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AUGMENTED REALITY FOR EFFICIENT MANAGEMENT OF GAS INFRASTRUCTURE

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Using Microsoft's HoloLens to support gas infrastructure management related tasks at N.V. Nederlandse Gasunie

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ABSTRACT

Recent developments in Augmented Reality (AR) and Virtual Reality (VR) technology result in the fact that these techniques are on the verge of wide range adoption in industrial companies. AR and VR allow companies to improve their workflows by applying these techniques to support complex tasks. In the context of gas infrastructure management, huge amounts of data are stored and many complex operations are needed to ensure continuous gas transport. This thesis focuses on the suitability of AR and VR in the context of gas management related tasks. The research question formulated is:

> How can we use AR/VR technology provided by the HoloLens to efficiently and effectively support the types of tasks mentioned in the context of gas infrastructure management?

First, an extensive requirements elicitation process is performed in order to find processes that could benefit from the application of one of the aforementioned techniques. Afterwards, an AR application that visually supports mechanics in gas combustion boiler reparation is developed using the HoloLens platform.

The results of the application are promising, although we noticed during development that creating an efficient HoloLens application is far from trivial. Therefore, a usability study was performed during the development phase. In this study, several User Interfaces and interaction techniques were designed and compared with each other. The goal of this user study was to find best practices in HoloLens application design.

Some of these practices were found, although a more extensive user study could be performed to gain more insights in HoloLens application design.

Any sufficiently advanced technology is equivalent to magic

— Arthur C. Clarke

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It has been great fun for me to perform this research and develop an application for such an amazing device. I hope you enjoy your reading just as much,

Bram Musters
Groningen, March 2017

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ACRONYMS

AR	Augmented Reality
AV	Augmented Virtuality
BIM	Building Information Modeling
CAD	Computer Aided Design
DoF	Degrees of Freedom
FOV	Field of view
GGV	Gaze, Gesture and Voice
HUD	Head-Up display
KLIC	Kabels en Leidingen Informatiecentrum
MR	Mixed Reality
PIMS	Pipeline Integrity Management System
PoI	Point of Interest
P&ID	Piping and Instrumentation Diagram
SDK	Software Development Kit
SIFT	Scale-invariant Feature Transform
UC	Use Case
UI	User Interface
VR	Virtual Reality

1 INTRODUCTION

Gasunie[1] is a European company that manages gas infrastructure and transport throughout the Netherlands and Germany. Roughly 12000 kilometers of pipeline, thousands of corresponding assets, and plants throughout the countries are currently being maintained and supervised. As a result, huge amounts of data are available about the state of pipelines, plants and assets. Also, new pipeline networks are continuously being designed and constructed and old constructions are being dismantled.

Gasunie consists of many different departments that each have their own tasks and duties. For example, Operation departments take care of building, maintaining, rebuilding and dismantling pipeline networks, plants, and assets. In these departments, many workers perform physical work in the field to guarantee continuous transport. Workers in Operation departments need training to be able to perform the needed tasks.

The IT department maintains the data that is being generated by the other departments. Inside the IT department, the geo-spatial IT department handles all geographically referenced data. The geo-spatial IT department is the stakeholder in this project, but research is not limited to only this department. Gasunie performs a wide range of tasks both at the office and in the field.

In an attempt to improve their workflows, Gasunie is working on a digital transition. In order to save money on the management of their assets, visualization techniques can be applied to make management more efficient. Recent developments in Augmented Reality (AR) could provide a great opportunity in showing visualizations while working in the field. Furthermore, recent developments in Virtual Reality (VR) could also greatly improve the workflow of several processes. However, since the fields are quite new, research has to be done if the usage of AR and VR can indeed help the management process. During this research, the advantages and disadvantages of AR and VR are being discussed.

An example AR application for Gasunie is the prevention of pipeline damages during excavation. Excavation close to pipelines might result in damaged pipelines. Therefore, AR might help in visualizing the locations of pipelines beneath the surface, reducing the risk of pipeline damages.

AR and VR are fields that are starting to emerge from research applications towards industries. Recent hardware developments made the technologies much more affordable for widespread use in companies. In specific, Gasunie sees a great opportunity in using Microsoft's HoloLens[2]. The HoloLens is an AR/VR device that is able to project 3D models in the real world. It is one of the first 3D AR devices developed for widespread commercial use. The research question treated in this thesis is:

> How can we use AR/VR technology provided by the HoloLens to efficiently and effectively support the types of tasks mentioned in the context of gas infrastructure management?

In order to answer this question, a clear description of AR and VR and their applications is given in Chapter 2. Furthermore, the technical possibilities of the HoloLens device are presented along with some applications developed so far.

Since AR/VR are relatively new techniques, it was not clear to Gasunie where application of these techniques could be beneficial. Requirements elicitation, presented in Chapter 3, is an important part in this thesis that tries to find suitable applications. During this process, different Gasunie departments were visited and employees were interviewed to have a clear understanding of common processes happening at Gasunie. Using these interviews, suitability scores of AR and VR applications are given to the analyzed processes.

After requirements elicitation, providing visual assistance to mechanics is selected as a suitable HoloLens application on which the remainder of this thesis will be focused. Chapter 4 presents an overview of the requirements needed for this Use Case (UC). Furthermore, design and technical challenges are described that are present in this type of application.

The conclusion of Chapter 4 is that 3D application design is hard and no best practices exist yet. Therefore, Chapter 5 describes the road towards a well designed and easy to use application. This is an important process because adoption of a new technology relies heavily on the ease of use and usability of applications developed for this technology.

Finally, Chapter 7 concludes this thesis by answering the research question described above. Furthermore, the limitations of the work presented in this thesis are described and future work is suggested.

2 BACKGROUND

This Chapter gives an overview into the field of Mixed Reality (MR). First, the key aspects and differences of MR types are briefly explained in Section 2.1. Then, for each reality type, practical applications are presented to get a better feeling of typical applications in industries. Finally, an analysis of the HoloLens and its current applications is given in Section 2.2 so we have an idea of what the current version of the HoloLens is capable of.

2.1 MIXED REALITY

It is important for the remainder of this thesis to have a clear definition of realities. There are several sub-types of MR that can be distinguished, Milgram[3] proposed a widely accepted taxonomy that defines the differences between the terms using strict definitions of real and virtual aspects. One of the main aspects used is called the virtuality continuum, see Figure 1, that describes the different classes of objects present in a particular display.

On the far left is the real environment, consisting only of real objects, and on the far right is the virtual environment, consisting only of virtual objects. Virtual Reality (VR) is placed on the far right, it immerses the user completely in a simulated environment with only virtual objects. Augmented Virtuality (AV) is similar to VR because the user is immersed in a virtual world, but in AV real video is augmented in this virtual world. Finally, Augmented Reality (AR) is the term in which a real environment is augmented by virtual objects. AR makes it possible to interact with real objects, while preserving the advantage of being able to show virtual information. MR is where virtual and real objects are presented in a single display, anywhere between the far right and far left of the continuum in Figure 1.

Figure 1: Virtuality continuum[3]

2.1.1 *Real environment*

Only real objects exist in the real environment. Real objects are objects that have an actual objective existence[3]. Video displays are considered real objects, since they have an actual existence.

Virtual objects are objects that exist in essence, but not formally. A virtual object is therefore always simulated and needs to have an existence model to be viewed.

2.1.2 *Virtual Reality*

Since the user is completely emerged in a virtual world in VR, simulation and training for emergency situations are the most common applications of VR in businesses. The general goal of these trainings is to increase productivity and safety. In the virtual world, it is possible to simulate emergencies that are rare in occurrence or would cost a lot of money to simulate in the real world.

In VR, two types of displays exist[3]. Completely graphic display environments are those that have displays attached to all walls, the user is able to walk in this environment. An example of such an environment is the CAVE[4], an implementation of the CAVE is seen in Figure 2. The other display type is an immersive Head Mounted Display. They are becoming cheap to manufacture and are starting to get adopted widely.

Figure 2: Molecule viewed in a CAVE

Source: http://www.rug.nl/society-business/centre-for-information-technology/research/hpcv/faciliteiten/realitycube

Many types of VR interaction techniques exist[5]. External devices like controllers or smartphones are mostly used, but hand tracking is also a common approach. The preferred interaction technique highly depends on the type of application that is needed.

A review[6] compares different VR training studies in the field of surgical training. Surgical training is a perfect example for VR training, since one can imagine what would happen with a patient when a surgery goes wrong due to insufficient training. The conclusion of the review is that VR training seems to decrease operating time and improve performance of trainees with limited experience compared with traditional training methods.

Gasunie is also researching the possibility to simulate emergency situations in VR. A report[7] describing the implementation costs and requirements of VR plant failure simulations is available. The conclusion of this report is that 3D simulation is very costly and that the benefits in their applications are not clear.

However, a more recent survey[8] in the manufacturing and product design industry shows many examples that are actually being used in companies to improve decision making. Reasons for this wide range adoption are the recent advances in technology and software support. Furthermore, the technology became a lot cheaper in the last years, which is an important aspect for wide range adoption in companies.

2.1.3 *Augmented Virtuality*

Since AV is similar to VR, similar applications are suitable as well. Recall that in AV, the user is completely immersed in a virtual world, but has real world data augmented on top of this virtual world.

An example application[9] shows an accident simulator for the training of field operators. The field operator is immersed in a virtual representation of a real plant. Live sensor data from the plant are taken and augmented on top of this virtual representation. The combination of real-world data and virtual data improves the user experience.

2.1.4 *Augmented Reality*

The big advantage of AR compared with VR and AV is that the user is able to see the real environment. This allows for many applications that are not possible in an immersive virtual environment.

In AR, different display types exist as well[3]. Head Mounted Displays with a see-through capability are the most common devices. The second display type is also head mounted, but captures the environment using video and displays that recording to the user. AR interaction techniques are similar to VR interaction techniques[5].

In 1990, one of the first applications of AR in the industry was made for the Boeing company called "the wire bundle assembly project"[10] (Figure 3). Wire bundle assembly was a time consuming, and thus costly, process. The goal of applying AR techniques was to reduce the cost of this process. By providing visual information on top of a physical board, the wire assembly process became more time efficient. Now, AR has been applied to many business fields ranging from the automotive and aerospace industry to tourism[11].

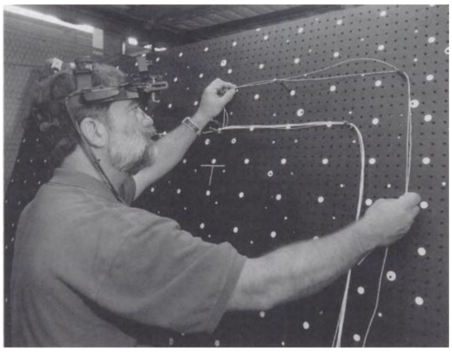


Figure 3: AR wire bundle assembly[10]

In the automotive and aerospace industry, Regenbrecht et al.[12] describe general applications of AR with specific examples. General applications are: servicing and maintenance, design and development, production support, and training. The most common goals are: improving efficiency, reducing complexity and increase of accuracy.

Also, the authors provide useful advice for anyone who wants to apply AR in industries[12]. Firstly, they state that the early consideration of real-world data is crucial for succeeding the project. Also, the integration of many parties at the company is considered good practice to increase chance of success. Finally, it is important to start simple and test with few people, and expand the accepted solution.

Another field where AR is applied is in science learning, Cheng and Tsai[13] give an overview of what is done and suggest further research. Cheng and Tsai[13] make an important distinction between image-based AR and location-based AR. Image-based AR augments relevant information based on surrounding features, while location-based AR augments information based on the user's location. They state that location-based AR is mostly used for inquiry-based activities. While image-base AR is mostly useful for learning concepts like spatial ability, practical skills and conceptual learning.

Location-based AR has been described in several papers. Geiger et al.[14] created an AR engine that uses the user's location to query Point of Interest (PoI) from a database. For example famous buildings are in this PoI database. The combination of location and orientation data provides enough information for the application to augment the corresponding information on top of a PoI. The general question asked is: "Can we draw PoI information on a mobile camera view corresponding to the real-world environment?". The goal of this application is to increase ease-of use, the user does not have to know the name of a PoI in order to get the relevant information.

AR in the gas industry has been applied already as well. Schall et al.[15] developed a mobile AR device that is able to visualize underground infrastructure using GPS information and rendering techniques. Here the central question is: "Are we able to provide users with 'X-ray' vision to show pipelines and cables under the ground?". Zhang et al.[16] developed a similar application using more recent technologies.

Wang et al.[17] illustrates several applications of AR in Building Information Modeling (BIM). The central question is "whether AR can be effectively used together with BIM to improve the way relevant information is accessed, resulting in improved productivity"[17].

Gasunie GOS[18], developed by Beyond Reality, is a mobile app that uses a 2D technical drawing of a gas receiver station as a marker to project the corresponding 3D model on top of it through the device's display. The user is also able to interact with the 3D model to get a virtual walk-through. Currently, this app is only a Proof of Concept that is able to show one gas receiver station as an example. An image giving an impression of this app can be seen in Figure 4.

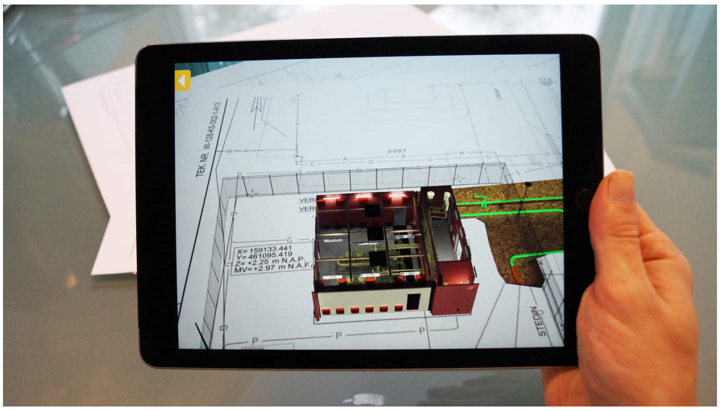


Figure 4: GOS AR app[18]

Another mobile app developed by Beyond Reality[19] uses a similar approach. The app uses image recognition techniques to detect different kinds of letters that are present on a poster. This poster is present at the excavation site. When the user points his device towards a certain letter from the poster, a video is shown with more information. By providing more information to the excavation workers, the hope is that the amount of excavation damages decreases.

In conclusion, the general task of AR applications is to augment visual information on top of the real world in order to provide guidance on processes. Goals of these tasks are, reducing complexity, reducing errors, increasing ease of use and increasing accuracy.

2.2 HOLOLENS

Gasunie is currently researching the suitability of AR applications in their company and processes. The Microsoft HoloLens is one of the first MR devices that tries to bring AR towards the industry for widespread use. Therefore, Gasunie would like to know whether they should adopt the HoloLens in their business processes. Before requirements elicitation, it is important to know the technical possibilities of the device, which are described in Section 2.2.1. Finally, Section 2.2.2 presents related work to get a better feeling of what kind of applications are being developed.

2.2.1 *Technical overview*

The technical overview is divided in three sections: Output modalities, which define what is presented to the user. Input modalities, which define how input gets to the device. Finally, limitations describes the current technical limitations of the HoloLens.

