VRIJE
UNIVERSITEIT
BRUSSEL

Graduation thesis submitted in partial fulfilment of the requirements for the degree of Bachelor in Computer Sciences

MUSEUM OF THE FUTURE: TOWARDS A MIXED-REALITY INFORMATION EXPLORER

BRENT WILLEMS
Academic year 2017–2018

Promoter: Prof. Dr. Beat Signer
Advisor: Payam Ebrahimi

Faculty of Sciences and Bio-Engineering Sciences

Afstudeer eindwerk ingediend in gedeeltelijke vervulling van de eisen voor het behalen van de graad Bachelor of Science in de Computerwetenschappen

MUSEUM OF THE FUTURE: TOWARDS A MIXED-REALITY INFORMATION EXPLORER

BRENT WILLEMS

Academiejaar 2017–2018

Promoter: Prof. Dr. Beat Signer
Advisor: Payam Ebrahimi

Faculteit Wetenschappen en Bio-ingenieurswetenschappen

Abstract

In this thesis, we introduce Museum of the Future. We investigate the role of mixed reality (MR) in a museum environment, and how it can improve the museum visitors' experience. We want to create an application prototype that enhances the ordinary museum experience by taking advantage of immersive mixed reality, and introducing explorative and interactive features. Immersion is achieved by using the Microsoft Hololens, a MR head-mounted display which can show holograms in the real world. The explorative part translates into the visitor being able to access external (online) information while looking at an artwork. This external information consists of online available related data, in the form of Linked Open Data (LOD). In addition to exploration, we also want the application to stimulate interaction, by utilising an intuitive and interactive interface. The proposed solution prototype combines these three aspects (Immersion, Exploration and Interactions) in an application that runs on the HoloLens. It allows users to look at artworks as they would in a traditional museum context. Information is displayed in a minimalistic way in order to immerse users into the experience. They can use queries to access relevant related information about artworks, which can be achieved by using simple interactions. The development process yielded meaningful findings from which we formulate three design requirements related to our problem statements. These can be used as a guideline for researchers who wants continue our work and create a fully functional museum-oriented mixed reality application.

Contents

1 Introduction

Museums have always played a major role in learning. For the most time in history, the word ‘museum’ was associated with a public place, where a collection of artefacts, objects or artworks are on display, with the purpose of educating and enlightening the visitor with new insights. And for the most part, up until the late 20th century, there was little to no technology involved in a museum visit: it was mostly comprised of looking at the collection in the museum, without much added interaction by technology. Fast forward to today, and we find ourselves in the midst of a digital revolution. Advancements in computational technology and the invention of the Internet has changed the way people interact with data and information. At the beginning of the Computer Era, interacting with available information was a fairly static, and a non-active process, where the user of the system sat in front of a screen, and used a keyboard to do the input. With the invention of the mobile phone, and more recently the smartphone, this long-held standard was starting to shift. Thanks to the Internet, information was already available almost everywhere, and people got access to it any time they desired by using their smartphones. This ever-available source of information started to integrate into our lives. Nowadays, with the introduction of such concepts as social media, there is a potential for creating social-driven applications.

Mixed reality technologies, which can be considered a collective name for immersive technologies, anywhere from basic augmented reality all the way to virtual reality, on the mixed reality spectrum, as described by Milgram et al [6]. Mixed reality displays put a virtual layer on top of the real world, enhancing or augmenting the physical world with digital information. This concept is known for quite some time, but recent advancements in display technologies allowed for the creation of hardware capable of delivering such mixed reality experience. The Microsoft HoloLens[1] is an example of such hardware device. It allows users to combine virtual objects with the real world by the means of holograms, which can be placed in the environment, as well as interacted with, depending on the application. The idea of enhancing real world objects with virtual data, while retaining full view of the real world, can be considered a very appealing concept for museums.

1.1 Problems

We identify three main problems, which our project will try to solve: the lack of available information, minimal social interaction, and lack of support for immersive mixed reality.

Limited information available
There is so much information available on the internet, yet museums often fail to include more information in their artwork exhibits. Paintings or sculptures are often only accompanied by a wording below or next to them. These texts usually only mention the artist, and a small description to give some limited context to the artwork. (See Figure 1.1*[2])

Not collaborative, lack of social interaction
Museums generally do not promote or stimulate interaction between visitors and artworks, or between visitors themselves. This is especially true for art museums, where there is a lack of technology to encourage user engagement.

Lack of support for immersive mixed reality technologies
At the moment, there are not much well-known projects that take advantage of recent developments in mixed reality technology in order to create a fully immersive user experience.

[1] `https://www.microsoft.com/en-us/hololens`
[2] https://en.wikipedia.org/

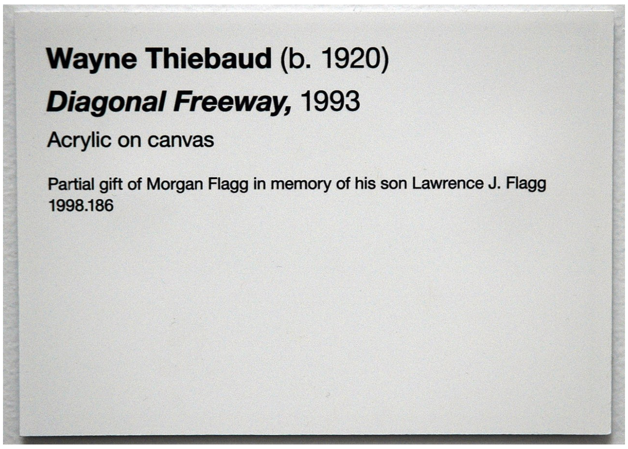

Figure 1.1: A typical description below an artwork. Adopted from Wikipedia

1.2 Research Question

In this thesis, we will search for an answer to the following research question: "How can mixed reality improve the user experience and the level of interaction inside a museum context?"

We will examine how mixed reality can improve users museum visit experience, as well as the access to information during their visit. To address the stated problems, we will consider three main solution criteria which correspond to our problem domains.

Information exploration trough semantic queries
To address the limited information part, we will make use of semantic databases to expand the amount of available information during the museum visit. By using SPARQL queries, the visitor will be able to retrieve any related information regarding the artwork they desire.

Social interaction and collaboration between visitors
Social interaction and collaboration can be stimulated by enabling the visitor to add notes to the artwork or even leave questions for other people. This way, visitors can interact more profoundly with the artworks.

Immersive experience
The user interface of Museum of the Future will be designed in a minimalistic style. This way, the application will enhance the user experience without distracting them from the original artwork.

1.3 Methodology

In order to provide an answer on our research question, we have followed the Design Science Research Methodology (DSRM) as specified in the article by Peffers et al. [7]. This methodology defines a set of steps for conducting scientific research in the field of Information Systems: 1) problem identification and motivation, 2) definition of the objectives for a solution, 3) design and development of the solution, 4) demonstration, 5) evaluation and 6) communication.

1. Problem identification: We covered this in section 1.1, were we identified the three problem domains. The development of the project solution revolves around solving these problem domains.

2. Definition of the objectives for a solution: In order to define specific objectives for our solutions, we used the problem domains and the related background context found in the related work as our baseline. Through discussion, we translated these problem domains into objectives for our solution. This is discussed in Chapter 3.

3. Design and development of the solution: The design of our solution has been shaped through various meetings. With iterative discussions, we formulated all the parts the solution has to be comprised of. These meetings also provided new pointers for the low-level design of the application. The high-level (theoretical) solution design can be found in Chapter 3, while the concrete implementation is discussed in Chapter 4.

