HoloNav: A Mixed Reality Indoor Navigation System

Interdisciplinary Project Thesis

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Abstract

Wayfinding indoors still has not been studied to the same extent as wayfinding outdoors. Though some approaches have been explored in recent studies for indoor navigation, no standard methods exist. Motivated recently-emersed Augmented Reality and Mixed Reality technologies, this research demonstrates a feasible workflow of developing a Mixed Reality indoor navigation system, HoloNav, on Microsoft HoloLens 2. The system utilized Azure Spatial Anchors as virtual markers for labeling landmarks. A user study was conducted on the two variants of HoloNav designed with two different navigation visualizations to help gain information about the kind of visualizations preferred in a Mixed Reality navigation system. Furthermore, the benefits of Mixed Reality navigation systems compared to traditional systems are also highlighted and discussed.

The implemented system contains two main functionalities: Mapping and Navigation. The mapping part is developed to manage the Azure Spatial Anchors and allow the user to create new anchors of interest in the environment. The navigation part focused on the wayfinding between two locations. The user can choose from the created anchors an origin and a destination. The system calculates the shortest path between these two anchors using Dijkstra's algorithm and renders the navigation visualizations indicating the route. The users will be guided either with transition lines on the ground or a floating arrow showing the direction to walk. Additionally, a static or a hand-invoked mini-map integrated into the system helps the user to locate them in the building.

From the user study on the two variants of HoloNav, it can be concluded that the visualization preferences mainly vary from users to users. In general, the transition lines were easier to follow. Moreover, the hand-invoke mini-map was more favored by the users. Color styles and symbologies of the mini-map do not make many differences. The benefits of Mixed Reality navigation systems lie in the efficient navigation and less perception load. Moreover, less wrong-turn were made compared to navigating with traditional navigation systems like Google Maps. Therefore, it can be argued that the system helps the user to navigate faster and in a more reliable manner to the chosen destination. This study demonstrates the possibilities for the implementation of further Mixed Reality navigation systems and highlights the problems involved.

Keywords. Indoor Navigation System, Mixed Reality, Augmented Reality, Microsoft HoloLens 2, Azure Spatial Anchors

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction and Motivation

Navigation indoors has not yet been researched as well as it is for outdoors. For outdoor spaces, a wide range of navigation systems is available to the public; for example, mobile applications, navigation systems on vehicles, etc. For indoor spaces, there are also some existing approaches, such as integrating traditional paper-based maps or building plans (e.g. Google Maps). However, the conventional approaches for localization outdoors (e.g. GPS) can not be simply adapted for indoors due to complicated building structures and technical limitations (e.g. weak GPS signals). The major problem is that there is no effective tracking methods in the compensation of weak GPS signals. "Longer integration times, effective strong/weak signal decoupling, and correct multipath detection and rejection" would be needed to achieve the localization [4]. Therefore, it is important to find new solutions for indoor navigation.

Combining navigating with new technologies like Augmented Reality (AR) and Mixed Reality (MR) opens new possibilities because devices like the Microsoft HoloLens 2 are equipped with various sensors and support methods like spatial mapping. Spatial mapping can be a good approach for finding solutions for localization. Already existing tools, like Azure Spatial Anchors (ASA) can be used as virtual markers for places and can be recognized by the devices at any time. There are also other benefits with AR and MR. One can assume that navigation with AR is very similar to wayfinding in the real world. Hence, the user experiences with such systems are very intuitive. In fact, AR/MR applications even allow more additional information to be displayed, which is considered one of the main advantages for a successful wayfinding[20].

Motivated by the benefit of AR/MR devices, the goal of this interdisciplinary project is to build a navigation system working on MR glasses. The selected platform is Microsoft HoloLens 2 and the developed system is called HoloNav, a combination of HoloLens and navigation. The first part of the project is the development of a working navigation system for indoors with different User Interfaces (UIs) elements like arrows, transition lines, and a mini-map. The second part of the study is to test the developed system in a user study to see benefits and opportunities for improvement.

1.2 Research Questions

This project concentrates not only on the implementation of a workable application but also on the design options of MR navigation systems (e.g. different visualizations) and the comparison of such systems with the traditional approaches. Therefore, the new navigation system (HoloNav) is designed and developed to contribute to the following research questions.