2.2.1.1 *Output modalities*

The HoloLens (Figure 5) is a pair of MR glasses that is able to project 3D holograms on top of the real physical world. It is a stand-alone wearable computer device, meaning that no external computer is needed for computations. As described in Section 2.1, MR is the generic term for AR and VR. This means that it is possible to create both AR and VR applications with the HoloLens. VR applications are created by rendering visualizations all over the device's display.

Figure 5: HoloLens

Source: https://www.microsoft.com/microsoft-hololens

Holograms have the same properties as real objects, with the difference that holograms are entirely made of light. Like real objects, they appear life-like and can move.

The second output modality is called spatial sound. The two speakers above each ear (the red part in Figure 5) allow the user to hear sounds coming from all directions around the user.

2.2.1.2 *Input modalities*

Since holograms are virtual, they can easily be moved, changed or removed using Gaze, Gesture and Voice (GGV) manipulations. GGV are the three types of user input modalities.

Gaze (in Microsoft terms) means that at all times, the user's head position and orientation is tracked, but not the user's eyes. Gaze can be seen as a vector pointing straight ahead from directly between the user's eyes[20]. In the middle of the screen, a cursor along this vector is rendered that acts similar to a mouse cursor.

Gestures are tracked with the user's hands. In standard applications, three types of gestures are implemented[21]. The air tap is a simple gesture that acts as a mouse click, the position where the air tap is done does not matter. When an air tap is registered, a ray is cast from the user's head along the user's gaze towards the cursor. The second gesture is called a navigation gesture, which is basically an air swipe gesture. It is performed by air tapping, and moving the hand along the X or Y direction while keeping the air tap state. Finally, the manipulation gesture tracks absolute movement in 3 dimensions.

Microsoft recommends to use only the presented gestures to keep input techniques simple and similar across applications. In their applications, only one handed gestures are supported, although it is technically possible to track two hands. One handed gestures have 4 Degrees of Freedom (DoF); a single finger per hand is tracked in the x, y, z positions, and the state of the finger is tracked (pressed/released). It is technically possible to have 8 DoF since the HoloLens is able to track both hands of the user. To increase the DoF in possible gestures, one can attach a Leap Motion[22] that allows for tracking of up to ten fingers.

Finally, Microsoft Cortana[23] allows for voice recognition. Developers can define voice commands that trigger certain methods. Several microphones are directed towards the user's mouth to improve recognition stability.

Another input modality needed for life-like placement of holograms inside the real world, is a digital 3D representation of the real world. HoloLens continuously scans the environment using depth cameras to compute the representation, called spatial mapping. Using RGB cameras, the user's position in the spatial mapping is then calculated. Because cameras are used, sufficient amount of environmental light is needed.

A spatial mapping example of a real world environment can be seen in Figure 6. The white sphere corresponds to the user's position, which is also the scene's camera. When the user moves his head, the scene's camera is moved along. This has the nice effect that when a user wants to see a hologram from a different angle, it naturally moves his head which results in the camera being rotated the same way. Because the user's position is tracked in 3D, along with the 3D rotation, viewing the scene has 6 DoF.

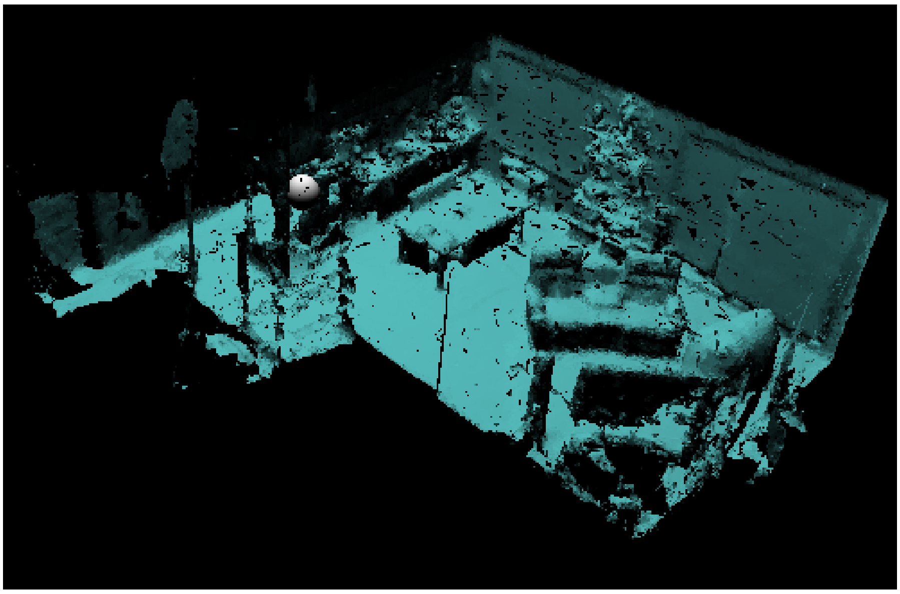


Figure 6: Spatial mapping used for hologram positioning. The blue surface represents the real world as computed by the HoloLens.

Hologram placement errors can be observed when the spatial mapping is not accurate due to a very dynamic environment or difficult light conditions. It is impossible to place holograms relative to real objects when spatial mapping fails completely due to insufficient environmental light. Therefore, the HoloLens will not be fully functional without spatial mapping and is only able to project a regular 2D screen in front of the user.

2.2.1.3 *Limitations*

The HoloLens is able to remember environments it scanned in the past, removing the need to do the same spatial mapping computations multiple times. However, when an unknown environment is entered, internet access is needed to compute the spatial mapping. It is not stated why internet acces is needed, and it is also not clear whether the networking requirement will be removed in the future. This is a practical problem for Gasunie, since many stations in the field do not have WiFi available, and the current version of HoloLens does not have its own mobile router. A workaround for this issue is to create a WiFi hotspot with a smartphone.

Another problem for applications in the field, with the current HoloLens, is that devices should have an explosion-proof certificate (ATEX) to be allowed in locations processing gas. Currently, the HoloLens is not ATEX-proof, and no plans to do so are announced yet.

Cheng[13] describes a distinction between location-based AR and image-based AR. The HoloLens falls in the latter category because of the lack of GPS location tracking and the use of spatial mapping. An example of location-based AR is Google Street View, which uses GPS locations to display augmented information to the user. Clearly, both types of AR serve different kinds of use cases.

The rendering area of the HoloLens, called Field of view (FOV), is roughly $30° \times 17.5°$. Figure 7 gives an impression of the FOV in practice, any holograms placed outside of the bright rectangle are not directly visible to the user. The depth scanning area, used for spatial mapping, is $120° \times 120°$ and scans anything between 0.8 and 3.1 meters. A benchmark[24] shows that roughly 80.000 triangles is the limit for rendering at 60 frames per second. After 80.000 triangles, frame-rate drops which can result in nausea.

Figure 7: HoloLens FOV visualized. The bright rectangle represents the area in which holograms are rendered.

Source: http://doc-ok.org/?p=1274

2.2.2 *Related work*

Scientific work related to the HoloLens is scarce due to its short existence. Hockett and Ingleby[25] describe in their manuscript several use cases of the HoloLens. One of them is particularly interesting, the visualization of architectural models. The biggest advantage they mention is the fact that the models can be visualized at real-life scale, this gives a true impression of size that is impossible to reach with a traditional display. Navigating through the model by walking through it is another advantage of projecting visualizations in the real world.

Chen et al.[26] developed a plug-in for Skype on HoloLens that allows for remote annotation in HoloLens's 3D spatial mapping. The advantage of this method is that only one person has to wear the HoloLens, the other user(s), called companions in the paper, can see the HoloLens users view. The companion is able to annotate the scene in 2D, the application computes the transformation to the HoloLens space and shows it to the HoloLens user in 3D. This plug-in is useful in many applications, like remote visual guidance of maintenance by experts at the office.

2.2.2.1 *HoloLens applications*

Applications in businesses are starting to emerge as well. For example, German elevator company ThyssenKrupp has started to apply the HoloLens in elevator maintenance[27]. As soon as a technician receives a call of an elevator malfunctioning, he is able to project visualizations of the specific elevator on his desk. A still of the video showing their application can be seen in Figure 8. As soon as the technician arrives on site, he is able to make a Skype call – using the application developed by Chen et al.[26]– to get remote visual assistance, while working hands-free. Early reports state that maintenance time is drastically reduced, by a factor four. Similar approaches could be used in pipeline or gas station maintenance.

Figure 8: Elevator visualization at the office

Source: still from video [27]

Another promising demo application is developed by Object Theory, an American company focusing entirely on HoloLens business applications. Their application[28] makes it possible to view 3D models as holograms in collaboration with other people who do not have to be in the same room. The remote collaborators are presented as avatars and their gazes are shown as well, making it convenient to understand where other people are looking at while they are explaining parts of a model. A still of the application can be seen in Figure 9. An article written by Pot[29] describes the user experiences with this application, the writer and costumer are positive towards this new technology.

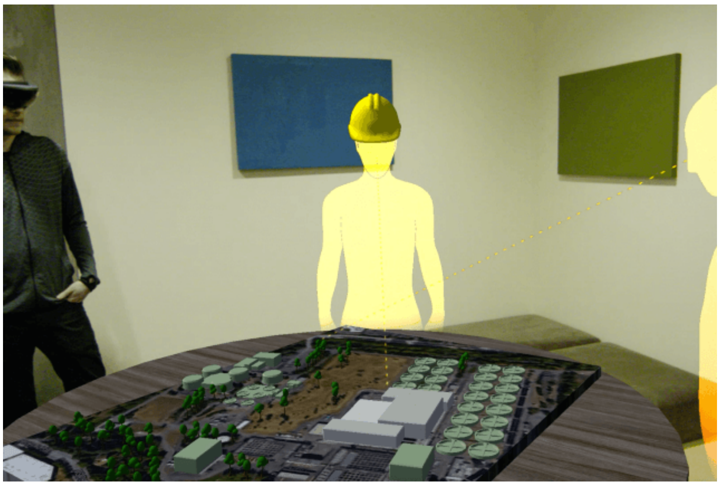


Figure 9: Collaboration in model design[29]

Trimble, a company creating innovative software for the design, build and maintenance of buildings wrote a paper[30] about the advantages of MR in their company. The biggest advantage they mention is the fact that there is no more need to visualize 3D models on 2D displays. Trimble released the first commercial app available for HoloLens, called SketchUp viewer[1], that allows for true 3D visualizations of SketchUp models.

Milgram[3] defined the Extent of World Knowledge, seen in Figure 10, that describes the amount of knowledge a system has about its surrounding environment. HoloLens falls in the middle-left Where/What category, spatial mapping only results in where objects are, as can be seen in Figure 6. Ideally speaking, a combination of Where and What is needed to be able to overlay virtual information relevant to the real objects.

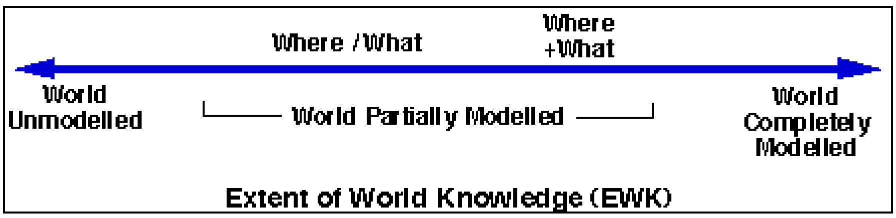


Figure 10: Extent of World Knowledge

The restriction of all HoloLens applications so far is that they do not make use of the environment's context, they fall in the Where cat-

1 www.microsoft.com/store/p/sketchup-viewer/9nblggh4338q

egory. Currently, applications only use the borders between air and objects, but they do not identify what the objects are to overlay relevant information.

2.3 CONCLUSION

In this Chapter we have seen that VR applications are now being adopted in companies due to better and cheaper technology[8]. In Section 2.1.4, we have also seen that many research AR applications were developed and build upon. Section 2.2.2.1 shows that now, with the introduction of the HoloLens, businesses are starting to adopt AR as well. Therefore, we decide to further investigate the suitability of AR applications in Gasunie using the HoloLens.

3 REQUIREMENTS ELICITATION

As explained in Chapter 1, the main aim of this thesis is to investigate the support of tasks in the context of Gasunie by using AR/VR techniques. In Chapter 2, we have reviewed such techniques, and concluded that the HoloLens offers a good platform for supporting a wide range of applications, in which our envisaged tasks also fall. However, to proceed with a realization of an actual tool, we need a specification of the tasks it will support.

The current Chapter focuses precisely on this goal. We start top-down by defining a methodology to find and describe such tasks, based on the knowledge and interests currently present at Gasunie. Section 3.1 presents this methodology, which is based on collecting and refining user stories. Section 3.2–3.14 then presents a number of so-called Use Cases (UCs), which are all potentially interesting for the user group and also fit well in the perceived capability range of the HoloLens. Section 3.15 summarizes the knowledge gathered from the creation and analysis of the aforementioned UCs, and concludes this Chapter.

3.1 ANALYSIS METHOD

UCs, which are user stories plus additional information distilled from them, were gathered by interviewing Gasunie employees from different departments. Employees working at the office and at gas stations were visited and asked what kind of work they do on a daily basis. During these interviews, user stories were selected that are potentially useful for the application of the HoloLens. In these user stories, the user is the employee who was interviewed. From these user stories, additional questions were asked to gather relevant information like the data needed for application of AR. Once all relevant information was gathered from the employee, other components like technical contributions needed to realize such an application were determined.

In order to create a good comparison, the different UCs were analyzed using a systematic approach. The components presented in this analysis are described below:

USER STORY describes the current process happening from the user's view.

HOLOLENS describes the added value of using a HoloLens to support the current process. Mostly, added value is noticeable most by the user. However, also on higher levels added value might be observable. An example of added value is the reduction of time needed to perform a user story. This is noticed directly by the user, but is also beneficial on management levels since it saves money in the long run.

DATA describes the data that needs to be available to the HoloLens in order to support the UC effectively. This can be any type of data, ranging from 3D models to time-series data.

FUNCTIONAL REQUIREMENTS describe the general functional requirements of the UC that the HoloLens needs to be able to cover.

NON-FUNCTIONAL REQUIREMENTS describe the general non-functional requirements of the UC that the HoloLens needs to be able to cover. Some non-functional requirements are applicable to all UCs, like internet access, sufficient amount of light, and the use of at least one HoloLens device.

ACCURACY describes how much hologram placement accuracy is needed for the application to be successful.

TECH CONTRIBUTIONS describe the technologies needed to support the UC with the HoloLens. An example of such a technology is computer vision, where the HoloLens has to know what kind of objects are present at certain locations.

SUITABILITY VALUE is the suitability of various display technologies (VR, AR, classical computer display) for the respective UC. For each device, the suitability is quantified on a scale of 1..5, where 1 is worst and 5 is best. This allows one to gauge whether the use of VR/AR is perceived as the technique of choice to be used for the respective UC. Note that these scores are mostly an estimate based on the previously described components and do not have any scientific basis.

3.2 ANNOTATIONS ON DESIGNS OF GAS RECEIVER STATIONS

USER STORY Gasunie receives several PDFs of 3D Computer Aided Design (CAD) models of a gas station that will be built. Gasunie annotates and comments the PDF on parts they want to be changed. Sometimes, the comments are not enough and Gasunie makes a call to the designer for additional feedback. Gasunie sends the PDF back to the designing company. The designing company incorporates the changes, and sends new PDFs of the s3D CAD model to Gasunie.