4. Demonstration: The demonstration of our application takes place during the thesis presentation.

5. Evaluation: The evaluation of our solution has been conducted internally, through discussion. This can be found in Chapter 5.

1.4 Structure

This thesis has the following structure:
Chapter 2: In this chapter, we introduce the concepts around which this thesis revolves. Further, we take a look at related work in order to find our

requirements for the solution.

Chapter 3: In this chapter, we translate our requirements into a theoretical solution. We discuss the various theoretical prototypes, and we also take a look at several scenarios in which our application could work.

Chapter 4: In this chapter, we go through the implementation process of our Museum of the Future application. We discuss in detail the separate components, and highlight important libraries that have been used during this development.

Chapter 5: In this chapter, we discuss our evaluation process.

Chapter 6: The conclusion contains our final findings concerning this thesis. We reiterate our solution, and also take a brief look at the possibility for future work.

2
Related Work

In this chapter, we observe the related work to search for insights and conclusions, in order to validate our initial problem statements or refine them. We will first look at mixed reality technology and how it has already been used in a museum context, before looking at the underlying concepts, corresponding to our three problem statements.

2.1 Mixed Reality and Immersive Experiences

For long, mixed reality was more of a conceptual idea, than a real thing. This was because there was simply almost no hardware capable of providing a mixed reality experience. In the last decade, thanks to advancements in smartphone and computer technology, some of these devices became powerful enough to emulate a mixed reality environment. These technologies may also have helped bringing mixed reality projects to a broader audience, instead of them being research projects only. The incorporation of mixed reality in a new setting or context can really increase the amount of engagement and user interest. For a part, this could be due to its novelty. Several recent real world mixed reality projects (or augmented reality) show this. For example, take a look at Pokémon GO. This AR Based game launched in 2016, and immediately sparked the interest of millions [1] The game took inspiration from the original Pokémon games, and transformed them into an interactive, outdoors experience, where users would walk around to track down digital monsters, using their internet or GPS enabled smartphones. Its popularity showed that people were ready for adopting this kind of technological interaction into their lives. People becoming familiar with the new technology also meant that AR (or MR) applications could find their way into other parts of entertainment or leisure activities, such as museum exhibitions.

2.1.1 Early Adoption in Museums

The use of augmented and mixed reality technology in museums has already been discussed many times in last two decades. For instance, back in 2001, the SHAPE (or "Situating Hybrid Assemblies in Public Environments") project of Hall et al. [4] studied the use of a mixed reality tools to enhance the experience in a museum and create more profound interactions. For their study, they let participants walk around in the Hunt Museum in Ireland, wearing a Sony Glasstron [2] head-mounted display. The Glasstron was connected to a portable computer that provided the visual content. The participants then used the Glasstron to look at actual artefacts, and compare them with virtual ones, while also hearing related audio fragments.

The SHAPE project shares similarities with Museum of the Future. As Hall et al. remarked[4], they wanted to create new ways to show supplementary visual and aural digital information in relation to these artefacts. The use of the head-mounted display, the use of hyperlinked media, as well as the intent to enhance the interaction and learning experience of museum visitors are considered in our project.

Needless to mention, this project is a very early form of using the mixed reality concept, and the technological limited hardware back then did not allow a more immersive mixed reality experience. For instance, Hall et al. [4] remarked that the Glasstron head mounted display "can be obtrusive" and does not quite allow collaboration.This stresses the fact that it is very important to have a setup which is non-obstrusive, allowing the user to go trough the museum freely. This would be possible with more modern hardware like the HoloLens.

A different early attempt at incorporating mixed reality in a museum context was a research project, conducted by Chen[2]. This project focussed on museum guidance. The project setup consisted of a camera, looking at a

[1] `http://www.businessofapps.com/data/pokemon-go-statistics/`

[2] `https://en.wikipedia.org/wiki/Glasstron`

Figure 2.1: Glasstron in use. Adopted from Hall[4]

set of 2D markers. These markers were associated with virtual 3D objects and the interactions that could be performed on them. The users were able to interact with the setup by holding their finger on a marker. The camera would detect this, and it would trigger the desired action on the virtual object. In this way, users could zoom or rotate virtual 3D objects. Their main goal was to create a AR-based guidance system, using this augmented reality technology so the user could "experience more intuitive and realistic interactions".

For the recognition of artwork in museums, 2D markers might be useful. These can also be used create associations with other data. Intuitive and simple interactions are important for project to be user friendly.

2.1.2 Modern Approach of Mixed Reality in Museums

The Skin and Bones [3] app is a simple example of how interaction between user and art display can be created using Augmented Reality. Using the app, visitors can select an an animal. Then, they can point the camera of their mobile device to the skeleton of the chosen animal, and the app brings the specimen to life by layering a 3D model on top of the skeleton. (See Figure 2.2)

While there is not much more to the experience concerning the interaction part, Ding[3] mentioned that according to a study in the Smithsonian, the

[3] `http://naturalhistory.si.edu/exhibits/bone-hall/`

users responded very positivelyThis shows that even relatively simple added interaction by the means of Augmented Reality has a positive effect on visit time and overall visitor satisfaction. The Skin And Bones application is just a very basic example of how Augmented Reality can be utilized in a museum context The user has to manually select an animal before they can point their device at a skeleton. This makes the experience not quite comparable to a truly interactive Mixed Reality application, where the visitor would be able to just point their device at the skeleton without having to do any manual input.

Figure 2.2: Skin and Bones AR app. Adopted from Ding[3]

The Playing with the Artworks project[9] describes an AR based game for children in a museum setting. The game involves using a tablet, with which the children can explore the museum. They have to colour a drawing, which they then need to find the corresponding painting or sculpture for. If they locate the correct artwork and point their tablet to it, the application will apply this drawing onto the artwork, effectively augmenting the physical artwork with a virtual layer (as shown in figure 2.3). This way, the kids create a personalized version of the artwork. Even though this described project is still in its early prototyping stage, they already made a working system. Instead of augmenting an artwork in the gallery, the application lets users augment a virtual 3D character, that can be triggered by pointing the tablet to a 2D marker on paper.

This project focusses on the exploration aspect of a museum experience, and it does share some underlying concepts with Museum of the Future. Both have a focus on engaging users to participate, allowing active exploration, and augmenting artworks with user created content. The level of interaction with the artwork is more in depth than the previously discussed projects, although it is fairly limited in its use of mixed reality.

Figure 2.3: Playing with the Artworks. Adopted from Pucihar et al. [9]

2.1.3 A Look at a Hololens-enabled Project

Until now, we mostly looked at older projects and initiatives that already use the concept of mixed reality itself to create a more interesting experience for museum visitors, but do not make use of modern mixed reality glasses like the Hololens. The use of hardware like the Hololens has the advantage of creating an even more immersive environment for its user. In the past few years, several new Hololens-driven projects have been in development for this very reason. A good example of such project is HoloMuse. Its creators, Pollalis et al., aims to use mixed reality to let visitors interact with archaeological artefacts "in ways that are otherwise not possible"[8]. With HoloMuse, users choose holograms from a virtual gallery, and use HoloLens' in-air gestures to rotate and scale the hologram, before placing it in the world. This way, users can add Holograms to their own space, becoming a curator of their personal exhibit gallery. The system also allows users to learn more about a specific artefact, by requesting more information using voice or text input. In future work, the authors also plan to implement a 'visitor mode', where users would be able to locate user-created exhibits of other visitors, adding a social aspect to their implementation. Out of all discussed projects in this paper, the HoloMuse project bears the most resemblance to our proposed Museum of the Future project. Having already conducted an evaluation with an interactive demo, Pollialis et al. [8] found that, although most users found the application enjoyable, some people did not fully understand how the HoloLens gestures worked. They suggest adding a small tutorial feature to the project could help to counter this problem.

