on the market, while functions are still very similar. The HoloLens technology or similar on the contrary is not as available. Solutions presented on the market vary not only in price (still quite expensive in comparison to phones/tablets), but in the technological level as well (Kalantari, 2018). This fact makes the acquaintance between users and smart glasses technology more difficult. The application is limited to the entertainment area so far. In such situations, users often experience it as something very new and exciting and might even accept it in this case although it does not always work perfectly, causes **technical issues**. While in a work situation when a person can be stressed, influenced by time pressure and work responsibilities, imperfections in technology can give negative experience and lead to technology rejection. Physical inconveniences can only intensify the negative impressions. What should be mentioned here is that although the smart glasses' idea was investigated for more than ten years and a lot of technical issues are improve, the problem of physical inconvenience is still not solved. For example, the unit is still heavy and bulky, people who wear glasses in everyday life cannot use HoloLens for a long time, etc.

One of the factors that can influence user acceptance is the way the **interface** is designed. A similar interface was used for both Tablet and HoloLens. Authors used human knowledge about the physical world and surrounding environment to create "a reality-based interface" (Jacob, 2008). This is to simplify the user's understanding of each task. Scenario 1 that included animation on how every part should be handled showed better results and confirmed the hypothesis. In 2D it could be compared to structural and action diagrams. In a 3D presentation, the interface provided an experience close to reality where "naïve physics theme" (Jacob, 2008) was used showing how each part should be manipulated. In this case, the users did not have to put time and effort into comparing different states, they could just follow the instructions step by step. A remark regarding **quality assurance** should be made here. It was noticed that participants were more often uncertain about the correctness of assembly when animation was not included. The following conclusion can be made. The animation could give more trust and confidence and help to avoid mistakes by providing exact positions and ways to align parts to each other. However, it should not be unnecessary detailed or long, otherwise, the operation can be experienced as being too complicated. Another point to be mentioned here is the influence of **product complexity**. It turned out that if the animation was included for simple and self-evident operations, instructions were ignored. For example, four screws were picked at the same time, which resulted in missed or dropped parts, stress and lost time. A conclusion here can be that animations might be more suitable when some level of complexity is included.

Scenario 2 did not produce any reaction, which was interpreted as a positive sign. In the authors' opinion users did not make any remarks because this scenario seemed to be a standard situation that did not differ from something that was expected to happen. No participant had any problems with finding where the parts were, and which part should have been mounted next. The reason for it might be the application of "naïve physics" as well as "environmental awareness and skills theme" (Jacob, 2008). The real-world environment with parts around the fixture was reproduced in the virtual world and overlaid on physical parts. To attract the user's attention a part that was supposed to be assembled was marked with color. Possessing the knowledge that a part should be gripped and manipulated in some way to complete assembly, users reacted on the color marker as on the command to pick a particular part. After the assembly step demonstration, a unit disappeared which corresponded to users' expectations and their real-world experiences.

Scenario 3 was the only difference between the interface for Tablet and HoloLens. Touch function on arrows for tablet and voice command for HoloLens was used to move between different steps in the sequence. Since Tablet is considered to be a technology widely spread in everyday life, the authors assumed that it can be included in "an environmental awareness and skills theme" (Jacob, 2008). It is natural nowadays to touch an arrow on the screen to move to the next step. This is exactly the same way of information presentation that is used on almost every smartphone. As a result, the hypothesis that the touch function would feel natural was confirmed and received the highest possible score. For HoloLens that was more integrated with the body than the Tablet, it seemed to be more suitable to use gesture or voice command to move through the assembly sequence. In this case, the voice command was chosen as an interactive tool that served as a bridge between the real and virtual worlds. “Social awareness and skills” (Jacob, 2008) of participants could help to make axiomatic the fact that to move and to reach something one has to either physically migrate to another position or to communicate to get help. Moving to a different position was clearly not the way of solving the issue since both fixtures and parts were in front of the eyes. Voice command, on the contrary, was supposed to be experienced in an intuitive way. The results of the experiment showed that this way of interaction is a suitable one. However, the only confusion with voice command was caused by language when a wrong word was used. This is a factor that should be noticed because for every person it is more given to use the mother tongue even although the English language is widely spread all over the world.