HOLOLENS The HoloLens could be of added value in the fact that the CAD model does not need to be converted to PDF anymore in order to be able to annotate the CAD, saving time and increasing ease of use. Another advantage is the fact that the model can be seen in true 3D, allowing for different insights to be seen then through converted 2D drawings, this can reduce the amount of errors made. This application is also of added value for the designing company, since it will receive an annotated CAD file instead of a PDF.

DATA Querying of data is currently done by downloading the 3D models from attachments in the received e-mail. In the near future, Gasunie expects to have a database consisting of those 3D models. Then, these models can be queried on demand from the database. The 3D models should be divided into sub-parts in order to be able to select and annotate parts of the model.

FUNCTIONAL REQUIREMENTS The application has to visualize the received CADs using HoloLens. It should be possible to annotate and make textual or vocal comments on (parts of) the CADs. The vocal comments should be connected to the selected part of the model and stored accordingly. It should be possible to show only parts of the CADs. It should be possible to move, rotate and scale the CADs for different types of insight. It should be possible to visualize multiple CADs at the same time.

NON-FUNCTIONAL REQUIREMENTS The model can have a maximum amount of triangles to be able to render the CAD smoothly with HoloLens. A Gasunie employee who makes comments on designed CAD models needs to wear a HoloLens. This UC will happen indoor, and sufficient amount of space is needed for the visualization. It would be beneficial if the CAD is projected on the building site in actual size. Interactions with the CADs happens using GGV input. The final output file should be presentable on non-HoloLens devices.

ACCURACY Having exact accuracy between the real-world and virtual objects is not of capital importance. For example, if the model is project just above a table, there is no problem in workflow. However, it has to be researched what the projection accuracy is, since it can be of importance to show models in real-scale.

TECH CONTRIBUTIONS Some kind of annotation functionality is needed to be able to make comments on certain parts of the CAD. Also, a data model has to be designed to store the comments on particular parts of the CADs. Voice recording is needed to record vocal comments.

SUITABILITY VALUE: Display 3, AR 3, VR 3. This application can be developed with all types of devices, currently there is an ongoing project at Gasunie that tries to improve this process by using a traditional display.

3.3 COLLABORATIVE VOICE ANNOTATIONS ON DESIGNS OF GAS RECEIVER STATIONS

This UC is an extension to UC 3.2. With the following additions:

HOLOLENS Because multiple users are wearing the HoloLens and seeing the same visualizations, chance of error is further decreased.

FUNCTIONAL REQUIREMENTS All users should see the exact same visualizations. The sum of all annotations should be stored in a single output file.

NON-FUNCTIONAL REQUIREMENTS Multiple users wearing the HoloLens are needed.

TECH CONTRIBUTIONS Networking between multiple HoloLenses is needed to be able to see the same model and annotations.

SUITABILITY VALUE: Display 2, AR 4, VR 3. This application has a favor to be applied in AR, because multiple people are involved.

3.4 LIVE COLLABORATIVE ANNOTATIONS ON DESIGNS OF GAS RECEIVER STATIONS

This UC is an extension to UC 3.3. With the following additions:

USER STORY While the designing company is designing the new gas station, a Gasunie employee is observing and making comments in real-time.

HOLOLENS Because the designer and Gasunie employee are working together, comments are made in real-time which should further reduce the time needed for the UC to finish.

DATA CAD data has to be sent continuously to the HoloLens so it is able to render changes made in the CAD software in real-time.

FUNCTIONAL REQUIREMENTS It should be possible to see the CAD model while it is being designed in real-time through the HoloLens. The designer should be able to see the CAD model annotations on his PC screen in real-time.

NON-FUNCTIONAL REQUIREMENTS The designer should be working on a CAD model design while a Gasunie employee is looking through the HoloLens to comment on new changes.

TECH CONTRIBUTIONS A real-time data sharing connection between a CAD designing application and the HoloLens is needed. This will take a lot of time to build.

SUITABILITY VALUE: Display 2, AR 4, VR 3. This application has a favor to be applied in AR, because multiple people are involved.

3.5 PIPELINE EXCAVATION PREPARATION AT THE OFFICE

USER STORY Inside inspection a process where sensors are sent through pipelines to measure pipeline quality. Using a combination of inspection data and pipeline data, calculations are made where defects in the pipeline exist. The locations of these defects are used to create Kabels en Leidingen Informatiecentrum (KLIC)[31] alerts in order to request pipeline, cable and geographical object location data surrounding the defects. By combining all data sources, the field workers can get a 3D insight into the complexity of the excavation location before starting. Currently, the field workers can only use a top-down view of the excavation location.

HOLOLENS The HoloLens can provide true 3D visualizations of pipeline data, along with the location and other details of the defect, allowing for better insights. Also, the field workers might be able to spot the defect more quickly during excavation and gain insight in the tools needed for repairing the defect.

DATA Gasunie pipeline data has to be visualized in relation to earth surface data. Example pipeline data is, amongst others, the pipeline's location, depth, diameter or gas pressure. Also, the location of the defect, calculated from the inspection data, has to be visualized. Both data is available and shown in the application Pipeline Integrity Management System (PIMS). KLIC data will be used to visualize geographical objects and cable location data of different companies. Other types of data offered by KLIC also has to be visualized. The data will be queried from several sources and large amounts of data will be received. 3D models of geographical objects are needed to represent the data.

FUNCTIONAL REQUIREMENTS A geographical location centered around the defect has to be selected that forms the base of the visualization. The application must be able to visualize the locations of pipelines in 3D, along with data corresponding to these pipelines. Furthermore, the location and size of the defect has to be shown on top of the rendered pipeline. More details about the gas state can be shown as well. Geographical objects have to be visualized according to their location relative to the defect.

The model should have different scaling options. The user is able to select which layers he wants to see.

NON-FUNCTIONAL REQUIREMENTS The application should have interaction to zoom in on parts of the pipeline network. All visualized objects that have some form of data connected to it should be selectable to show the extra data with some visualization technique. All data sources should be rendered in separate layers.

TECH CONTRIBUTIONS Connections to different data sources are needed. Geographical locations have to be converted to model space locations.

SUITABILITY VALUE: Display 4, AR 3, VR 3. Since this application will not make use of the environment and complex 3D insights are not present, the application of AR/VR is not of added value.

3.6 PIPELINE EXCAVATION PREPARATION AT THE EXCAVATION LOCATION

This UC is a variation of UC 3.5, with the following differences:

USER STORY The field workers use the information from UC 3.5 to estimate where underground topographical objects near the excavation are located. By combining all data sources, the field workers can get an insight into the complexity of the excavation location before starting.

HOLOLENS The HoloLens can visualize the location of underground objects using a combination of location tracking and the angle of the device. This gives a simulation of X-ray vision that allows for the field workers to get an insight into the pipeline network structure and defect beneath the surface. Furthermore it can show historical data about the excavation location, for example KLIC alerts that happened before.

DATA Gasunie pipeline data has to be visualized in relation to the location and angle of the HoloLens. Also, the data of the defect, calculated from the inspection data, has to be visualized. Both data is available and shown in the application PIMS. GPS location data and gyroscope data is needed to know the position of the user and the angle he is looking at. 3D models of geographical objects are needed for rendering. KLIC data will be used to visualize geographical objects and cable location data of different companies. Other types of data offered by KLIC also have to be visualized. The data will be queried from several sources and large amounts of data will be received. 3D models of geographical objects are needed to represent the data.

FUNCTIONAL REQUIREMENTS The application must be able to visualize the locations of pipelines under the ground in 3D along with data corresponding to these pipelines, relative to the user's location. Furthermore, the location and size of the defect has to be shown on top of the rendered pipeline. Geographical objects received from KLIC alerts have to be visualized at the correct location as well. By selecting geographical objects, more data should be shown. The user is able to select which layers he wants to see.

NON-FUNCTIONAL REQUIREMENTS The application should have interaction to select parts of the pipeline network. The location of the visualizations should correspond to the real locations of the geographical objects. The user has to wear a HoloLens and needs to be at the excavation location.

TECH CONTRIBUTIONS A connection with a location tracker and gyroscope has to be established to provide location information to the HoloLens. Connections to different data sources are needed. Geographical locations have to be converted to model space locations.

SUITABILITY VALUE: Display 2, AR 4, VR 1. This application is highly suitable for AR because of the connection with the environment. However, with the current limitations of the HoloLens, it is not a suitable choice for implementation in this thesis.

3.7 INSIDE INSPECTION DATA VISUALIZATION

USER STORY Observed damages found in inspection data are often very small and hard to observe with the naked eye because of dirt on the pipelines. Using a traditional application, this data is visualized and handed to the field worker. The field worker has to estimate where exactly the defects on the pipeline are, and perform measurements at these locations to get the exact size of the damaged area.

HOLOLENS The HoloLens could visualize the small errors using the same techniques as the current inspection software is doing. However, the HoloLens can project this visualization on top of the pipeline to provide visual assistance in the field. This way, the field worker does not have to translate the position from a visualization to the real world, increasing accuracy.

DATA Some form of pipeline data is needed for the application to know which part of the pipeline it is looking at. Inspection data visualizations have to be projected on top of the pipeline, at the location of the damages.

FUNCTIONAL REQUIREMENTS The visualization has to be projected at the exact real-world location using object recognition to be valuable to the user.

NON-FUNCTIONAL REQUIREMENTS The user has to see the pipeline from close range. The user has to wear a hard hat and comply to other safety measures because he is at an excavation location.

ACCURACY Near-exact accuracy between real-world objects and virtual objects is of capital importance. This accuracy is currently not reachable with the HoloLens. Current accuracy of computer vision is tested in Section 5.1.1.

TECH CONTRIBUTIONS Some form of computer vision is needed to determine where the visualizations have to be projected.

SUITABILITY VALUE: Display 1, AR 4, VR 1. This application is highly suitable for AR, but the accuracy is not enough, and HoloLens is optimized for visualizing 3D data. Therefore this UC is not feasible with the current version of HoloLens.

3.8 MECHANIC TRAINING

USER STORY Mechanics receive training in order to gain knowledge on how to do maintenance work at gas stations. They learn the specific parts that are present at the stations, and how to work with them. Lectures are given and at the end a test has to be passed. This UC covers many areas, in the sense that training happens on many different aspects in gas management.

HOLOLENS The HoloLens could be used for interactive training by displaying visual simulations on top of real objects, allowing for better insights for the trainee. A study[32] measured the assembly time and quality at Boeing using three different methods; a traditional desktop, manual book instructions, and AR. Participants did not do the assembly process before, AR turned out to be the fastest and most reliable method. Similar studies[33, 34] confirm these results in different settings. Although maintenance training is different than assembly training, they both consist of similar tasks.

DATA Animated 3D models are needed to visualize on top of the real world components. A 3D model of the component to be trained on has to be available.

FUNCTIONAL REQUIREMENTS The animated model has to be shown on top of the real world object so the trainee can see what he has to do with the actual object in sight. A training scenario should be separated into multiple smaller steps. The physical tools needed for the scenario have to be shown. A part of the object has to be highlighted to give visual feedback on which part he has to work next. The system has to give feedback to the trainee to tell whether he did the step correct.

NON-FUNCTIONAL REQUIREMENTS A physical component is needed for the setup of the training.

ACCURACY Accuracy in the order of centimeters is enough to be of added value.

TECH CONTRIBUTIONS Animated 3D models have to be created. Registration algorithms, such as provided by computer vision are needed to show animations at the correct place. Furthermore, the registration algorithm has to understand when the trainee did something wrong so it is able to provide feedback.

SUITABILITY VALUE: Display 2, AR 4, VR 3. AR is the best type of application here because of the connection with the real world.

3.9 REMOTE ASSISTANCE

USER STORY A Gasunie mechanic is trying to repair a problem at a gas station, but he does not know how to do it exactly. He calls a specialist located at the office who provides support to fix the problem.

HOLOLENS The HoloLens could be of added value in the fact that the specialist at the office is able to see the same as the mechanic in the field sees. Also, the specialist is able to annotate the scene, making it more easy for the mechanic on sight to follow the instructions.

DATA No additional data is needed for this application.

NON-FUNCTIONAL REQUIREMENTS The mechanic needs to wear a HoloLens. This is a safety issue since the mechanic also needs to wear a construction helmet and safety glasses. Furthermore, in some cases all devices need to be explosion-proof.

ACCURACY Accuracy between real and virtual objects, annotations in this case, has to be in the order of centimeters to provide helpful visual feedback to the mechanic.

TECH CONTRIBUTIONS Almost none, Skype for HoloLens[26] already exists that provide this functionality.

SUITABILITY VALUE: Display 2, AR 4, VR 1. This application is favored in AR because the mechanic has his hands free while calling. The most useful case is when this UC is added into other applications like UC 3.10.

3.10 INSPECTIONS OF GAS INFRASTRUCTURE ASSETS

USER STORY A mechanic is performing maintenance inspections at a gas station. He needs information from certain parts of the station in order to check whether everything is still functioning like it should. This UC is very broad since maintenance inspections can cover any type of asset that Gasunie runs. Examples are gate valves, pipelines and boilers.

HOLOLENS The HoloLens could project the necessary data next to the object that needs to be checked, improving ease of use and reducing time needed. This data can have time values as well, so data over time can be visualized using interactive techniques, which is impossible with static physical documents. In the case of actions to be performed, they can be animated through HoloLens.

DATA Data regarding specific parts at a gas station needs to be visualized. Example data is: last replacement date, manuals, gas state data. This data has to be queried on demand from a database.

FUNCTIONAL REQUIREMENTS Visualization techniques have to be applied on the data to provide more insight. The final rendering has to be shown next to the real-world object. Some form of computer vision has to be implemented to understand which real-world object the user is looking at.

NON-FUNCTIONAL REQUIREMENTS The mechanic has to stand in front of a real-world object that is present in the database. The mechanic needs to wear a HoloLens, this is a safety issue with some inspections since the mechanic also needs to wear a construction helmet and safety glasses, and can only bring explosion-proof devices. Different visualization techniques have to be applied for different types of data.

ACCURACY Accuracy in the order of centimeters is enough, since the virtual objects only indicate the state of a machine as guidance.

TECH CONTRIBUTIONS Computer vision has to be implemented in order to recognize the correct real-word objects and their locations. A connection to a database is needed to query the right data at the right time.

SUITABILITY VALUE: Display 3, AR 4, VR 1. A head-mounted AR display has favor here since the mechanic is able to work hands-free while seeing additional information about the environment.

3.11 LIVE VISUALIZATIONS OF GAS STATIONS

USER STORY The user want to have an overview of the current state of a gas station. He checks several databases for states of components.

HOLOLENS The HoloLens is able to bring together several data sources to give an overview of the current state of a gas station in true 3D, increasing ease-of-use.

DATA The gas station consists of a static part and a dynamic part. The static part corresponds to asset data; the position and serial numbers of pipelines and other physical components in the gas station. The dynamic part consists of sensor data, maintenance data and other types of data that change through time. The 3D models of the components in the gas station have to be rendered. Dynamic data has to be rendered on top of corresponding static data.

FUNCTIONAL REQUIREMENTS Different types of 3D visualization techniques have to be chosen for different types of data. The data layers should be rendered separately so that the user can specify which layers he wants to see.

NON-FUNCTIONAL REQUIREMENTS Sufficient amount of space is needed for the projection to be of use.