2.1.4 Comparison between mixed reality projects

Now we mentioned some mixed reality-driven projects that have already been used in a museum context, we can compare some of these with our own proposed system, in order to show that there is a lack of direct competition for our proposed system at the moment. We will compare our proposed system to the two more advanced systems in terms of content and use: HoloMuse and Skin and Bones. First of all, both systems do not implement some kind of explorative features that allows search in an extensive database, like our proposed project will be able to. They only allow to access predefined content. Skin and Bones lacks the social collaboration part altogether, while HoloMuse plans to implement a visitor mode. Regarding the creation of an immersive experience, Skin and Bones does not dispose of true immersiveness, due do it being a phone-based AR app. HoloMuse however delivers on this by using the HoloLens, combined with a clean, minimalistic interface.

	Our project	HoloMuse	Skin And Bones
Explorative info	Semantic data Queries	Predefined	Predefined
Social collaboration	Yes	Yes	No
Immersive Experience	Yes	Yes	No

2.2 Immersive Experiences with MR

Now we will take a look at how the design of the user interface integrate those two domains into the system to create an immersive user experience. There are two important factors to consider: choosing the hardware, and designing a clean interface. For these aspects, we will compare our proposed system to the HoloMuse project from earlier on, as it has very similar goals in terms of user experience compared to our Museum of the Future. The authors of the HoloMuse project recognize the problem of many AR based systems of today. With the majority of current smartphone or tablet-based mixed reality projects, their 'mobile device-guided' approach causes a lack of immersiveness. [8] Users often have to look away from the original artefact to then look at the virtual one so they can actually experience the 'augmentation' the system provides.This is one of the main reasons HoloMuse uses the HoloLens for their project. Of course, choosing appropriate hardware is not sufficient to create an engaging experience.

The user interface is what actually delivers the ‘immersiveness’ part. In our own proposed system, our goal is to create a minimalistic UI. When looking at an artwork for instance, the interface should interfere as little as possible with the view of the user, at least initially. With this, we want to avoid that the user is distracted by obtrusive interface elements, or an interface that overlays the artwork itself, hindering the viewing experience. When we examine the user interface of HoloMuse, it seems that Pollalis et al. share this opinion. They point out that their system has been designed to “facilitate learning and engagement with museum collections without taking away from the experience of viewing an original artefact within the context of an exhibit”[8]. For instance, the standard interface, as illustrated in figure 2.4, really shows this design goal. Only a small blue icon gives away that the user is rotating the artefact. Another good example is the informative rectangle that pops up when a user requests additional information (see Figure 2.5). Although the interface shows quite a bit of data, it does not overlap the artefact. By using white text and thin white lines for the rectangle, and keeping the rectangle itself transparent, it does not take away much of the users’ view.

Figure 2.4: The default interface is very minimalist. Adopted from Pollalis et al. [8]

One remark to make, is that the use of white text could pose some issues when using the system in a brightly lit environment, and especially in galleries with white-coloured walls. This can be taken into consideration when tailoring the application for a specific museum. In general, a configurable font colour could eliminate this issue altogether. This issue aside, we can conclude that even already using hardware that induces immersiveness by design, a minimalistic interface can be an important factor to improve this. Of course, when using functionalities like querying data or using social collaborative features, this interface could expand a bit more, making it more noticeable to the user.

Figure 2.5: The menu interface is also minimalist. Adopted from Pollalis et al. [8]

2.3 User Interaction is Essential

2.3.1 Interaction in General

According to the Oxford Dictionary, interaction is the "communication or direct involvement with someone or something" [4]. In a museum context, this can be translated into 'the involvement of the visitor in an interactive exhibition'. We can wonder whether user interaction is important for a museum visit or not, or if it has a place in museums visits at all. For this, we look at an article by Bell [1], which describes some interesting statements and findings regarding museum interaction and the role of technology in it. For the largest part in the history of the modern museum, 'technology' and 'interaction' were keywords that did not belong to a museum experience. A museum has essentially been a place where spreading acquired knowledge was the main priority. The visitor was more or less a "passive recipient of the

[4] `https://en.oxforddictionaries.com/definition/interaction`

museum's messages", as Bell describes. This is in stark contrast with the evolution they are going trough since the beginning of the twenty-first century. More and more often, museums were being regarded as place for entertainment, or some kind of amusement park as Bell says. This re-interpretation of the educational and entertaining value had some implications for the design and setting of the museum. Curators needed to meet the expectations of the visitors, by adding interactive elements to their exhibitions.

It is important to note that not all technological additions contributed to this evolution. For instance, the audio guide handheld devices have been used quite extensively in museums. Although some people might like these, the technology is often considered to be hindering rather than improving the user experience. However, Bell [1] explains that audio guides do have an important role in guiding the museum visitor. They provide an way of accessing more information from the museum, and "empower the visitors and help to overcome the sense of alienation". This can also be linked directly to our first problem statement. Due to a shortage of available information in a museum gallery itself, people need some form of additional source in order to better understand the context of the gallery and grasp the ideas it wants to pass to its visitors. As Bell [1] notes, it seems that the audio guide tends to impede the social aspect of a museum visit. When people use these devices, they tend to isolate themselves from their surroundings, effectively preventing social interactions to take place.

As confirmed by the article, interaction plays a crucial role in a modern museum environment. It could be considered an 'optional necessity'. Not all museums promote user interaction, but it can add value and meaning to the museum visit. By adding new kinds of technology to the exhibitions, museums are also able to keep up with this multimedia and entertainment-driven evolution from the twenty-first century. Though, it is important to note that not all kinds of technology add interactive value to the exhibit, as is the case with audio tours.

2.3.2 Social Aspect of Interaction

Now, we want to zoom in on this, and look at the social part of this. When talking about social interaction, we can divide this is multiple categories: Local social interaction and external social interaction. With local social interaction, we mean the engagement between different visitors at a museum itself. External can be described as social interaction with online third-party platforms like Facebook or Twitter. Our research is more focused on the local variant. In the article from Bell [1], she also noted the importance of sociality. She explains that, while a museum tour needs to satisfy the visitor's need to be entertained and educated, it should also encourage social interactions.

An other study, conducted by Dieck et al. [11], in which they wanted to formulate the requirements for a wearable smart device in a museum context, they also mention the importance of social functions. They found that most visitors valued the integration of sharing functionality, either inside the museum context itself, or by means of third-party platform like Twitter or Facebook. It is easy to agree with this finding. When considering the use of a bleeding edge mixed reality platform like the Microsoft HoloLens, allowing for immersive interaction with both the digital and physical world simultaneously, it is no surprise that it can and will be used to share this interaction, or parts of it, in some way or another. At its core, mixed reality is about connecting the digital world with the physical one, and an MR-enabled device like the HoloLens acts as the medium to communicate with with the two.

2.4 Incorporation of Semantic Web

In our introduction, we already stated that often, museums do not offer an extensive description for every artwork they put on display. While a part of the visitors do not care a lot about this lack of available information, most modern museums also have an educational purpose. This aspects could play a more prominent role in the museum user experience if visitors could utilise some sort of information retrieval service, with which they could explore and learn as much as they want.