6. Conclusion

The experiment illustrated that AR can be used as a helpful instruction tool during the assembly where all participants were able to fully assemble the drone. However, the need for this type of instruction can be limited to the first few products. It is quite common in an assembly line to do repetitive assembly operations of similar products. After the first few products, the operators would be accustomed to the assembly process and might find the instructions presented via HoloLens or Tablet more of an obstacle than a guide. However, AR can be quite suitable for a more complicated assembly process of products with multiple variants and components. There are also many features in Vuforia Studio that facilitate the connectivity of the process to external data. These features were not used in the experiment, but it could be implemented in the software to access external data provided by industrial servers. It would allow the assembly process to be connected to what is known as the Internet of Things, IoT. This would enable countless possibilities for software developers and manufacturers.

To summarize everything that was discussed above, an AR-based interface should be created similar to the real-world, support the user's experience and knowledge about the surrounding environment. In multilanguage organizations, language should be either avoided or included as a part of private knowledge about reality. A possibility to choose a language should be provided. Detailed AR instructions are more suitable for relatively complicated tasks. Clear animations can serve as a built-in quality tool and help to avoid mistakes. Some technologies are more accepted than others. In the authors' opinion, to smoothly introduce new technology in a process similar to the assembly process a user habit should be developed first. AR-based instruction introduction can be started with Tablet applications. To be introduced as a part of everyday work tasks technical issues should be solved or at least minimized. Users should not experience any physical inconveniences (this is concerned both HoloLens shape and weight, as well as positioning of the tablet at a working station) since they will be in touch with the technology at least eight hours per day.

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8. Appendix

Questionnaire

1. **Age**
2. **Sex**
3. **What AR device did you use?**

Hololens Tablet

4. Have you ever been in contact to AR technology? What type of contact was it?

Yes No Comment

To what extent do you agree with the following expressions:

5. I was comfortable with using AR-based instructions

1 - Not comfortable at all 2 3 4 5 - Very comfortable

6. I would rather prefer traditional instructions, for example, text or pictures.

1 - Yes 2 3 4 5 - I would rather prefer AR instructions

7. I needed more information on how the system works before you started carrying out tasks

1 - Yes 2 3 4 5 - Information was more than enough

8. I needed to ask for assistance during the assembly process

1 - Yes 2 3 4 5 - I was able to deal with it by myself and without any significant time losses

9. I felt physical inconveniences when using the AR instructions

1 - Yes 2 3 4 5 - I did not feel any inconveniences

10. I got stressed when I was carrying out assembly

1 - Yes, a lot 2 3 - Sometimes 4 5 - Not at all

11. It was clear to me how to move to the next step or to make a step back

1 - No, absolutely not 2 3 - Yes, but I had to think before 4 5 - Everything was very clear

12. I understood directly how every part should be mounted

1 - No 2 3 4 5 - Yes

13. I had problems understanding how every single part should be mounted

1 - Yes 2 3 4 5 - No

14. I needed confirmation that a part was mounted in a correct way

1 - Yes, every time 2 - Yes, often 3 - Sometimes 4 - Almost never 5 - No, I did not need any confirmation

15. I made mistakes and had to correct them by disassembling parts

1 - Yes, all the time 2 3 - Sometimes 4 5 - Never

16. Was there any task that went extremely smoothly in comparison with others? In your opinion why?

17. Was there any task that went extremely unsmoothly in comparison with others? In your opinion why?

18. Is there anything you would like to change? Remove? Add?

19. Do you have any further comments, ideas, thoughts about AR technology you want to share?