ACCURACY Accuracy between real-world and virtual objects is not crucial, since a complete virtual visualization is made.

TECH CONTRIBUTIONS Several database connections are needed to bring together the different data sources. Multiple visualization techniques are needed for different types of data.

SUITABILITY VALUE: Display 3, AR 3, VR 3. Since this application is a data visualization, the application of AR/VR has no added value.

3.12 CONTROL VALVE SCHEME VISUALIZATION

USER STORY A field worker receives a call and gets told he has to open and close some specific control valves in a particular scheme. The field worker goes to the specific control valve station and sees only a series of manhole covers. By experience he knows in which manhole covers the specific control valves are. He opens the manhole covers and opens and closes the specific control valves.

HOLOLENS The HoloLens is able to provide visual assistance by projecting the underground pipelines and their states at their locations. Visualizing gas flow of surrounding pipelines decreases chance of errors. Providing visual feedback increases ease-of-use.

DATA The control valve scheme has to be projected in 3D, 3D models of some schemes exist. The control valves that have to be opened and closed should be highlighted on top of the scheme. Furthermore, additional data (like maintenance data) of the control valve scheme and their components can be projected on top of this scheme.

FUNCTIONAL REQUIREMENTS A specific control valve scheme has to be selected from a list. The model of the control valve scheme has to be projected at the location of the real world scheme. Different types of 3D visualization techniques have to be chosen for different types of data.

NON-FUNCTIONAL REQUIREMENTS The field worker has to be at the control valve scheme location in order to see the underground pipeline projections.

ACCURACY Accuracy in the order of centimeters is enough to get useful help with finding the correct control valve.

TECH CONTRIBUTIONS GPS location tracking is needed to project the pipelines under the ground. Another option is to use object recognition to project the pipelines and control valves according to the manhole cover locations.

SUITABILITY VALUE: Display 2, AR 4, VR 1. AR is the best method of application because the real world environment is involved. However, since the HoloLens lacks location tracking, this UC is not suitable for this thesis.

3.13 CONTROL VALVE SCHEME SIMULATION

USER STORY A dispatcher needs to know which control valves to open in order to get gas to a specific location. He uses a Piping and Instrumentation Diagram (P&ID) to control the gate valves, by training and experience he knows the meaning of those diagrams.

HOLOLENS The HoloLens is able to provide visual assistance by simulating the opening and closing of control valves to see what happens with gas flow, this should decrease chance of errors. Providing a 3D visualization of the P&ID makes it more easy for the dispatcher to know what the gas infrastructure network looks like in real life, increasing his understanding.

DATA The control valve scheme has to be projected in 3D, 3D models of some schemes exist. Calculations are needed to do the actual simulation. Additional data (like maintenance data) of the control valve scheme and their components can be projected on top of this scheme.

FUNCTIONAL REQUIREMENTS Control valves can be opened and closed. P&IDs have to be converted to 3D models. Simulation calculations are needed to generate the data for visualization. Different types of 3D visualization techniques have to be chosen for different types of data.

NON-FUNCTIONAL REQUIREMENTS The dispatcher can be in any suitable room, but using this application in the control room seems most reasonable.

ACCURACY Since this visualization does not make use of surrounding objects, accuracy is not important.

TECH CONTRIBUTIONS Simulation calculations are needed. Visualization techniques are needed to show the gas flow. The control valve scheme has to be split in several parts so it can control the simulation.

SUITABILITY VALUE: Display 3, AR 3, VR 2. This is an application that can run equally well on a traditional display, since no relation with the environment exists and 3D is not of capital importance.

3.14 SIMULATION OF COMPONENT MALFUNCTIONING

USER STORY Operational managers want to know what happens when a certain component in the gas infrastructure fails. Usually they see a schematic visualization in order to understand what happens inside. The operational manager has to make an imagination of what such a failure looks like in real-life.

HOLOLENS Visualizing the components through HoloLens allows for more insight in the failure, without the need for imagination. Especially for new employees this is an important issue, since it is harder for them to do the imagination.

DATA The component has to exist as a 3D CAD model. Failure data visualizations are needed to be rendered on top of the 3D CAD model.

FUNCTIONAL REQUIREMENTS It must be possible to see the component without failure. Extra data about the component has to be shown, for example temperature. The simulation must be an animation that shows how a component changes over time during the failure. Possible dangerous situations have to be shown.

NON-FUNCTIONAL REQUIREMENTS The operational manager can see this simulation in any suitable room.

ACCURACY High accuracy between real-world and virtual world is not needed, since the projection does not overlay information relevant to the direct environment.

TECH CONTRIBUTIONS Animated 3D models of the simulation has to be created.

SUITABILITY VALUE: Display 2, AR 3, VR 4. This application works best in VR because a simulation of a virtual object is made.

3.15 USE CASE OVERVIEW

Table 1: Use case overview

UC #	Display	AR	VR	Type of improvement
3.2	3	3	3	Time, accuracy, ease-of-use
3.3	2	4	3	Time, accuracy, ease-of-use
3.4	2	4	3	Time, accuracy, ease-of-use
3.5	4	3	3	Time, accuracy
3.6	2	4	1	Time, accuracy
3.7	1	4	1	Time, accuracy
3.8	2	4	3	Ease-of-use, accuracy
3.9	2	4	1	Time, accuracy, ease-of-use
3.10	3	4	1	Time, Ease-of-use
3.11	3	3	3	Ease-of-use
3.12	2	4	1	Accuracy, ease-of-use
3.13	3	3	2	Accuracy, ease-of-use
3.14	2	3	4	Ease-of-use

Table 1 gives an overview of the analyzed UCs. The second, third and fourth column relate to the suitability values presented in the individual UCs. The final column describes the type of improvement the application of a HoloLens could have.

In general, most discussed UCs are more valuable to support in AR than VR. This makes sense since in most UCs interaction with real world objects is needed.

Inspection data visualization(3.7) scores relatively best in AR applications as seen in Table 1. However, due to technical limitations this is not feasible to implement yet. The needed accuracy is not reachable now. Pipeline excavation preparation in the field(3.6) is another UC that scores high in AR suitability and low in the other two types, but due to the lack of GPS tracking it is not able to reach with the current version of the HoloLens. Control valve scheme visualization(3.12) has the same problem. Finally, remote assistance(3.9) is already possible by installing Skype.

Therefore, we conclude that the perfect UC for HoloLens support is not found yet. However, with advancing technologies, these UCs should be taken into account when looking at possibilities in the future. Because we do want to show the possibilities of AR in the industry, we decide to create an application on an adapted application context, which is described in Chapter 4.

4 CONCEPT

The conclusion of Chapter 3 is that the perfect application of HoloLens in the context of gas infrastructure management has not been found yet. Therefore, the application conceptualized in this Chapter will serve the goal of introducing AR with HoloLens in a more general sense to Gasunie and its employees. More specifically, a scenario on a gas combustion boiler is chosen because it serves as a recognizable example of possibilities in AR to all Gasunie employees. Mechanic inspection guidance(3.10) and mechanic training(3.8) are chosen as the basis of this application.

This Chapter presents an overview of the application's requirements and challenges. Because this application is a combination of two UCs, a compact overview using a similar fashion as described in Section 3.1 is given in Section 4.1. Section 4.2 – 4.4 present a more detailed description of the UC. Afterwards, application-specific problems are described in Section 4.5 – 4.7.

4.1 OVERVIEW

USER STORY A mechanic receives a call that a boiler at a gas station is malfunctioning. The mechanic arrives at the gas station, locates the boiler and determines the fault code. He grabs the textual manual, finds the correct fault code in the manual and reads the instructions. Afterwards, he carries out the instructions on the relevant parts. If he forgets one of the actions he has to carry out, he has to re-read the instructions.

HOLOLENS The HoloLens is able to visualize the instructions in 3D, making them more easily understandable. Furthermore, due to the 3D placements of the visualizations, the instructions can be augmented right on top of the relevant parts, which removes the need to search for them.

DATA 3D models of individual parts are needed to be able to render them as animations.

FUNCTIONAL REQUIREMENTS Textual instructions should be visualized using animations of 3D models. The system should be able to walk through the step-by-step instructions in a similar way as the textual manual. Computer vision is needed so the HoloLens is able to know where the boiler is located in the real world. Individual parts need to be located, so the instructions can be rendered at those specific locations.

NON-FUNCTIONAL REQUIREMENTS The mechanic has to wear a HoloLens and stand in front of a boiler. The goal is to support the mechanic in performing maintenance. Therefore, it is important to have an application that is simple to interact with.

ACCURACY Accuracy in the order of centimeters is enough, since the holograms only indicate the position of internal parts and how to interact with them.

TECH CONTRIBUTIONS Computer vision has to be implemented in order to recognize the correct real-word boiler and its location.

INTEREST VALUE: Display 2, AR 4, VR 1. A head-mounted AR display has favor here since the mechanic is able to work hands-free while seeing additional information about the environment.

4.2 SCOPE AND VISION

The scope of this application is a reparation scenario on a water boiler of type Remeha Quinta 65. This boiler is chosen because it is the most used type in Gasunie, roughly 1200 boilers of this type should be maintained. Ultimately, the user should be able to use this application on any boiler of this type. Gasunie maintains many boilers because they are used at gas receiver stations to increase the temperature of the gas where gas pressure drops.

Currently, reparation scenarios are textually described in a paper manual. This manual consists of step-by-step instructions, sometimes these instructions include images to provide the user extra guidance. Using a paper manual has two major disadvantages: First, it can be hard to understand the textual descriptions of instructions and parts, especially for inexperienced mechanics. Second, the user has to use his hands to check the manual at each step, meaning that his hands are not free to perform the actions. For experienced users this may not be the case, since they may remember (parts of) the instructions by heart.

The goal of this application is to remove the disadvantages by augmenting instructions on top of the real world. This should lead to less errors and a more pleasurable experience. A study done at the International Space Station[35] used a Head Mounted Display to display visual instructions during a maintenance procedure. The authors compared the AR method to textual based instructions and found that the amount of errors decreased. Also, the subjects found that the AR system reduced cognitive workload and was therefore preferred over textual instructions. However, maintenance time did not decrease due to limiting hardware and the possibility to watch videos.

4.3 REQUIREMENTS

As described earlier, we want to present textual instructions in a visual manner to the user. Therefore, we use 3D models to create animations of the instructions. Because we use a textual manual as basis, we want to have a similar structure in the application. Since we want to render objects on top of the real world, some form of computer vision is needed to automatically recognize the boiler. Section 4.6 describes the different approaches that can be used.

Users of this application will be Gasunie mechanics who are trained to maintain boilers. Therefore the same amount of detail will be used as described in the textual manual.

The main goal of the application should not be forgotten during requirements elicitation. Many requirements are nice features to have in general applications, but in this UC the main goal is to support the mechanic during maintenance. The cognitive load to use the application should be as low as possible, so the mechanic is focused on repairing the boiler and not on controlling the application. Therefore, the most important non-functional requirement is that it should easy to traverse through the scenario.

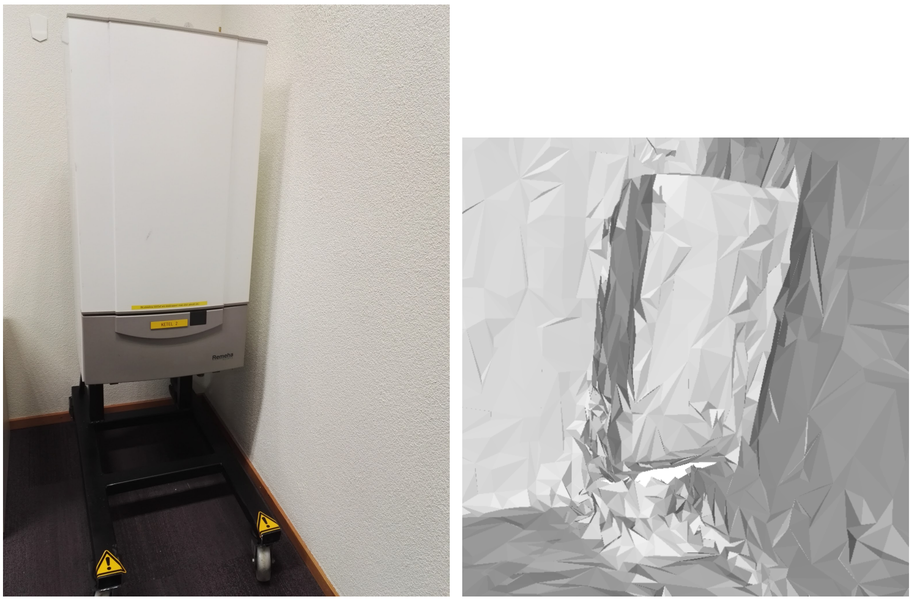
4.4 SCENARIO

The full scenario based on which we will further design our prototype is described in Appendix A, this scenario is chosen because it is the most common malfunctioning of this boiler. The textual manual consists of a step-by-step list with three different entry points, called A, B and C. Each of the entry points handles a different severity of the fault, where A is the most severe problem. When point A is observed, all steps have to be performed. When point B is observed, only steps after B have to be done. When point C is observed, only steps after C have to be done.

An environment is created to simulate this scenario, as can be seen in Figure 11a.

The general flow of the application is as follows:

1. A Gasunie mechanic wears the HoloLens in front of the boiler.
2. Using registration algorithms, the boiler is localized by the HoloLens.
3. The mechanic sees instructions of a specific task and performs that task on the boiler.
4. When the task is completed, the mechanic specifies the next step.
5. Step 3 and 4 are repeated until the scenario is finished.



(a) Simulation setup (b) Spatial Mapping

Figure 11: Simulation environment

4.5 DEVELOPMENT

HoloLens applications can be developed using either pure DirectX or using the Unity[36] gaming engine. Using Unity allows for high-level programming which makes it easy for developers to add new objects in the scene, or add functionality to them. Furthermore, the HoloToolkit for Unity[37] provides some basic HoloLens-specific functionality in Unity. Therefore, it is decided to develop the application using Unity.

In Unity, all entities are GameObjects. GameObjects can be visual objects in the scene, but can also hold managers that take care of functionality in the application. Functionality of GameObjects is added by attaching scripts written in C# to them. For example, when one wants to have a moving cube in the scene, a cube GameObject is created and a script that moves the cube over time is attached.

4.6 LOCALIZATION TECHNIQUES

Some form of computer vision is needed to be able to determine the 3D positions needed to project the instructions at the correct place. This is a challenging task, since the application is capturing the world in 3D, therefore the pose of the boiler has to be in 3D as well. To find the correct pose of the boiler, several approaches can be taken:

3D MESH REGISTRATION compares the spatial mapping mesh to the 3D mesh of the boiler.

IMAGE RECOGNITION uses 2D graphical images to determine the 3D pose of real world objects.

MARKER RECOGNITION uses markers to identify where a real object is located.

MANUAL RECOGNITION the user has to specify where the boiler is located.

Once the pose of the boiler is determined using one of the recognition techniques, the sensors inside the HoloLens will take care of tracking the boiler over time. The following sections describe the different recognition approaches in more detail.

4.6.1 *3D Mesh registration*

Since the spatial mapping and the boiler CAD are both triangular surface meshes, this approach is in theory the most accurate. The idea is that two surface meshes are laid on top of each other and the difference is calculated. Several algorithms that compare surface meshes exist [38, 39]. However, the problem with these algorithms is that they are designed to calculate the distance between two meshes that are very similar. An example of a pair of meshes suitable for these algorithms is a triangular mesh and its downscaled version. In this case, both meshes have the same origin and do not have any polygons unrelated to the actual object.