When designing an application with this explorative aspect in mind, one could implement some sort of querying functionality. This could allows users to search through semantic databases, and doing so, bring the InternetâĂŹs wealth of information to the museum gallery. However, this approach imposes some challenges that need to be overcome. Reynolds et al. [10] wrote an article about the inclusion of linked open data [5] in a mixed reality application. First of all, the authors mention the importance of management of the retrieved linked data. When doing a query on, for instance, all related artworks from a certain artist, the amount of data you get back needs to be filtered or sorted in some way. This allows the system to show it in a well-structured manner. They also remark that it needs to be considered whether these queries (to be more specific, SPARQL queries), have to be executed on the client device, or whether it is possible to delegate some part of this to a server side platform. Thirdly, they mention that even though linked data

[5] https://www.w3.org/DesignIssues/LinkedData.html

provides some provenance mechananisms through URIs (Uniform Resource Identifiers [6]), choosing which data sources to use for as library for your application has to be thought of carefully. [10] When looking at sources, we can consider two main collections of data: semantic databases, like dbpedia [7], and museum-specific sources. Dbpedia would be used to get the majority of our linked data, by using queries on its semantic database. Some museums, however, could have large collections of informations that have not yet been added as part of the semantic web. Ideally, this information could be added to the semantic web, allowing the Museum of the Future, as well as other systems using linked open data, to access this information. In a paper written by Hyvönen [5], they describe MuseumFinland, an application developed to facilitate the process of adding museum content to the semantic web. Their system transforms museum-specific database entries containing the data, first to XML cards, and then to RDF cards. By using what they call 'term cards', they allow museums to map their specific naming conventions to universal terms. A similar process could be used by museums to add their own database collection to dbpedia or another semantic database, allowing other systems to take advantage of this knowledge. These remarks can be taken into account when designing our Museum of the Future application. When a visitor wants to get additional information, we would need to limit the amount of content we show to the user.

2.5 Further Remarks Concerning Design

In the previous sections, we looked at different mixed reality projects, their unique features and how they compare against our proposed Museum of the Future application. Now, we will briefly mention some other remarks and thoughts which are important to consider when designing a mixed-reality application. After all, there are several specific requirements and design challenges to consider in order for the application to be user friendly and enjoyable to use. For this, we look at the study from Dieck et al. [11], which was also mentioned in section 2.3. They conducted a study at the Manchester Art Gallery in order to formulate a list of requirements for a wearable smart device in a museum context, which were Google Glasses [8] They made a test application where the users could interact with artwork in several ways. They could take pictures from it and share these pictures online. The application also provided the user with information about the

[6] https://en.wikipedia.org/wiki/Uniform_Resource_Identifier
[7] http://wiki.dbpedia.org/
[8] https://www.x.company/glass/

painting, the painter and related artworks.

The research also revealed some challenges to overcome when working on a mixed reality application for Google Glasses or similar hardware. Firstly, when working with this radically new kind of devices, the learning curve for working with these devices needs to be considered. Not everyone is able to operate new technological, consumer-oriented devices the first time using them, and this is especially true for these smart glasses, which introduce a entire new range of user controls and gestures.

In the article from Ding et al. [3], some additional insights concerning the adaptation of museum itself to the use mixed reality applications for museums are mentioned. From a practical point of view, the importance of a user-friendly hardware setup itself, and the museum's capability of running such setup, are not to be neglected. When looking at wireless, battery-based MR headsets like the HoloLens, battery life can be a challenge to overcome. In order to successfully deploy this kind of interactive exhibition, the museum using it needs to consider whether they can provide the necessary infrastructure to accommodate this. Besides, it is important to determine whether the application needs an persistent internet connection for it to work properly. This is another issue the museum needs to be aware of.

2.6 Requirements

The idea of the Museum of the Future application is take the current existing ideas and principles regarding Mixed Reality in museums, and combine them into a new application, which will form a framework for a Mixed Reality museum experience.

2.6.1 Requirements for tools

The goal of the project is to create a Mixed Reality application, so it is needless to say that this will be run on a Mixed Reality enabled device. Initially, the intention is to use the Microsoft HoloLens to run the application on. In the future, the application could even be adapted to support other devices that are capable of running Augmented Reality applications, like Google Tango [9] or ARCore [10]enabled devices.

As for software tools, the development of the applications will consist mainly of using Unity together with Visual Studio to develop the interface

[9]https://developers.google.com/tango/

[10]`https://developers.google.com/ar/`

and to deploy it to the HoloLens. Additional software libraries like the MixedRealityToolkit [11] and others are being used as well.

2.6.2 Functional Requirements

Access to Linked Information

First of all, being able to access a large database of linked information will play a major role in this application. The short description below the artwork will be complemented by additional related information from online (and local) sources. The application will make use of a semantic database (like for example DBPedia) and could even use museum-specific informative sources to provide the user a wealth of linked information. The artworks will act as the anchor point, which the system can use to query and retrieve related information. The user would be able to access a separate menu in the application. Here, they can use some kind of input method to formulate a specific query. This query could be a predefined one. For instance, when a visitor is looking at a certain painting, the application could propose queries like "Show some information about the family tree of the painter", or "Show some related artworks from this artist". On the other hand, when a user want to know very specific information, it should also be able to do some custom queries, like for example "What is the chemical composition of the paint used in this painting". Furthermore, the system could also show other related content, like for instance a video about how restoration of paintings are done, etc.

Museum Interaction and Community aspects

Another major part of the Museum of the Future application will be the interaction features. By using Mixed reality holographic elements, an artwork can be 'augmented' in several ways, creating a two-fold interaction between artwork and visitors. Obviously, it provides interaction between visitors and artworks. On the other hand, it also creates an interaction between visitors themselves. When looking at an artwork, a visitor can open a separate menu, where they can interact with the artwork and augment it in different ways. A simple way of interaction is adding some notes. This could be used to share thoughts, a little story related to the artwork or some questions that could be answered by others. Another way to 'augment' the artwork can be by drawing figures or lines on top of the artwork. For example, when a visitor spots a noteworthy little detail in a painting, they could draw a circle

[11] https://github.com/Microsoft/MixedRealityToolkit-Unity

around it, so other visitors will see it too. A final way of augmenting an artwork is by adding new information. When people with lots of expertise in a related domain visit an artwork exhibition, they could for example know some details or facts that aren't yet available through querying the semantic database. The expert could then add new information to the artwork, which in turn would be added to the semantic database.

One of the challenges that arise when allowing this extent of content creation and interaction, is the management of this new content. When lots of users add notes or questions to an artwork, the application has to be designed in a flexible way to ensure the User Interface won't be not cluttered. To achieve this, some kind of ranking system could be used. Notes, comments and questions can then be ordered (by date or popularity for instance), and only a few are shown at any given moment. The drawings could be shown as separate holographic layers, which could be turned on or off by the user.

Extending Experience Beyond Museum Visit

Visitors of a museum of the future will be exposed to even more information than a traditional museum. To help retaining all that information and to enable users to continue their cultural journey at home, the application could offer the possibility to bookmark the information seen during the visit. For instance, the user could be able to snapshot a view of the painting together with its notes or comments. This could then be linked with an online platform, so the user will be able to consult the info later.

Immersive User Interface

All features of the application need to be accessible to the end-user via a clean User Interface. This interface should be as minimalistic as possible, so that it does not interfere with the experience of being in the museum. The main home interface could show only icons at first at one or both sides of the painting or sculpture. Text should be kept to a minimum here, as this interface would probably be shown the majority of the time. When the user wants to access a certain features, it could use HoloLens gestures to open up a specific sub menu.

Queries

The linked information section should allow the user to input a query (using gestures, text input or maybe even voice) or use one of the predefined queries. When a query succeeds and returns related information, it should be shown in a way that does not cover up the artwork (or at least not entirely). This sub-menu could show a ‘query bar’ (similar to a search bar) where the user can visually see what query is being used, together with some buttons for the predefined queries. When related info has been found, it could be shown in the form of information cards, positioned next to the artwork.

Notes and questions

The notes section will show multiple different notes, ordered, and in a way that does not cover up the artwork. It should also allow the user to write a note themselves using gesture, text input or voice. This section could look similar to the ’cards’ mentioned earlier, and questions would be shown similarly.

Drawings

The drawing section should allow users to draw lines and figures by using gestures (or touch). This sub-menu would only need to show a drawing button to enable drawing, and toggles for enabling the visual layers of drawings by other visitors. These toggles wouls be shown next to the artwork, and would also be sorted (by popularity for instance), to avoid a cluttered interface.

3 Museum of the Future

In this chapter, we take a look at the theoretical solution of the Museum of the Future. First, we give an overview of the general application, starting from our theoretical requirements which we extracted from the related work. Then we discuss the process of designing the prototype solution in more detail, followed by some scenarios in which our application could be used. Finally, we formulate our findings as three requirements that can serve as a guideline the implementation of a full-fledged Mixed Reality Information Explorer as future work.

3.1 Application Overview

The Museum of the Future application consists of two main components: A mixed reality user interface, running on the Microsoft HoloLens, and a server to be queried. These two components correspond to our three problems which we focus on. The mixed reality UI represents the Immersive and Interactive domain. The Explorative aspect is driven by the server, which can query online available semantic data (Linked Open Data) to get related information about artworks the user sees, as illustrated in figure 3.1.

The user interface consists of the HoloLens-driven information in the form of holograms, and the real world environment upon which they are displayed. The HoloLens itself also gets information from the museum environment,

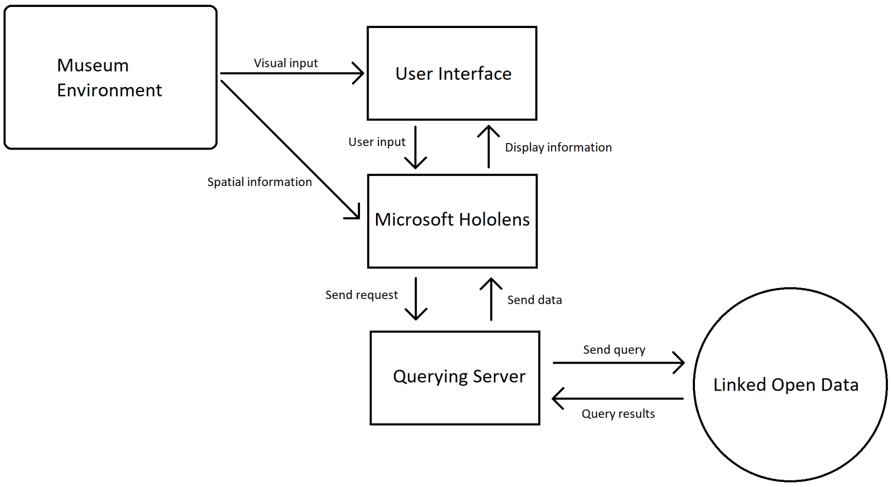

Figure 3.1: Museum of the Future overview

namely spatial information about the position of the user inside the museum. When a user interacts with the UI by the means of gestures (see Section 3.2.3), the HoloLens will get this information. When the user performs a query, the HoloLens sends this request to the server. The server is responsible for translating the HoloLens request to a SPARQL Query, which is then sent to a semantic database like DBPedia. Upon receiving the query results, the server sends the information back to the HoloLens, which in turn translates this information to displayable content.

3.2 Visual Solution

At the start of our thought process, we investigated the three domains as our primary focus for our application. The application had to be explorative, interactive and immersive. In our theoretical concepts, we mainly put focus on the visual part of the application.

3.2.1 Initial Concept

Initially, we examined the possibilities for creating an immersive user interface. After all, the application has created an engaging mixed reality environment, whilst not interfering with the core museum experience. In other terms, the interface should add some depth to the experience, while not obstructing the user's view. Our first theoretical concept tries to capture this design goal. As seen in Figure 3.2, the concept shows how a user would look at an artwork (in this case, a painting). In the centre, the user would see the artwork, with a small caption above the artwork containing name and artist. Several icons on both sides of the artwork represent the functionalities of the application. For instance, the question mark stands for 'Querying', while the notepad icon represents the 'Notes' section. This interface concept only depicts the home screen of the application, which would be de default user interface during a museum visit.

Figure 3.2: An early theoretical concept of the user interface

While this design contains some pointers in what the visual user interface could look like, there are some remarks concerning the usability that we discovered through discussion and some initial testing. We found that, even though the interface is looking quite minimalist already, it could still be obstructing the experience if this virtual icon layer stays visible while walking through the museum. It could even be possible that a visitor does not want to explore additional content during (a part of) their visit. This remark is taken into consideration in the following concepts.

3.2.2 Prototypical Interface Features

Quadrant Template

After thinking about the initial interface presented before, we considered the representation of data and information. Like our initial concept, minimising clutter and obstruction in the interface remained the main design goal. In order to fit a reasonable amount of data on the screen, we came up with 'Quadrant' design. The concept depicts a template interface which consists of four information areas: one for every corner of the visual field of view, hence the term 'quadrant'.

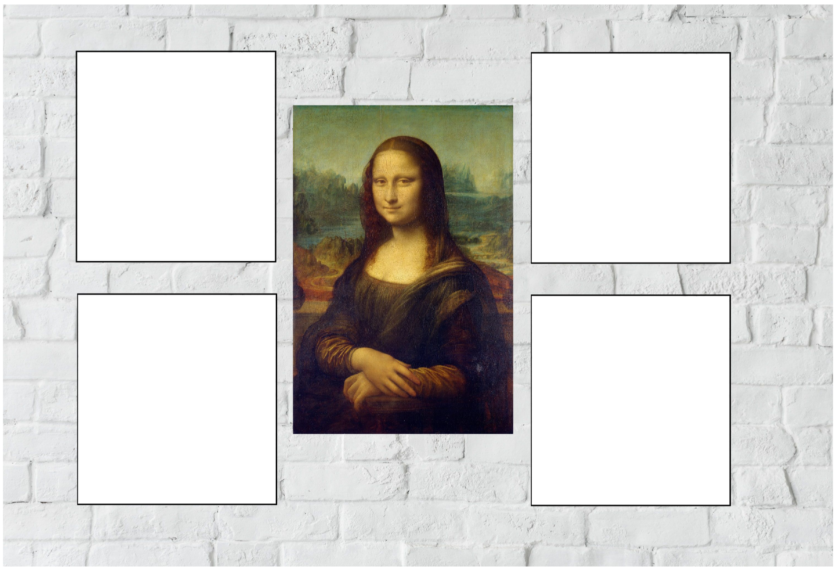

Figure 3.3: Quandrant design for displaying information

In terms of use, the quadrant interface could be used for most of the features that the application offers. For instance, when using the query feature to explore new information, the left quadrants could show relevant related information (semantic data), while the right side can be used for searching, applying filters or performing advanced queries. In reality however, this design is not usable for this application. The width of this layout causes parts of the interface to fall outside of the field of view of the HoloLens. This problem is described in Section 3.3.

3.2.3 Towards a Functional Prototype

After creating a design for the user interface, a functional UI prototype was made to showcase the core interface and interactions with the application.