In our case, the spatial mapping is not only defined for the boiler, but also for surrounding unrelated objects. The simulation setup and its corresponding spatial mapping can be seen in Figure 11.

The spatial mapping result is a mesh which is not dense enough for registration. 45 seconds of scanning was needed to get to the result seen in Figure 11b. The boiler is reconstructed using roughly 2000 triangles, less scanning time results in an even more coarse spatial mapping, starting at roughly 100 triangles. The implemented point cloud surface reconstruction algorithm results in the fact that walls and other flat planes have fewer triangles than the more detailed regions. Unfortunately, the raw point cloud is not accessible for developers.

A recent study[40] published during the writing of this thesis works around this issue by attaching an external depth camera to the HoloLens. The resulting high resolution depth scan is sent in real-time to the HoloLens which makes it possible to do mesh registration.

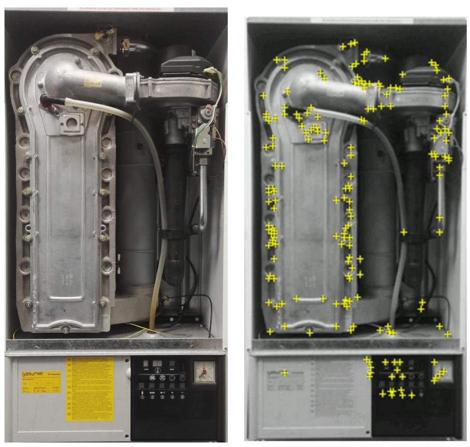
4.6.2 *Image recognition*

Image recognition works by using natural feature detection and tracking on image sequences from the video feed of the HoloLens. Important here is that the 3D projection is translated to the correct pose of an object, [41] describes such an approach using Scale-invariant Feature Transform (SIFT) feature tracking. A similar approach can be used in the HoloLens.

Vuforia[42] is a platform for creating AR applications that is able to recognize and track images in real-time. Vuforia is commercially licensed, but free to use in the development phase. Vuforia is currently the only computer vision Software Development Kit (SDK) with support for HoloLens.

A problem arising with image recognition is the fact that features are detected on edges and corners in areas with high local contrast. In Figure 11a, one can observe that the object has no clear edges and is mostly a big white surface. To tackle this issue, the front panel of the boiler is removed and then used as image target. This is not a problem for the end users of the application, since they have basic technical knowledge and can remove a front-panel without visual help.

An image of the boiler is cropped and used as image target, which can be seen in Figure 12a, the resulting features are shown in Figure 12b. The recognition results of using Figure 12a as image target



(a) Cropped image of boiler

(b) Boiler features [42]

Figure 12: Image target

can be seen in Figure 13, where the red plane represents the recognized pose of the boiler. The recognition is not completely accurate, but should be enough for guidance to the correct parts inside the boiler. The slight error exists partially because of the cropping of the image target, Figure 12a shows that the cropping is not completely at the edges of the boiler.

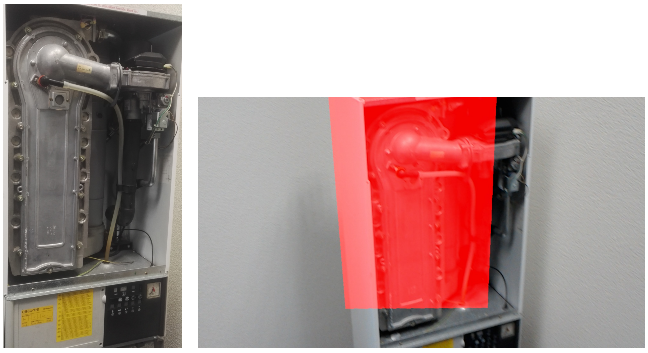
A disadvantage of this approach is that a 2D image target is used. The boiler itself is a 3D object with parts at different depths in it, meaning that the 2D representation will change from different viewing angles. Therefore, the boiler can only be recognized from roughly

(a) (b)

Figure 13: Boiler tracking using a 2D image target

straight viewing angles. In practice, this angle turns out to be roughly 30 degrees from both horizontal sides.

Adding multiple image targets from different viewing angles is a potential solution. Figure 14a shows an example image target with viewing angle. Because Vuforia only allows rectangular images as image targets, the boiler cannot be cropped correctly.



(a) (b)

Figure 14: Bad recognition by using an image target with viewing angle

Figure 14b shows the recognition results with Figure 14a as image target. The observed recognition error is a lot larger because of the incorrect cropping. The image target shown in Figure 14a is not usable in this context and therefore recognition from larger viewing angles is not implemented.

Another constraint with image recognition is the amount of light shining at the object. When the light conditions vary, recognition can be a problem[43]. For example shadows can add or remove image features that are not present in the target image. This problem is partially tackled by using multiple image targets with different lighting conditions, but still poses a problem in some cases. Therefore, a fallback mode is also present where the user can specify the location of the boiler manually using the approach described in Section 4.6.4. In the future, one can imagine that a flashlight will be attached to the device, however no plans to include this feature are announced yet.

Recognition of individual parts in the boiler is hard with image recognition. Some parts are too small, others are inside other parts and impossible to see with a camera. Therefore, recognition of individual parts is not implemented.

4.6.3 *Marker recognition*

Many AR applications use marker tracking to know where visualizations should be rendered. Since we prefer not to attach markers to all boilers, the image recognition approach is preferred. However, when image recognition does not perform well enough, marker recognition can be used. In some UCs, for example when an application is able to recognize different boilers which look similar, it might be beneficial to user markers as identifiers.

4.6.4 *Manual tracking*

Finally, manual tracking is always possible because it is performed by the user. However, it is most error prone, and also poses the most effort for the user. An approach to be able to perform manual tracking is rendering a cube with the same size as the boiler, and letting the user drag the cube so that it aligns with the boiler. Since this approach works in any circumstance, it is included in the application as a fallback mode.

4.7 USER INTERFACE DESIGN

Acceptance of a new technology is an important factor for this application to succeed in the company. Adoption of innovation depends on two crucial aspects: *perceived usefulness* and *perceived ease of use*[44]. In visualization, usefulness is better known as effectiveness, which measures whether the completion of one or more low-level tasks actually solve a high-level goal. Ease of use is better known as efficiency, which measures the effort needed for someone to complete a certain low-level task.

User Interface (UI) elements in this application can be divided in two main categories: elements controlling the state of the system and elements displaying visual instructions of the current state. The first category is an important aspect defining mostly the application's efficiency, research on this topic is presented in Section 4.7.1. The second category defines the system's effectiveness, related research is described in Section 4.7.2. Conclusions and guidelines from the described literature are used in the realization of the UI.

4.7.1 *System controls*

All elements controlling the state of the application are considered system controls. There are many aspects of system controls design that determine the efficiency and effectiveness of an application, a subdivision of these aspects is made to give a clear overview. System controls can be subdivided, amongst others, in four categories:

- UI presentation: How do I see the UI elements?
- UI placement: Where do I see the UI elements?
- UI interaction: How do I control the UI elements?
- UI activation: When do I see the UI elements?

These categories are described further below.

4.7.1.1 *UI presentation*

A workshop[45] defined the challenges of 3D interaction, and suggests to borrow design ideas from either the real world, 2D UI design or other disciplines. A rule of thumb they mention is that "one should never have to read a label to understand how to use an object, its affordances should convey this information". Iconography can be used to reach this goal, for example by using icons and colors to relate to other objects. It is also important to use general design guidelines[46], like consistency among UI elements.

Sound should be used as well, for example when pressing a button to substitute for the feel of pressing it[47]. Also, speech output can be used to confirm to the user that an action has taken place. It is important to be consistent in this sense as well.

4.7.1.2 *UI placement*

UI placement is an important aspect in 3D AR applications because virtual objects can be placed anywhere in the real world. The basic problem here is that system controls are generally a one- or two-dimensional task, while the user interacts in 3D[47].

Virtual object placement is subdivided in three different categories[48]:

DISPLAY-LOCKED CONTENT is locked on the device's display - like a Head-Up display (HUD) - and is discouraged by Microsoft because it tends to feel unnatural.

BODY-LOCKED CONTENT is similar to display-locked content. However, it places the content not on a fixed location of the display, but it follows the user's gaze, making it feel more natural.

WORLD-LOCKED CONTENT is located in a fixed position in the real world. This category is the most useful for designing AR content. The disadvantage is that this content can be hard to find by the user because it is placed somewhere in the real world where the user is not looking at.

It is suggested to use a natural spatial reference for placement of the interface[47]. The reference point of our application is the boiler that has to be repaired. We assume that while performing the needed tasks, the user always knows where the boiler is. Section 5.1 describes how the HoloLens localizes the boiler. Once the boiler is localized, the virtual content can be initiated around the boiler. Since the boiler is static, thus world-locked, the virtual content can be world-locked as well.

O'Connell[49] provides guidelines for designing 3D AR experiences, although he states that - because of its infancy - no best practices for 3D AR design exist yet. O'Connell states that it is crucial to understand the technical capabilities of the used device to create a good UI design. Constraint of the HoloLens, as mentioned in Section 2.2.1.3, is the limited FOV.

A snapshot of a quick test, where several planes are rendered around the localized boiler, can be seen in Figure 15. The red plane represents the localized boiler, while the green planes represent areas surrounding the boiler. Figure 15 shows that HoloLens's small FOV is a serious constraint for this specific application. The planes rendered above and below the boiler are not visible at all.

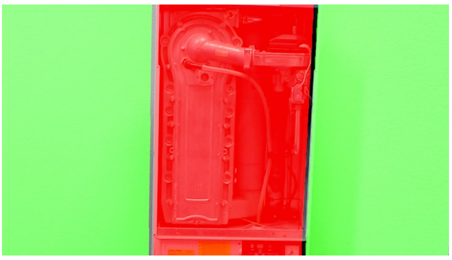


Figure 15: FOV in the simulation environment from a distance of approximately 2 meters

Any world-locked content rendered above or below the boiler can not be seen directly by the user from a distance up to approximately two meters without rotating his head. In practice this results in users not knowing virtual objects exist above or below the boiler, thus this behavior should be avoided. However, there is plenty of space on both sides of the boiler, therefore the virtual content should expand mostly horizontally around the boiler.

Another guideline[50] says to provide accurate representation of locations of graphics and text. With HoloLens this is an important consideration because of the limited FOV. Whenever objects are rendered outside the FOV, visual indicators need to be present to guide the user towards the correct position that needs attention.

4.7.1.3 *UI interaction*

UI interactions can be any type of Gaze, Gesture and Voice (GGV) input. Controlling the application by voice has the advantage that the user has his hands free during maintenance, but it comes with the cost that he needs to remember the commands as it is not always clear which commands can be used at what time. Another problem could be environmental noise, although voice commands work quite good in noisy environments due to multiple directional microphones being present.

Gestures can also be used to control the application, simple actions like next step and back can be implemented by recognizing gestures from left-to-right or right-to-left respectively. However, it is harder to define meaningful gestures when more options exist.

Combining voice commands with graphical buttons is an interesting option[51], design guidelines for such multimodal UIs exist[52]. The authors state that it is important to take advantage of each modality to reduce the user's cognitive load. For example, when a command is issued by voice, the confirmation should be done by speech.

4.7.1.4 *UI activation*

The question when to present UI elements to the user is an important one in AR, because the user has to interact with the real world and virtual world simultaneously. UI elements can be permanently visible, or can be triggered using similar interaction techniques as described above. For example, a hand gesture from left-to-right can be used to trigger a menu. This gesture is inspired by mobile phones, where a swipe from left-to-right to trigger a sidebar menu is widely used. Another example is a head movement gesture to create the metaphor of a user looking down at a keyboard to trigger a menu.

4.7.2 *Instructions design*

Well designed instructions form the basis of an effective application. UI elements describing instructions can be subdivided in two main categories: concrete and abstract elements[53]. Concrete elements are those that mimic real-world objects or motions, which are 3D models and animations. Abstract elements are elements that symbolically represent real-world properties, for example arrows pointing to positions.

The author performed a user study to evaluate the differences between concrete UI elements – called concrete AR – and abstract UI elements – called abstract AR – in assembly tasks[53]. Assembly tasks were divided in four sequential steps:

1. Part identification: identifying the correct part(s) for the current task.
2. Indication of part manipulation: understanding how to manipulate the identified part(s).
3. Tool identification: identifying which tool(s) to use.
4. Indication of tool usage: understanding how to use the identified tool(s).

The results of the study show that concrete AR instructions lead to faster assembly time and better user confidence. However, the study shows that in complex operations concrete AR is not interpreted the same by different users, which suggests that concrete AR alone is not optimal. In conclusion, the author recommends to use a combination of both concrete and abstract UI elements to leverage the strengths of both, although he mentions that this highly depends on the type of application[53].

The author extended his research to find out whether the decision between abstract- and concrete instructions should be based on the difficulty level of a task. Tasks were divided in two difficulty levels and the performance between abstract- and concrete instructions were compared. The hypothesis was that abstract instructions are more suitable for difficult tasks because abstract instructions are more easy to interpret. However, the conclusion is that this is not the case and that concrete instructions are preferred, even in tasks considered difficult[54].

Placement of instructions is another aspect that should be taken into account. Since the HoloLens is a Head Mounted Display that projects light directly in the users view, it is possible that placing instructions at the task location hinders the mechanics view.

4.7.3 *Conclusion*

There are many factors in 3D UI design that determine the effectiveness and efficiency of this application. However, as stated in several papers [45, 47, 49, 53], best practices do not exist yet. Therefore, the application's design must be carefully thought out from a user-centered approach. Chapter 5 presents such an approach where we try to find an optimal design. During design, the presented guidelines that do exist are taken into account.

5 DESIGN DECISIONS

The conclusion of Chapter 4 is that design paradigms for 3D AR like in traditional 2D applications do not exist. Therefore, the process of reaching a well designed application is presented in this Chapter. First, localization design and results are described in Section 5.1. Then the design of the UI related to showing instructions is described in Section 5.2. Because design paradigms are incomplete in this context, an extensive testing and evaluation process is done and presented in Section 5.3. Finally, the results of the design process are presented in Section 5.4.

5.1 LOCALIZATION

Image recognition, as described in Section 4.6.2 proves to be a suitable solution for recognition. Because image recognition is used, it is important for the user to know what the HoloLens camera sees. Therefore, a screen-locked green wireframe is used that is rendered in the middle of the screen to help the user. Figure 16 shows a snapshot of the localization phase. When the green borders align with the boiler, the HoloLens has an optimal view that maximizes recognition success rate.