It is a combination of our initial home screen, and the quadrant design for displaying content. Figure 3.4 shows the initial home screen interface concept brought to life. When walking around in the museum, the interface shows nothing but a '+'-sign, indicating that the interactive interface can be opened. When a user stands in front of an artwork and wishes to do some interaction, they can open the menu. This way, we keep the interface as minimalistic as possible. When the menu is opened, it shows the four main interaction buttons. The left two buttons depict, from top to bottom, Querying and Notes, while the buttons on the right represent Bookmarking and Navigation. These last two functionalities are envisioned for future work. Of the left two, only the Query button currently has some functionality. The Notes function would have been included in the application, but due to time constraints regarding the input problem and what it means to solve it (see Section 3.3), this is not the case for this prototype application.

Figure 3.5 depicts the redesigned quadrant-like interface when opening the Query menu. In here, the left area shows the information field, which is used to display content. The right side shows the artwork's name, as well as a text-button, to open predefined (default) content filters. These serve as a way to quickly find related information, without having to deal with manual querying. Currently, the description is being shown next to the artwork.

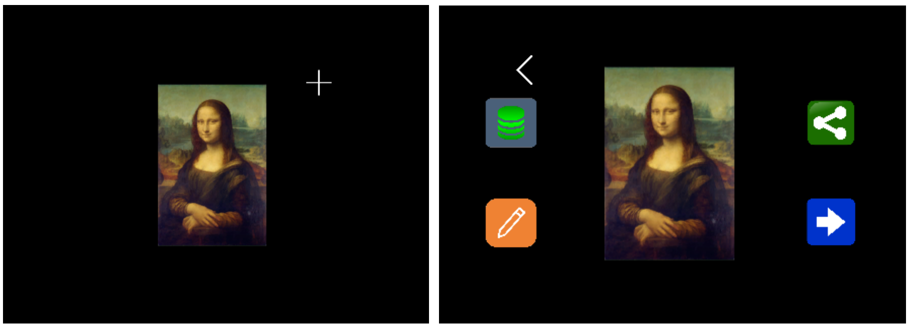

Figure 3.4: Main screen, with interface initially hidden behind '+'-sign

Interaction

When using our application, or most mixed reality-based applications for that matter, user interactions can be done by using hand gestures. The most used hand gesture for the HoloLens is the so-called 'Air Tap', in which the user interacts by holding their hand in front of them and perform an in-air

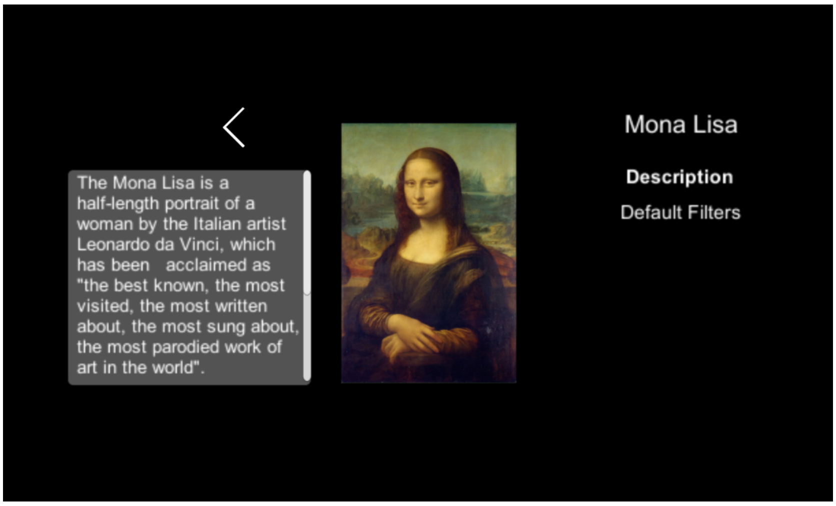

Figure 3.5: Minimal Quadrant-like interface for queries

'clicking' action with their index finger, as if they were using a computer mouse.

Dealing With Spatial Information

In order to use the system in a real-world environment, it needs a way to deal with spatial information. In order to do this, there are several possibilities: Image recognition, or Spatial Mapping.

Image recognition in a real world environment works by utilising visual tags. Each artwork would have its own tag containing a visual pattern, which acts as an unique identifier for the artwork. When the system is close enough to such a tag, it can then interpret the tag in order to know which artwork is in front of it.

Spatial Mapping is the alternative to this. With Spatial Mapping, the HoloLens itself contains a model with spatial (3D) information about the museum environment. By loading this model prior to starting the main application, the HoloLens is able to tell where the user is located in the museum room, by matching real-time scans of the environment to the pre-loaded world environment.

3.2.4 Scenarios

Throughout our discussion sessions, we analysed the typical museum interactions and scenarios. We then matched these scenarios with the functionalities of our application, resulting in a few specific use-case scenarios. We consider two main scenario's: Information Exploration and Interaction.

Information Exploration

This scenario represents a visitor that wants to know more information about a specific artwork. When the user is standing in front of the artwork, they tap the 'Query' icon. The interface pops up, from which the user can then ask for a specific query. (Note that we use predefined queries for the facilitation of the user input). The user confirms their query, which is den sent to the server. The information is retrieved from DBpedia, which is processed and send back to the HoloLens. Finally, the visitor sees the requested related information about the artwork in the information area of the UI.

Social Interaction

The second scenario involves interaction with the artwork itself. The user stands in front of the painting, and notices some specific detail about the artwork. It can then browse through a FAQ-section, which provides the most frequently asked questions from visitors about the artwork. This type of information can be provided by the museum itself. In a future version of this application, we envision the possibility of user-based content creation. (See Future Work, Section 6.2)

3.3 Design Requirements for a Mixed-Reality Information Explorer

During the development of this application, there are several findings, challenges and design implications we encountered concerning the use of mixed-reality in a museum context.

3.3.1 Intuitive Interaction

Virtual Keyboard

Dealing with user input in a mixed reality-driven application in itself is not straightforward. As pointed out in Section 3.2.3, the use of gestures is the most common and simple way to provide user input. However, when dealing with textual input or even queries, using a simple 'Air-tap'-gesture becomes a bit more tricky. When you want to do textual input only using the HoloLens, you generally have two options: a virtual keyboard, or voice commands. In its current form, the virtual keyboard of the HoloLens is theoretically usable, yet unwieldy and not very practical to use. Using this keyboard would be

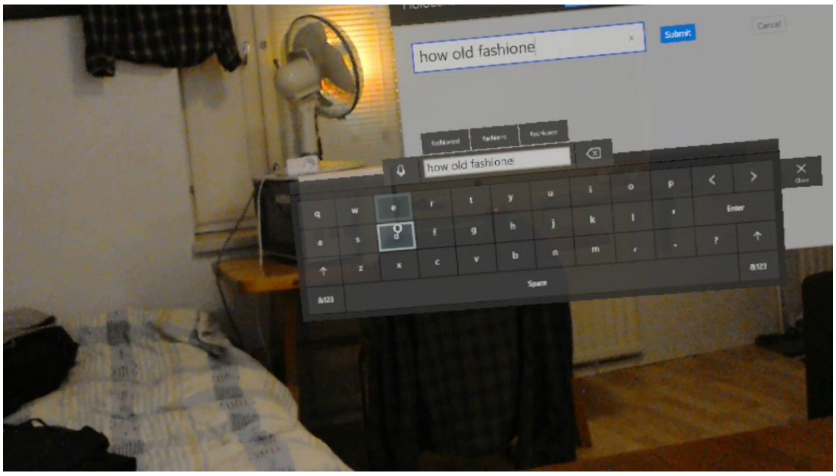

Figure 3.6: Hololens Keyboard (Wikipedia, Creative Commons)

slow, which could result in users having to type for possibly several minutes for a simple text input. Additionally, the virtual keyboard would obstruct a large portion of the users field of view, possibly breaking the immersive feeling. This contradicts one of our main goal of immersion.