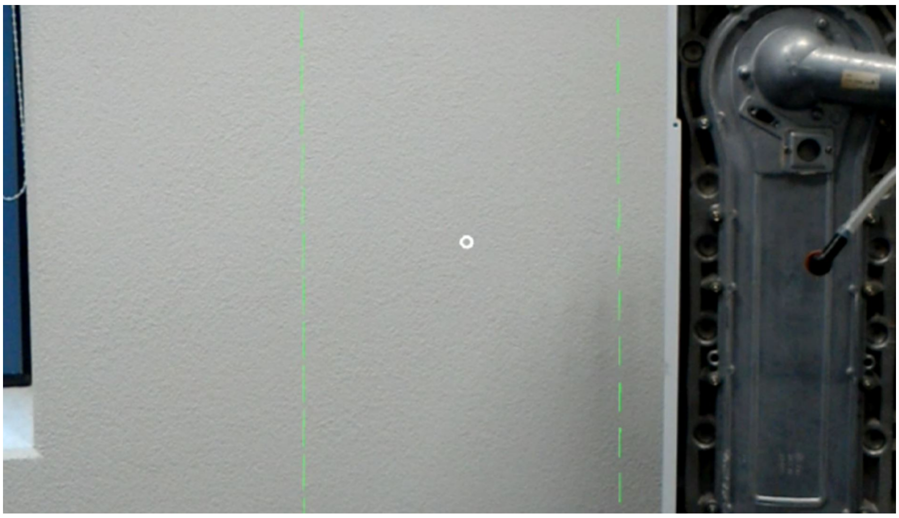


Figure 16: Visual guide for recognizing the image target

5.1.1 *Accuracy*

In order to verify localization accuracy, the boiler is recognized 10 times from different poses. The maximum found horizontal and vertical differences between tracked positions are respectively 1.8 cm and 4.7 cm. The maximal depth difference is much bigger, 18.9 cm, explained by the fact that a 2D image feed is analyzed. It must be noted that the differences are only big when recognition happens from extreme viewing angles. The localization algorithm has to determine the boiler's position by comparing the observed image feature locations to the original image features seen in Figure 12b. When recognition happens from a relatively extreme angle, the observed image features will be closer to each other. This is the same effect as observing the boiler from further away. Therefore, the algorithm finds that the boiler is farther from the camera when viewed from extreme angles than it really is.

On rare occasions, the boiler is recognized turned around, meaning that the y-axis rotation is incorrect by 180 degrees. This can happen when the image target features are symmetric, but this is not true in our case (Figure 12b). Therefore we can not explain this behavior, but suspect it is limitation in the Vuforia API.

We provide a workaround by calculating the absolute difference in y-axis rotation between the camera and the boiler, called Δy. In theory, the boiler's rotation should be fixed when $\Delta y > 180$. However, in practice the maximum recognition angle is roughly 30 degrees. To be on the safe side, we use a 40 degrees offset on both sides. Therefore, we check whether the condition $\Delta y > 120$ and $\Delta y < 320$ holds true. If so, we rotate the boiler 180 degrees around y. Finally, we make sure the rotation around x and z are set to 0 because we know the boiler is always mounted vertically.

5.1.2 *Axis alignment*

In HoloLens applications, the internal orientations of axes are determined during start-up. The vector pointing in front of the device is the z axis, while the vector pointing to the right is the x axis. The result is that the axis are oriented different in the real world when the device is not oriented exactly the same during start-up. In our application, this means that we need to determine the position of all elements relative to the image target's location and orientation. We use the local coordinate system of the boiler to make sure all elements are always placed at the same positions in the real world. In Unity, this is achieved by making sure all GameObjects are a child of the GameObject corresponding to the image target.

5.2 INSTRUCTION REGION

It is important for the mechanic that he is always able to see the instruction visualization, therefore a world-locked instruction region is rendered to the left of the boiler. Figure 17 shows a snapshot of the instruction region. Note that due to recording quality, the snapshot does not look very readable. However, in practice both text and animations are in much higher quality.

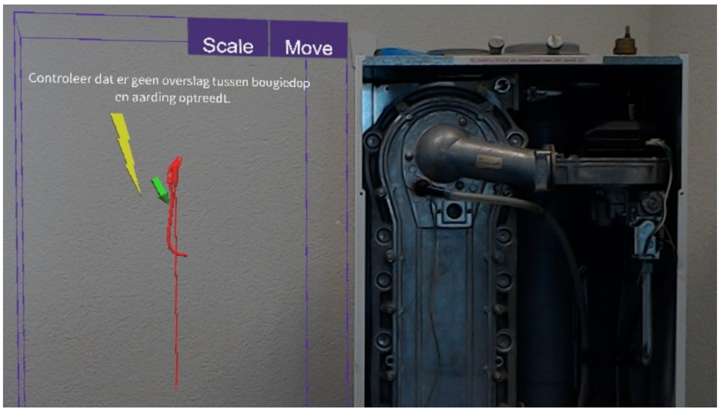


Figure 17: Snapshot of the instruction region

The instruction visualization consists of concrete and abstract elements, as recommended in Section 4.7.2. Furthermore, a textual description directly copied from the manual is rendered to increase effectiveness. A purple wireframe represents the border of the instruction region. This wireframe is used so it is clear to the user that the textual description and animation are related. UI elements like buttons and the wireframe are rendered in purple because purple is a color that is rare in occurrence in the real world.

In order to provide some flexibility in the application's UI, the instruction region can be manipulated. First, the instruction region can be moved by selecting the move button and hand dragging while looking in the purple cube seen in Figure 17. Second, scaling functionality of instruction animations is added because the user might want to see the animations in different sizes.

Scaling is implemented using a two hand gesture consisting of the following steps:

1. The user has to make sure both hands are tracked. If so, two virtual hands are rendered so the user knows he can start scaling.

2. Both hands should be air-tapped. If so, the algorithm calculates the initial Euclidean distance between both hands.

3. While both hands are in air-tapped state, scaling occurs. The algorithm continuously keeps track of the difference between the new Euclidean distance and the initial distance. The difference

can be either negative or positive and determines the amount of scaling that should be added. A negative difference corresponds to scaling down, while a positive difference results in scaling up. Scaling happens continuously, so a bigger difference results in more scaling.

Notice that the initial Euclidean distance is not updated to the new Euclidean distance. Meaning that it is possible to scale indefinitely large or small using only a single gesture, since the difference is added to the precious scaling value. In similar touchscreen scaling gestures this is often not the case, since that approach updates the initial distance in each iteration. The touchscreen approach results in multiple gestures when one wants a lot of scaling. This approach was tried as well, but proved to be rather clumsy in practice because starting the scaling gesture is not as convenient as using a touchscreen.

5.3 UI DESIGN EVALUATION

Three test iterations are done in order to find the best design for certain UI elements. Each iteration compares different versions of a single aspect. In the first two iterations, menu placement and menu activation are tested. These aspects are evaluated because they determine the application's efficiency. In the final iteration, instruction design is tested. Having a well designed instruction design determines the application's effectiveness. To make sure one test iteration is evaluated on a single specific design aspect, all other aspects do not differ.

Testing is done with four Gasunie testers who follow a step-by-step test scenario to simulate a boiler reparation session. Afterwards, the testers are asked to answer questions relevant to the tested aspect of that iteration. A Likert scale[55] is used for answering the questions, meaning that a scale from 1 to 5 is used. A value of 1 corresponds to completely disagree, and 5 corresponds to completely agree. Before performing the scenario, testers were given time to get used to general HoloLens interaction techniques to make sure evaluation is not biased on those techniques.

The snapshots shown below are an approximation of the FOV, where virtual objects can be rendered. Keep in mind that the user is able to see more of the real world, but in those areas no renderings are shown. The snapshots are taken approximately two meters away from the boiler.

5.3.1 *Menu placement*

The goal of the first test iteration is to find the best menu placement in this application. In the different versions described below, menu interaction is done using the common combination of gaze movements and air tap gestures. Also, menu activation is not needed because the menu is always visible. The red sphere indicates the PoI, the location where the task should be performed, of the current step.

Recall the three types of content that can be used, as described in Section 4.7.1.2: display-locked, body-locked, and world-locked content. Four different menu placements are created, explained below.

5.3.1.1 *Menu at a fixed world-locked location*

The first menu is world-locked and placed to the right of the boiler. The advantage of this approach is that it is always placed on the same spot, which is easy to remember for the user. The disadvantage is that the user has to look at that specific spot in order to control the application. The idea behind this approach is the metaphor of reading a book, from left-to-right. First, the user sees the instructions to the left of the boiler. Then, he does the actual work on the boiler, which is in the middle. Afterwards, he looks to the right so he can control the application to go to the next step. In the next step, he looks back to the left to see the new instructions, and so on.

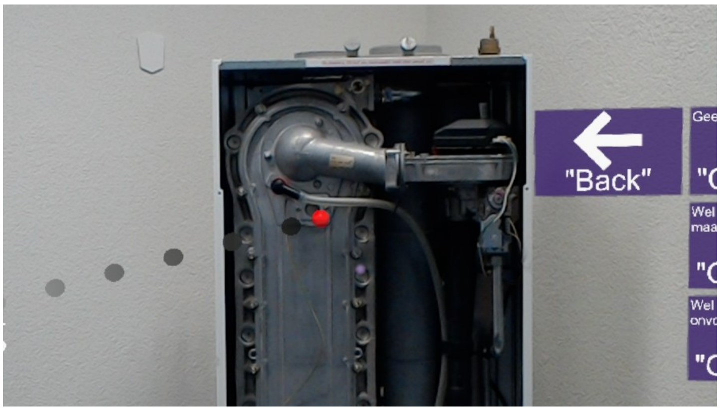


Figure 18: Snapshot of the first world-locked menu

As Figure 18 shows, the FOV is a serious problem with this approach. Even from two meters, the buttons are not completely in the FOV. When the user is doing real maintenance close to the boiler, he has to look far to the right to see the buttons to control the application.

5.3.1.2 *Menu at a changing world-locked location*

The second menu is also world-locked, but the location changes after each step. Here, the buttons appear just below the PoI of the current step. The idea behind this approach is that the user is working on a task at a specific location during a step. When he is finished performing that task, the menu should always be relatively close to him. In this way, the menu is always placed near the user's focus of attention.

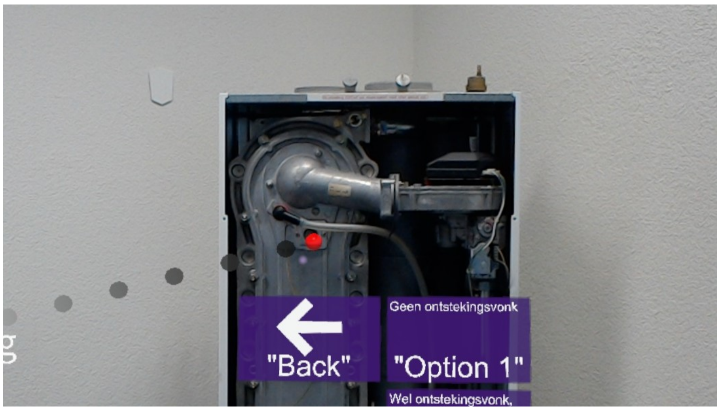


Figure 19: Snapshot of the second world-locked menu

Figure 19 shows that the buttons are indeed close to the PoI. The disadvantage of this approach is that the menu changes its position after each step.

5.3.1.3 *Body-locked menu*

The third menu is body-locked. With body-locked content, an optimal region is needed in which the content will be placed. Body-locked content is easily created using the HoloToolkit[37]. In this modified approach, the optimal location of the menu is set to two meters in front of the camera in the z direction, and 30 centimeters down in the y direction. A sphere with a radius of 50 centimeters is calculated around the optimal location. Whenever the menu is inside this sphere, it will stay world-locked. When the user rotates his head or moves so that the menu moves outside this sphere, the menu will replace itself towards the optimal location, so that it always stays inside the sphere. In this way, the menu follows the user in his movements, but is not completely display-locked.

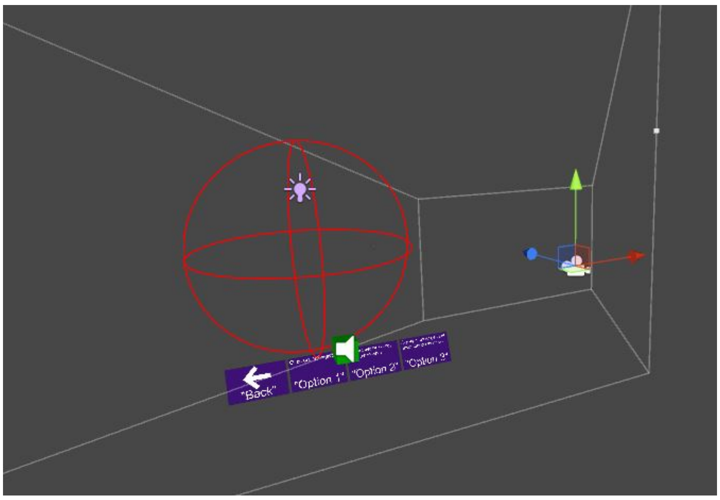


Figure 20: Scene representation of body-locked menu

Figure 20 shows a scene representation of body-locked content. The camera can be seen on the right, along with it's view frustum. The red sphere is placed two meters along the z direction, and -30 centimeters along the y direction of the camera. The green cube represents the location of the menu, in this example it is placed on the edge of the sphere. When the camera rotates upwards, the sphere will move upwards along with the camera. This means that the menu will be placed out of the sphere, and thus the menu will move upwards as well. However, when the camera rotates downwards, the menu will stay inside the sphere and thus it will not relocate.

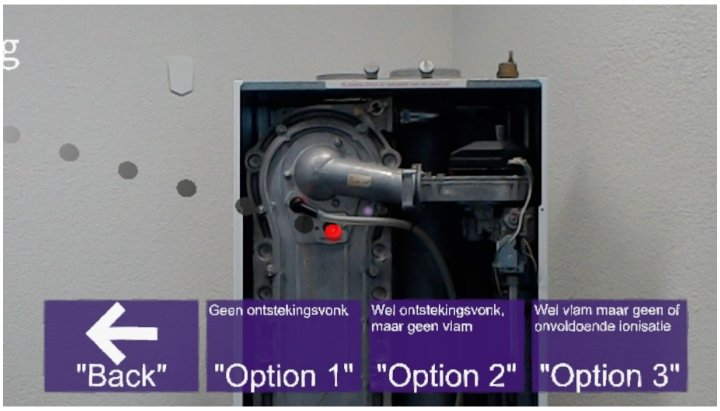


Figure 21: Snapshot of a body-locked menu

Figure 21 shows a snapshot of the body-locked menu. The buttons are now placed side by side because the optimal location is at the bottom of the FOV. Since the menu follows the user's movements, the buttons are always close by and easy to reach.

5.3.1.4 *Display-locked menu*

The display-locked menu can be seen as a HUD as it always stays in a fixed location of the display. The menu is placed 3 meters in front of the camera in the z direction, and 30 centimeters down in the y direction. In this approach, the buttons can never reach the middle of the screen. Therefore, the traditional method where a ray is cast from the camera towards the centered cursor will not work, and a customized input method is needed.

Real-time hand tracking is implemented that tries to track the hand of a user at all times. Whenever the hand is tracked, a virtual hand is rendered. When the user performs an air tap gesture, a ray is cast from the camera towards the virtual hand. If this raycast hits a button, the button is activated.