Voice Commands

A logical alternative to textual input in a mixed reality context would be voice-based interaction. While voice input is a possibility, it is not quite suitable to use in a museum environment which tends to be a relatively quiet setting. As voice input generally requires well articulated words or sentences, mumbling or talking quietly is not really an option. When scaling this to many visitors using voice commands at the same time, the noise level would increase by a fair amount. This could be a source of nuisance for other visitors that prefer not to use the system or like the near-silent environment a museum generally offers. Of course, in museums or other environments where this noise-convenience trade-off can be made, using voice input might be a great way to introduce more advanced textual user input.

Multimodal Input as a Solution

An alternative for museums where the previously mentioned trade-off cannot be made, would be the use of an external input device. Today, a large percentage of people carries a smartphone with them throughout the day. An application like Museum of the Future could take advantage of this by introducing the functionality of multimodal user input, where they could use their smartphone as the primary input device for textual input inside the HoloLens application. This can be accomplished by introducing a proprietary app which visitors can download, should they want to use their phone as an input device. With this kind of setup, doing text input becomes almost effortless, as most people are already accustomed to a smartphone keyboard. Although the user would have to look at their smartphone for a brief period, thus shortly breaking the immersion, this setup would be more viable and easy solution for the problem.

3.3.2 Easy Query Handling

Ideally, doing dynamic or manual queries would allow visitors to find all linked information they would want to know. It would mean that a visitor can input specific keywords or even their own custom query. This is how we initially envisioned the exploration process should be. However, there are several arguments why this would not be suitable in a museum context. First of all, the vast majority of museum visitors do not have the knowledge to write correct SPARQL queries. But still, even when using a simplified input form where users only have to enter keywords and use filters, the problem of input remains.

3.3.3 Immersion by Choosing Right Hardware

Hardware Limitation of HoloLens Limits Immersion

When designing an MR application for mixed reality glasses, one has to take into account all possible hardware limitations. This is especially true when developing for the Microsoft HoloLens. For instance, during the design process of our UI, we realised that while our Quadrant interface (Section 3.2) could have been usable under perfect circumstances, the design as-is would have been impossible to use in an engaging manner on the HoloLens. The culprit is its very limited field-of-view (FOV). It only has a diagonal FOV of about 35 degrees, which limits the amount of content that can be displayed in a user's field of view of the user. Add to this our goal of keeping the centre free of content in order to not obstruct the user's view of the painting, and we quickly concluded that we cannot use this type of interface without making compromises of the content representation.

Future Hardware to the Rescue

In the near future, this limitation will probably be less of an issue. Newer mixed reality glasses will likely have a larger field of view than the HoloLens, thus enabling the use of more expansive user interfaces. This would greatly increase the possible level of interaction and allow developers to push more content in an elegantly presented way to the end user.

4

Implementation

In this chapter, we will discuss the general implementation of our application and the software tools and technologies used in this project. We will first give an overview of the software architecture, followed by a more detailed look at the specific components.

4.1 Overview

The implementation of our Museum of the Future application has an architecture which is almost a 1:1 mapping from the theoretical solution components. Figure 4.1 shows these components.

The client side, which runs on the HoloLens, consists of two 'subcomponents': The user interface and the client application. These are considered separate components because of the nature of their design. The UI is based on Unity-concepts, while the Client application itself is interconnected with the UI, but developed using Unity-based C# code. The server side on the other hand runs on a separate machine, which is a laptop in our case. It runs on Java, and uses a Socket-based connection for communication with the Client application.

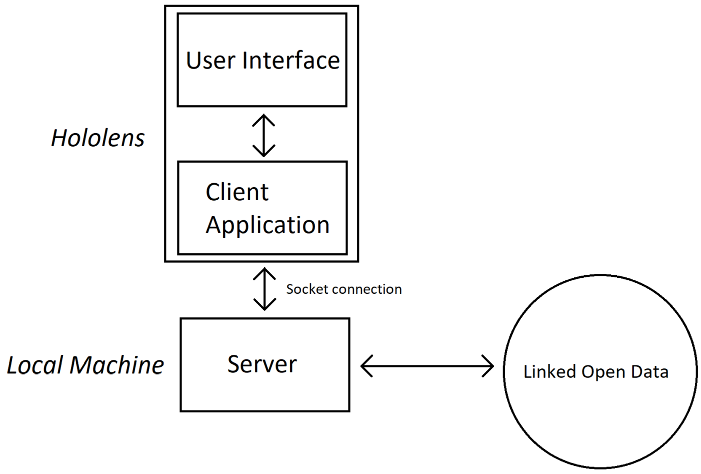

Figure 4.1: Museum of the Future software architecture

4.2 Client application

The client component of Museum of the Future consists of the user interface itself and the accompanying logic to make it run properly. More specifically, the client application houses logic for defining the UI, code for network communication and query handling. These components are all coded in C#.

4.2.1 User Interface

The user interface has been developed using Unity (version 2017.2.1f1). It consists elements called GameObjects, which are Unity-specific visible (or non-visible) elements in the Unity world environment. More specifically, the User interface contains so-called UI-elements, which are specifically made for creating overlay based user interfaces. Basic interactions and button presses (like the icons of the main menu) are implemented using Unity's built-in button scripts. For more complex interactions or triggers for queries, we use custom Unity-compatible C# scripts. In order to make the application compatible with the HoloLens, made use of the HoloToolkit [1]

[1] Note: The name of HoloToolkit has been changed into MixedRealityToolkit: `https://github.com/Microsoft/MixedRealityToolkit-Unity`

4.2.2 Networking

The networking part of this application uses a socket connection, also written in C#. The socket connection sends and receives data as a stream of bytes. Specifically, the actual communication uses JSON formatted data, which is converted in this script to a representable text format. This way, the application can load the text into the existing text-field (UI element of the interface), so the user can see the this information.

4.3 Server

The server is a separate application, coded in Java. It consists of several parts responsible for its operation. The most important component is the DataFetcher, which is responsible for the interaction with the semantic database. It uses the Jena library [2] for handling the SPARQL Queries. The SPARQL Listing 4.1 shows an example query for getting all related paintings for a certain painter. When given a certain name of a painter, the server will replace the name variable by the exact name, thus applying a filter. This way, we can get all related paintings for a certain painter. (Note that this example excluded the Java variable in order to show the complete SPARQL Query). These queries are sent to the DBpedia SPARQL endpoint. The retrieved data is formatted as JSON, in order to send it to the client application.

```
PREFIX foaf:        <http://xmlns.com/foaf/0.1/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs:        <http://www.w3.org/2000/01/rdf-schema#>
PREFIX owl:         <http://www.w3.org/2002/07/owl#>
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX dbpedia:     <http://dbpedia.org/property/>
PREFIX sindicetech: <http://sindicetech.com/ontology/>

SELECT ?Name ?RelatedWork WHERE {
?painting a dbo:Artwork .
?painting dbo:author ?painter.
?painter rdfs:label ?Name .
?painting rdfs:label ?RelatedWork .


FILTER (LANG(?Name) = 'en')
FILTER (LANG(?RelatedWork) = 'en')
}
LIMIT 100
```

[2] https://jena.apache.org/

Listing 4.1: Example SPARQL query

The networking part is based on a socket connection, just like the client-side. It uses the built-in java.net sockets in order to send a stream of bytes to the client.

5 Evaluation and Reflection

In this chapter, we take a look at the the testing and evaluation of our application. We also reflect on the difficulties and challenges we encountered during development.

5.1 Testing

5.1.1 Client Side

Testing has been done in several ways during implementation of this application. On one hand, for the client-side of our application, we mainly used the Unity Editor and the HoloLens for testing. At the start of the UI design, we mainly ran tests using the Unity Editor to explore the possible interactions, menus and layout styles. After coming up with a possible concept, we then ran this on the HoloLens to test interactions using gestures. These tests gave us feedback on how to adapt the interface to get better interaction, and even forced us to rethink the core UI concept from which we originally started. Initially, we wanted to make a 3D interface that acts as a hologram in the real world. However, this had some major implications on both the visual side of the UI, as well as the core of the Client application. This option turned out to be much more challenging and time consuming, while also possibly being less visually appealing and intuitive. This led us to changing it into the 2D 'overlay'-style interface that we have now.

5.1.2 Server

The server side testing was done using the Debugging mode of the IDE (IntelliJ). For instance, we did tests on connecting with DBpedia for data retrieval. In order to test the Socket connection, we used an external program called Hercules [1].

5.2 Challenges

In the process of developing this prototype application, we encountered several (unforeseen) challenges and difficulties regarding implementation.

Being cutting edge technology, developing for Microsoft HoloLens is not trivial. Apart from designing and thinking out a way to code the application components themselves, there are a lot of technical things we have to take into account. First of all, the main challenge actually comes from the platform on which the application runs itself, namely Windows. During development of this very project, Microsoft pushed several major updates to its Windows 10 operating system, which caused (temporary) compatibility issues regarding coding for the HoloLens. Secondly, the combined use of the Unity engine and the use of the Universal Windows Platform has posed an additional challenge. When we wanted to use an external library to facilitate the use of some functionality, like handling JSON for instance, we could not just use any simple C# library for this. Every single library we wanted to use, had to be specifically made for use in HoloLens development, as both Unity and UWP have specific requirements concerning what functionality is available. This significantly reduced the amount of libraries that we could use for this application. However, both components were a necessity, as we needed Unity for designing the application in a 3D environment, and Universal Windows Platform for running the application on the HoloLens as a Microsoft App.

[1] `https://www.hw-group.com/software/hercules-setup-utility`

6 Conclusion

6.1 Conclusion

We presented Museum of the Future, which is a mixed reality information explorer. With this project, we aimed to create a prototype offering an immersive museum experience using the Microsoft HoloLens. In related work, we found that there are already a lot of projects that can only partially solve our problem statements. However, there has not been a project that combines information exploration, advanced interaction and immersion. With our prototype, we show an application that transforms a normal museum experience into a more interactive one, by incorporating explorative functionalities. By using SPARQL queries, we allow users to quickly find related information about the artwork while they are looking at it. Designing our prototype has led to the discovery of several important findings, which we reformulated as three requirements for future researchers. These requirements directly link back to our initial problem statements. The lack of interaction in museums can be solved, partially by using the HoloLens and its gesture system, and partially by introducing an intuitive way of doing more complex input. Allowing queries helps to bring the information of the Internet right to the eyes of the museum visitor, but there is a need for handling these queries in an easy way, by introducing filters and predefined queries, or even keyword based query creation. Finally, the level of immersion of an MR application can only be as high as the hardware allows. Making the correct choice of what hardware to use and not to use make sure that the application can be made the way its creators envisioned it. With our prototype and more importantly, these guidelines in mind, there are a lot of research opportunities that can be addressed in future work.

6.2 Future Work

The prototype solution of this thesis merely acts as a concept of what would be the final solution. There are several aspects of the application that have not yet been fully implemented. Some parts we are envisioning, which are not the focus of this thesis, can be important for the total user experience. In future work, several missing features that have been mentioned earlier can be added. The 'Notes'-feature can be added by also introducing a intuitive way to handle user input, like for example a smartphone. Bookmarking functionality can be added by implementing a way for visitors to save the identifier of an artwork, so they can look this at later, or even at home trough a Web-Service. The navigation component can also enhance the experience considerably, by providing an easy way for visitors to find other artworks in the same museum, and possibly even guiding them to that artwork by the means of holographic arrows. Lastly, the core feature of this application, which is information exploration through querying semantic databases, can be further improved. This could be achieved by allowing batch queries to be executed, for which the user can select multiple (related) characteristics about the artwork. Albeit at the cost of some time to process the batch query, the system could then serve the information in a textual or graphical way, allowing users to really see relations between the data in an intuitive way.

Bibliography

[1] Genevieve Bell. Making sense of museums: The museum as 'cultural ecology'. *Intel Labs*, Jun 2002.

[2] Chia-Yen Chen, Bao Rong Chang, and Po-Sen Huang. Multimedia augmented reality information system for museum guidance. *Personal Ubiquitous Comput.*, 18(2):315–322, Feburary 2014.

[3] Mandy Ding. Augmented reality in museums. *n.p.*, pages 1–12, 2017.

[4] Tony Hall, Luigina Ciolfi, Liam Bannon, Mike Fraser, Steve Benford, John Bowers, Chris Greenhalgh, Sten-Olof Hellström, Shahram Izadi, Holger Schnädelbach, and Martin Flintham. The visitor as virtual archaeologist: Explorations in mixed reality technology to enhance educational and social interaction in the museum. In *Proceedings of the 2001 Conference on Virtual Reality, Archeology, and Cultural Heritage*, VAST 2001, pages 91–96, New York, USA, 2001. ACM.

[5] Eero Hyvönen, Miikka Junnila, Suvi Kettula, Eetu Mäkelä, Samppa Saarela, Mirva Salminen, Ahti Syreeni, Arttu Valo, and Kim Viljanen. Publishing museum collections on the semantic web: The museumfinland portal. In *Proceedings of the 13th International World Wide Web Conference on Alternate Track Papers &Amp; Posters*, WWW Alt. 2004, pages 418–419, New York, USA, 2004. ACM.

[6] Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies*, volume 2351, pages 282–293. International Society for Optics and Photonics, 1995.

[7] Ken Peffers, Tuure Tuunanen, Marcus Rothenberger, and Samir Chatterjee. A design science research methodology for information systems research. *J. Manage. Inf. Syst.*, 24(3):45–77, December 2007.

[8] Christina Pollalis, Whitney Fahnbulleh, Jordan Tynes, and Orit Shaer. Holomuse: Enhancing engagement with archaeological artifacts through gesture-based interaction with holograms. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*, TEI 2017, pages 565–570, New York, USA, 2017. ACM.

[9] Klen Pucihar, Matjaž Kljun, and Paul Coulton. Playing with the artworks: Engaging with art through an augmented reality game. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA 2016, pages 1842–1848, New York, USA, 2016. ACM.

[10] Vinny Reynolds, Michael Hausenblas, Axel Polleres, Manfred Hauswirth, and Vinod Hegde. Exploiting linked open data for mobile augmented reality. In *W3C Workshop Augmented Reality on the Web*, volume 1. June, 2010.

[11] M. Claudia tom Dieck, Timothy Jung, and Dai-In Han. Mapping requirements for the wearable smart glasses augmented reality museum application. *Journal of Hospitality and Tourism Technology*, 7(3):230–253, 2016.