Figure 22 shows a display-locked menu. A virtual hand is shown that represents the location of the tracked finger. Keep in mind that although Figure 21 and Figure 22 look similar, their behavior is different. This is the only approach where the menu buttons are always

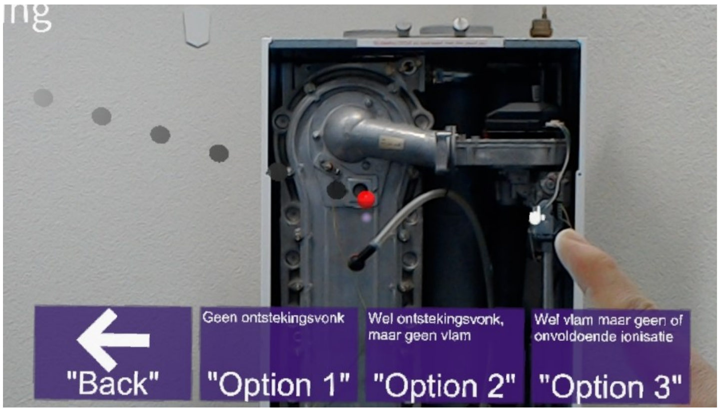


Figure 22: Snapshot of the menu as a HUD

directly visible and controllable, but the evaluation will have to show whether this approach is comfortable for the eyes of the user. Also, the customized input method will be evaluated.

5.3.1.5 *Menu placement evaluation*

Before evaluating the different versions of menu placement, the following scenario must be performed:

1. Start the application.
2. Position yourself straight in front of the boiler.
3. Read instruction, move towards the Point of Interest (PoI), choose malfunctioning code 02.
4. Read instruction, move towards the PoI, choose option 2.
5. Choose to go back.
6. Read instruction, move towards the PoI, choose option 1.
7. Read instruction, move towards the PoI, choose next.
8. Repeat step 7 until the process is finished.

The PoI is the location on or near the boiler where a certain action must be performed. The tester moves there to simulate a mechanic performing actual maintenance in that specific place.

After the tester walked through the scenario, the tester filled the corresponding questionnaire that consists of the following questions:

1. I am sure I chose the option I wanted to choose.
2. The placement of menu buttons makes it easy for me to quickly navigate through the scenario.
3. The placement of menu buttons results in a comfortable experience.

4. It would be easy for me to become skillful in using ARepair.

For each of the versions described in Section 5.3.1.1 – 5.3.1.4 the scenario is performed and the questionnaire is filled in according to Likert scale. Figure 23 shows the results of the questionnaires.

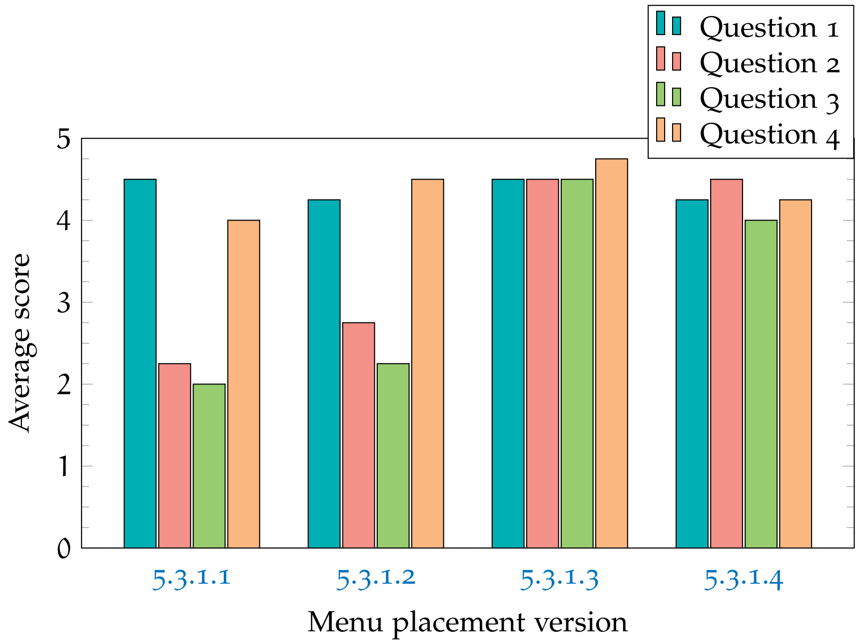


Figure 23: Grouped bar plot of menu placement questionnaire results

In version 5.3.1.1, it is not easy to quickly navigate through the application. Furthermore, the respondents reported that it made them uncomfortable to rotate their heads a lot during the process. Version 5.3.1.2 shows similar results, although the respondents preferred this technique slightly more because the menu is always close to the PoI of the current task.

Menu buttons that follow the user make it more easy to quickly navigate through the application. Although version 5.3.1.3 and 5.3.1.4 show similar results, the body-locked content is rated slightly better. It must be noted that although *Q3: "The placement of UI buttons results in a comfortable experience"* is rated only half a point higher in 5.3.1.3 compared to 5.3.1.4, this difference could increase when the usage time of the application increases. Testers commented that they imagine that menu buttons always being in a fixed location of the display could cause eye strain over longer periods of use. Therefore, testers requested to have the ability to disable the buttons so the user's view is clear to perform the actual tasks. This behavior is automatically reached in version 5.3.1.3 because sometimes the buttons are just below the FOV. Respondents mentioned that they liked this behavior.

A general comment about version 5.3.1.1 was made which stated that moving the buttons more towards the boiler would make interacting more easy and comfortable. A comment about version 5.3.1.2 was that the buttons should have been presented horizontally as in the body-lock and display-locked UIs. However, after discussion with the respondents they concluded that these improvements will probably not result in equally good experiences as in the latter two versions.

It is interesting to see that the custom input method present in version 5.3.1.4 does not have significantly lower scores in questions 1 and 4 compared to the versions with the default input method. However, it neither results in a more quick way to navigate the process, compared to version 5.3.1.3. Apparently testers do not mind to move their head a little to focus on a button.

In conclusion, menu buttons that follow the user results in an overall better experience.

5.3.2 *Menu activation*

An always visible menu can obstruct the user's view during the maintenance tasks, therefore it could be beneficial to allow the user to disable the menu. Several approaches to toggle the menu are presented and evaluated in this section. The body-locked menu presented in Section 5.3.1.3 is used in all versions described below.

5.3.2.1 *Hand recognition*

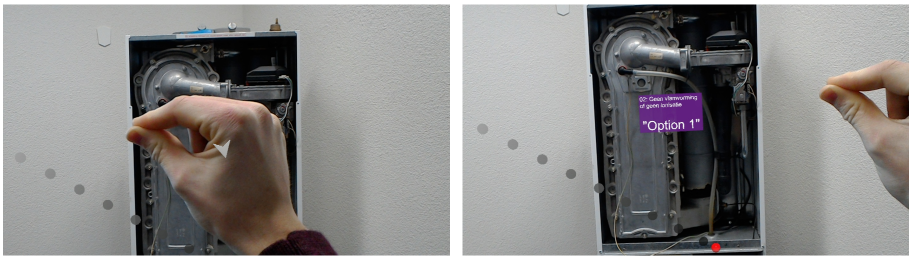
In this approach, the menu is enabled as soon as a hand is tracked. A hand is tracked by placing it in front of the camera and forming a L shape with the index finger and thumb. As soon as the tracked hand is lost, a 3 second time-out is initiated. If no hand is tracked in those 3 seconds, the menu is disabled.

Hand recognition is in theory the most easy to use approach, since a user needs to have his hand tracked anyway to perform an air tap on a button. The disadvantage could be that unwanted activations are done during maintenance.

5.3.2.2 *Gesture recognition*

In this approach, the menu is enabled using a left-to-right swipe gesture. A swipe gesture is recognized by performing an air tap and moving the hand to the right while holding the fingers in "air tap state". When the swipe gesture along the x axis of the camera is bigger than 10 centimeters, the menu is enabled. Figure 24a show the starting state, Figure 24b shows that the gesture is recognized and the menu is initiated.

The menu is disabled using a similar approach as in Section 5.3.2.1. As soon as no more hands are tracked, a 3 second time-out is initiated. If no hand is tracked in those 3 seconds, the menu is disabled.



(a) (b)

Figure 24: Swipe gesture from left-to-right

The left-to-right swipe is inspired by a general design approach seen in smartphone applications, where a swipe from the left of the screen towards the right is a very common method to display a menu.

5.3.2.3 *Voice command*

This approach is simple, the menu is enabled using the voice command: "Show buttons". Again, the menu is disabled when 3 seconds have passed where no hand is being tracked.

A disadvantage is that it might be impossible to trigger the menu in noisy environments.

5.3.2.4 *Camera position*

This approach continually calculates the Euclidean distance between the user's head position, which corresponds to the camera, and the PoI. Whenever the distance is bigger than 1 meter, the menu is enabled. Whenever the distance is smaller than 1 meter, the menu is disabled.

The motivation here is that the user does not want to see the menu while performing a task. The advantage is that he does not have to perform an activation step in order to trigger the menu. However, this approach could lead to unwanted behavior because it seems not exactly clear when the menu is triggered.

5.3.2.5 *Menu activation evaluation*

During this iteration, testers were asked to perform the activation step several times between visual checking of the boiler. After the tester did this until he felt comfortable rating the approach, he filled the corresponding questionnaire according to Likert scale. The questionnaire consists of the following questions:

1. This activation approach does not hinder my workflow.
2. I am sure my activation step is performed.
3. I prefer this activation approach over an always visible UI.

4. I find this activation approach easy to use.

For each of the versions described in Section 5.3.2.1 – 5.3.2.4 the scenario is performed and the questionnaire is filled in. Figure 25 shows the results of the questionnaires.

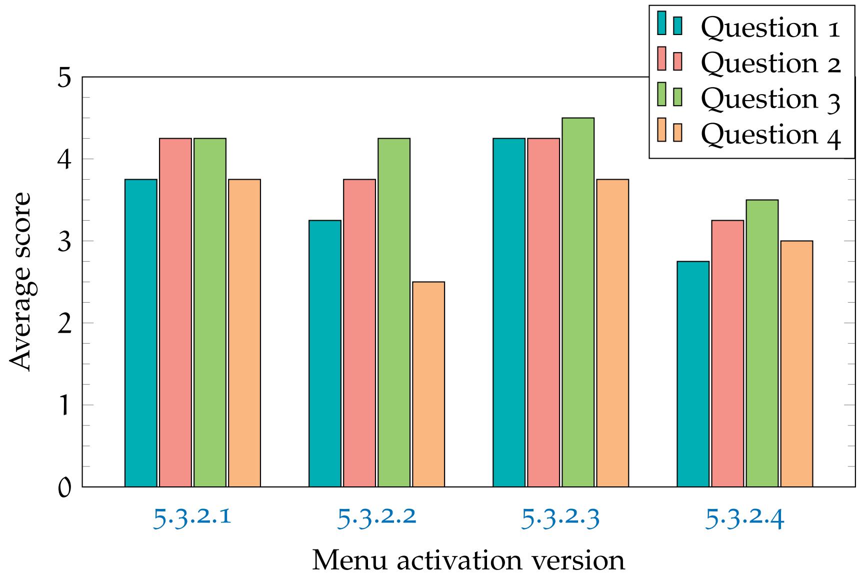


Figure 25: Grouped bar plot of menu activation questionnaire results

Overall, the scores are lower than Figure 23. During testing we noticed that adding steps to enable a menu introduced a small learning curve. However, testers reported that they do prefer some activation functionality over an always visible menu, as seen in Figure 25 Question 3.

The voice activation approach (Section 5.3.2.3) scores best, followed by version 5.3.2.1. Since these two approaches use two different modalities (Gesture and Voice), they can be combined to form a multimodal approach. After discussion with the respondents, the conclusion was that the combination of version 5.3.2.3 and 5.3.2.1 seems to be the best option, indeed.

The results of version 5.3.2.2 and 5.3.2.4 show that activation of a menu should take as less effort as possible. A swipe from left-to right is already considered too much effort.

5.3.3 *Instruction design*

Apart from a instruction region, we also want to have some visualizations at the PoI to guide the user to the relevant parts. Since visualizations are directly rendered in the users view, the design of instructions at PoIs must be carefully chosen. The most straightforward approach, placing the 3D animations on top of the relevant parts, comes with the cost that the real relevant parts are obstructed by the virtual models. Therefore, we performed a test iteration to find a solution for this issue. To make sure only differences in instruction design are evaluated, the menu placement and menu activation are kept the same across the different versions.

We cannot recognize individual parts as stated in Section 4.6. Therefore, visualizations are placed at the correct location by calculating the distances from the center of the boiler in x, y, z directions. This approach is quire error prone, but unfortunately there is no other way to position the animations correctly.

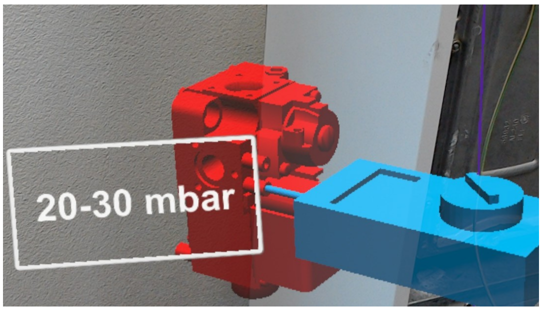


Figure 26: Snapshot of an instruction animation corresponding to the task "Make sure that the admission pressure of the gas is sufficient"

Figure 26 shows a still of the animation that is being used to explain the different versions. The corresponding task is: "Make sure that the admission pressure of the gas is sufficient (20-30 mbar)". In the animation, a pressure gauge moves into the lower valve of the gas control valve.

5.3.3.1 *Sphere at PoI*

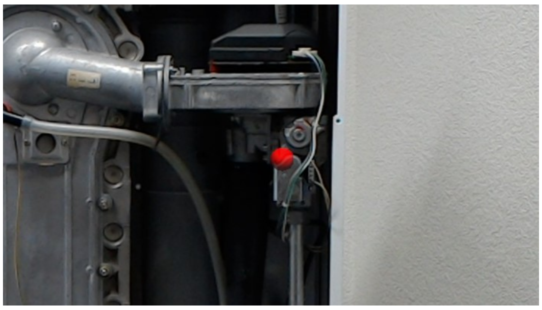


Figure 27: Snapshot of a sphere at PoI

This approach renders small red spheres at the PoI. The user's Euclidean distance to the PoI determines the sphere's opacity. When the distance is bigger than 1.5 meters, the sphere is fully opaque, from 1.5 meters towards 0.75 the opacity is smoothly reduced, and within 0.75 meters the sphere is fully transparent. Figure 27 shows a snapshot. Because the localization is not completely accurate (Section 5.1.1) there is the possibility of a small placement error. Advantage of this approach is that it occludes the user's view minimally. Disadvantage of this approach is that it always renders small spheres, even if the relevant boiler part is large and has a different shape.

5.3.3.2 *3D model at PoI*

This approach is similar to version 5.3.3.1, but renders the 3D models on top of parts instead of spheres. Opacity is also changed according to the Euclidean distance, Figure 28 gives an example. A small placement error can be observed which might negatively impact the experience.

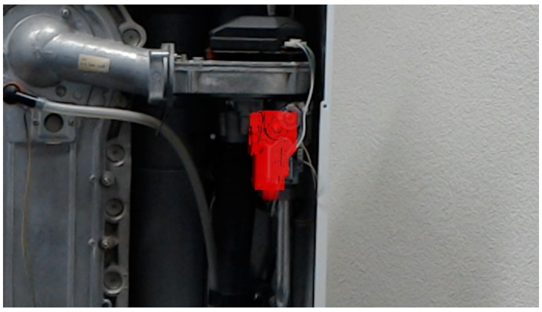


Figure 28: Snapshot of a 3D model at PoI

5.3.3.3 *3D outline at PoI*

In this approach, a 3D outline is rendered on top of the PoI. The advantage of an outline could be that the real object is not obstructed but highlighted. However, as Figure 29 shows, registration errors might negatively impact the experience. Again, opacity is changed according to the Euclidean distance. In practice, the rendering flickers due to hardware limitations.

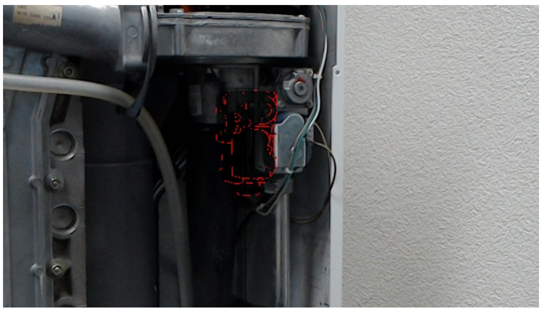


Figure 29: Snapshot of a 3D outline at PoI

5.3.3.4 *Instruction animation at PoI*

In this approach, the complete instruction animation is rendered on top of the PoI. The user is able to toggle the instruction visibility using the voice commands "hide instruction" and "show instruction". Figure 30 shows an example.

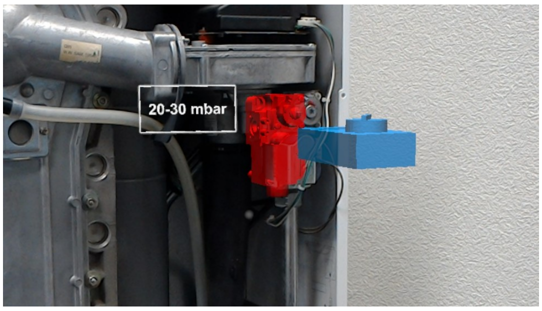


Figure 30: Snapshot of a 3D animation at PoI

5.3.3.5 *Instruction design evaluation*

Testers were asked to perform two tasks, one being shown in Figure 26, the other task being: "Make sure that the connection between the spark plug and the ignition electrode is correct". After performing these two tasks, testers were asked to fill the following questionnaire according to Likert scale:

1. It is clear to me how I have to perform a task.
2. The small placement error is not a problem.
3. This approach did not hinder my workflow.
4. This approach makes the application more useful.

Questions are related to task performance and hardware limitations. The questionnaire results can be seen in Figure 31.

As Figure 31 shows, the animation at PoI approach (5.3.3.4) makes it most clear how a task must be performed. Furthermore, respondents thought placement errors matter least in 5.3.3.4. Also, workflow was best due to the manual toggle compared to the automatic fades based on Euclidean distance. Finally, the final approach was considered most useful as well. In conclusion, the final approach was superior to the other presented approaches.

5.4 FINAL DESIGN

The final design consists of three main UI parts and is a result of the test iterations described in Section 5.3. From each iteration, the best solution is taken and combined in a single version.

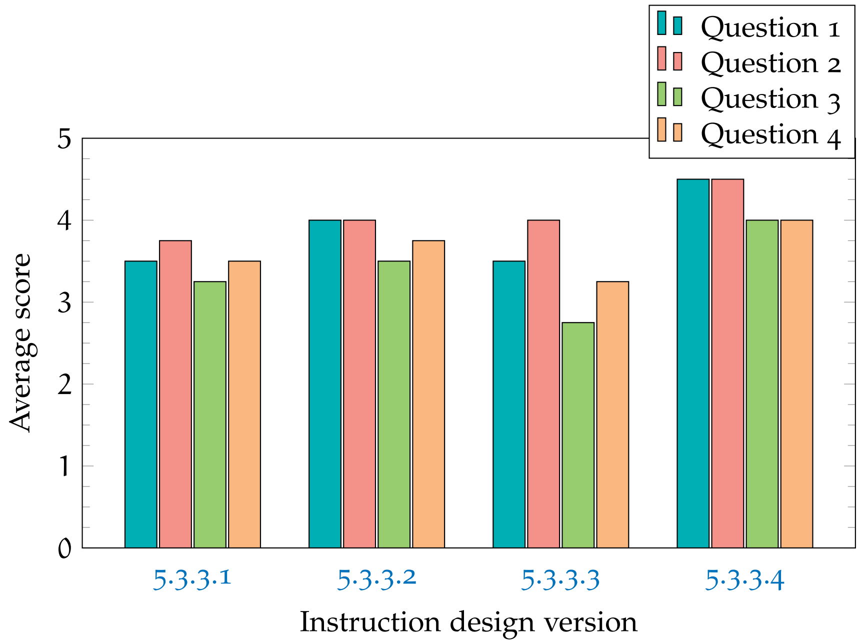


Figure 31: Grouped bar plot of instruction design questionnaire results

The first part is the menu, it is body locked(Section 5.3.1.5) and activates by performing a "L" gesture(Section 5.3.2.5). The second part is the instruction design at the PoI, this is a 3D animation that can be toggled using voice commands(Section 5.3.3.5). Finally, an instruction region is rendered that is always visible to the user so he is able to see the animation at all times, even while working. The implementation of the instruction region is described in Section 5.2.

Multimodal interaction techniques are recommended in Section 4.7.1.3 to increase efficiency. Therefore, voice interaction is also implemented and described in Section 5.4.1. Finally, a small feature that hugely increases efficiency is the direction indicator, it is described in Section 5.4.2.

5.4.1 *Voice interaction*

Multimodal interaction techniques increase the user's flexibility for interaction. Efficiency is increased by being consistent between both the visual interactions and voice interactions. Therefore, every action that can be performed by an air tap, can also be performed by a voice command. These voice commands correspond to the text that is present on a button, like "Next". All available voice commands are shown by saying "Show help". Finally, it is possible to perform an air tap – also known as click – by saying "Click".

When a voice command is registered, a text to speech generator is used that confirms the action in speech. This is different from an air tap confirmation, which uses a tap sound.

5.4.2 *Direction indicator*

Because it is possible that the user does not see any renderings of the application, it is important to always have an indication where the renderings are placed. Therefore, a direction indicator is rendered that guides the user towards the objects when the user has no virtual objects in his FOV. The arrow is placed around the middle cursor and always rotated towards the PoI.

The opacity of the indicator is gradually changed according to the angle $\angle ABC$ between the user's current view and the PoI. A is the current PoI position, B is the camera's position, and C is the cursor's position, which is two meters in front of the camera position along the camera's forward vector. Once we know A, B, and C, we can calculate the angle, which is a value between 0 and π. We divide the angle by π to get a continuous value from 0 to 1. The result is a smoothly fading direction indicator during movement towards the PoI.

6 DISCUSSION

This chapter discusses the experiences during the writing of this thesis. First, experiences regarding development are discussed in Section 6.1. Then, practical experiences and challenges are discussed in Section 6.2.

6.1 DEVELOPMENT

Considering the results shown in Section 5.4, we see that development of AR applications using the HoloLens is indeed possible. We were able to localize an object in the user's space using Vuforia[42]. With this localization step, we are able to reach the Where+What category in the Extent of World Knowledge shown in Figure 10.

Unity[36] indeed allows for relative easy development of AR applications. Since Unity is a gaming engine, it is advised to appoint game developers for future HoloLens applications. Official Unity support for HoloLens only arrived during the writing of this thesis, so some refactoring was needed to keep the application compatible. HoloToolkit for Unity[37] is definitely another requirement for creating HoloLens applications. Basic functionality like the Cursor and the input message system are already implemented in this toolkit, using it saves a lot of time. Like with Unity, it is still in development and refactoring was needed to use new functionalities while staying compatible.

The same holds for Vuforia, at first it was not possible to stop recognition once the target was found, meaning that the image target was relocated every time the target was recognized (slightly) different. This resulted in jittered virtual objects that are placed relative to the image target. However, an update made it possible to disable Vuforia on recognition, which means that HoloLens could take over tracking. After this update, the virtual objects where just as stable as in other HoloLens applications. Basically we can conclude that development of HoloLens applications is quite mature, although new features are still being developed.

The platform (called Windows Mixed Reality) is currently being opened up, which allows external manufacturers to create new MR devices. HoloLens is a device that demonstrates the platform, but more possibilities will open up when new devices are being released, which is an important consideration for Gasunie. Another important consideration for Gasunie in their quest towards digitalization is that the Windows Mixed Reality devices are not the only head-mounted devices available. Other device types, like 2D AR head-mounted devices are available that could support some mentioned UCs. Of course, AR applications are also possible with mobile phones or tablets, although it comes with the cost that the user is not able to work hands-free anymore.

6.2 EXPERIENCES IN PRACTICE

Although recognition accuracy was not completely accurate, users of the application did not mind the accuracy error in this context. This is explained by the bright and vivid display. Users tend to focus on the virtual objects instead of the real objects when they look at both types at the same time. Of course the accuracy error could become a problem in different contexts, for example in applications where smaller parts are present. Real world occlusion by virtual objects is an important aspect that should be considered carefully. Users should have the ability to remove the virtual objects from the scene if interaction with real objects is needed. For example, dismantling an object that is occluded by its virtual model is basically impossible in practice.

Finding UCs that maximize efficiency in business processes is a challenge, especially when one is not completely familiar with the processes happening within a company. Requirements elicitation is an important aspect to cover this knowledge gap, although in practice it is hard to gain knowledge on highly specific UCs. During interviews, employees tend to explain their tasks at a higher level. However, for AR application highly detailed descriptions are needed.

Furthermore, it is important that the needed 3D models are available. Without relevant 3D models, it is impossible to create useful HoloLens applications. During this thesis, it took quite some time before Remeha provided the relevant 3D models. Therefore, an advice for Gasunie is to start collecting 3D models for their newly purchased assets, so they do have a basis for future applications.

In the evaluation phase, we discovered that some practice is needed to become skillful in interacting with the HoloLens and using the application. For example, we noticed only during testing that making an "L" gesture with index-finger and thumb is crucial to maximize the reliability in hand detection. This is directly one of the caveats in our evaluation results. Although testers were given time to get familiar with HoloLens, we still observed that they became more skillful over time during testing. It is difficult to make sure that comparing the different versions is done using the exact same circumstances across different versions and iterations. There is not really a solution to this issue other than the fact that testers need enough time to get familiar with HoloLens interaction. Finally, it was difficult to make sure questions were asked that expose usability problems in 3D AR applications.

7 CONCLUSION

In this thesis we presented research on the applicability of AR/VR technology in the context of gas infrastructure management related tasks. The related research question presented in Chapter 1 is:

> How can we use AR/VR technology provided by the HoloLens to efficiently and effectively support the types of tasks mentioned in the context of gas infrastructure management?

To answer this question, several departments inside Gasunie were visited and potentially applicable UCs were selected and analyzed. Many suitable applications were found. However, it must be noted that not all of these applications are indeed most suitable in AR/VR. Using AR/VR techniques may be tempting due to their wow-factor, but it must be considered carefully whether traditional displays do not suffice. Furthermore, some applications were not feasible to develop in this thesis due to technical limitations of the current version of the HoloLens. Other applications are restricted by non-functional requirements like the lack of explosion-proof certificates.

Finally, gas combustion boiler reparation was selected as UC for support using AR techniques provided by the HoloLens. In this application, instructions are visualized using animations of 3D models and augmented on top of the real parts. The development of this application has proven that it is possible to support tasks related to gas infrastructure management using the HoloLens.

The research question did not only check whether AR/VR are applicable, but also whether they can efficiently and effectively support gas infrastructure management. During the application development phase, we noticed that creating an *efficient* HoloLens application was one of the major challenges. Therefore, an agile user-centered design evaluation approach was used during development that focused on several design aspects. Furthermore, new interaction techniques were developed and evaluated. The question whether this specific application answers the research question positively is hard to answer, since only simulations at the office were done.

For Gasunie, the purchase and incorporation of multiple HoloLenses in their processes is not advised now. First, 3D models of needed components are not always present at Gasunie. Second, the HoloLens itself is still in the development phase. Improvements, like ATEX certifications and safety glass are needed before adoption in many processes is possible. As we have seen, some external applications already exist, and other potentially useful applications are being developed. It makes sense to keep an eye on further developments, perhaps the HoloLens will be an interesting device for AR applications in the (near) future.

7.1 FUTURE WORK

There is still a lot of work to be done in order to adopt this application in the current process. First, the application represents only a part of the textual manual, more fault codes have to be implemented before adoption is possible. Second, this application only handles one specific boiler. While it is the most common boiler at Gasunie, other boiler types are used as well.

In the future, the developed source code can be generalized to create an AR-manual platform that allows for visual help in more Gasunie assets. Also, a trainer mode can be created so that it is possible for expert mechanics to easily create visual manuals themselves using the HoloLens. Furthermore, connections to Gasunie databases can be established to visualize sensor data or upload new data to the database. Finally, help at distance can be integrated so that an expert can video-call with the mechanic and annotate the sight of the mechanic in a similar fashion as the current Skype application[26].

In the case of research, our design evaluation used four Gasunie testers to evaluate the different design decisions using a qualitative approach. Quantitative research can be done to improve understanding of why certain design decisions are better than others. Also, research is needed to conclude whether creating a visual manual indeed saves time, and thus costs, in this specific task.

A

MAINTENANCE INSTRUCTIONS FOR FAULT CODE 02

Remeha Quinta 45/65

02	Geen vlamvorming of geen ionisatie (na 5 startpogingen) **Opmerking:** Meting ionisatie in volts tussen klem 4 van de klemmenstrook en aarde (1 V ≡ 1 μA)	a. Geen ontstekingsvonk. Controleer: - de aansluiting van ontstekingskabel en bougiedop - de ontstekingskabel en de elektrode op ‘doorslag’ - op ‘overslag’ tussen bougiedop en aarde / massa - de elektrodeafstand, deze moet 3 à 4 mm zijn - de aarding / massa b. Wel ontstekingsvonk, maar geen vlam. Controleer of: - de gaskraan geopend is - de gasvoordruk voldoende is (20 -30 mbar) - de gasleiding ontlucht is (denk aan de eerste vulling van de tank bij propaan, hierin zit een hoeveelheid stikstof) - de gasklep wordt bekrachtigd tijdens het ontsteken en deze ook opent - de elektrode schoon en juist gemonteerd is - er een verstopping / montagefout in de gasleiding zit - er een verstopping / montagefout in de luchttoevoer of rookgasafvoer zit (bv. verstopte sifon) - er geen recirculatie van rookgassen optreedt (intern en / of extern) - de instelling van de instelschroef op de venturi juist is. Eventueel 1 slag linksom draaien en ketel opnieuw starten. Herhaal dit tot de ketel brandt a c. Wel vlam maar geen of onvoldoende (< 4 μA) ionisatie, controleer: - vlambeeld, is de vlamkern zichtbaar en de vlam stabiel?, - afstelling CO_2 op laaglast en vollast, - de aarding van de ontsteekpen, - de temperatuursensoren op lekstroom (vochtig bij sensoren), - de ontstekings/ionisatie elektrode visueel, door controle op witte oxidehuid (deze met een schuurpapiertje of schroevendraaier schoonkrabben) of door controle op de vorm (hebben de pennen de originele vorm en is de afstand tussen de twee uiteinden van de pennen tussen de 3 en 4 mm.

Figure 32: Maintenance instructions for fault code 02

Source: Remeha Quinta 65 manual

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