1. What kind of visualization is preferred in Mixed Reality navigation systems?
2. What are the benefits of a Mixed Reality navigation system compared to traditional navigation systems for wayfinding in indoor spaces?

The user study after the implementation of HoloNav should help to answer the following questions. Accordingly, three hypotheses are formulated and serve as a basis for the questionnaires and observations during the user study. The three Hypothesis are:

1. HoloNav has good system usability.
2. HoloNav is better than Google Maps in terms of efficiency.
3. HoloNav is better than Google Maps in terms of correctness.

To answer the first research question, two variants of HoloNav were developed. They differ slightly in the UIs, explicitly in the visualization of the navigation guides as well as in the visualization and interaction with the mini-map. One system is developed with a guiding arrow showing the way to go and a non-static mini-map which can be shown by a hand-command. A slightly different UI is shown in the second development. This contains instead of a guiding arrow a transition line connecting passing stones. The mini-map here is permanent and always in the field of view of the user. More detailed descriptions of the two systems are explained later in this report (Chapter 3).

1.3 Objective of the Work

Based on the research questions, three major objectives are defined for this project:

1. Develop and compare different effective and visually pleasing interaction concept for navigating indoors
2. Create a routable 3D representation of the ETH HIL Building
3. Create a meaningful and effective interactive mini-map visualizing the current location

These objectives help structure the project. For every objective, the minimal, medium, and maximal solutions are defined.

For the first objective, the minimal solution is to design and implement the representation of the routes. For example, using cubes as the indicators of places and connecting these cubes to form the transition lines as one type of visualizations for navigation. For the medium solution, more advanced navigation visualizations (e.g. arrow) are implemented and used for guiding. For the maximum solution, the navigation visualization is more mixed with the reality; for example, the arrows are embedded to the ground, marking the way on the floor and voice commands are added. Examples for voice commands can be updating the distances before the next turn or giving safety instructions such as warning the user with stairs and glass doors in case users are somewhat distracted by MR and less focused on the real environment.

For the second objective, the minimal solution allows the user to select out of two pre-rendered routes for navigation. For example, the use can choose to navigate either between room A and room B, or between room C and D. For the medium solution, it should be possible to navigate on one floor by choosing any origin and destination point. Mostly all rooms should be available here to navigate from every position on this floor. The maximum solution would then be the expansion to the entire building including elevators and stairs.

The third and last objective is to implement a mini-map which works as an overview and should help the users to locate themselves in the building. The minimal solution is to show the current floor, the temporary position of the user as well as the chosen destination. The medium solution should show the remaining part of the route from the actual position to the destination. To achieve the maximum solution, the mini-map supports dynamic rotation according to the users' direction as a forward-up map.

1.4 Overview of the Contents

In the next chapter (Chapter 2), the related works are summarized, where aspects of indoor navigation, the benefits of AR and MR as well as the techniques for localization with these devices are discussed. Subsequently, Chapter 3 explains the study area and the used data, the implementation details about HoloNav, the structure, tools, and statistical methods of the user study. In Chapter 4, the different parts of the application are demonstrated and the hypotheses together with the statistics from the user study will be presented. Later, the in-depth interpretation of results, the discussion of results with respect to the related research, and the contribution of the work are given in Chapter 5. Finally, the project is concluded in Chapter 6 with a summary of the work and a future outlook.

Chapter 2

Related Work

2.1 Key Aspects of Indoor Navigation

Navigation methods. There are different types of methods for human navigation in indoor or outdoor spaces. One method is path integration, which means if people know their origin point on the map, they are able to orient themselves relative to the origin given the paths in the environment and the map. Another method is landmark-based navigation, in which perceptual cues are combined with an external or cognitive map. During the navigation process, the recognition of landmarks, as well as the estimation of distance, is mostly done by visual sense [6].

Landmarks. Similar to the outdoor navigation, where landmarks such as famous buildings, rivers, etc. are used for localization [3], landmarks are also a great help for indoor navigation. Landmarks in indoor spaces (e.g. good readable room numbers, stairs, pillars, or posters, etc.) can be used as guideposts. It is also worth mentioning that it would be useful if architects would include landmarks when planning a building to later help people (or even robots in the future) to navigate in the building. This would be helpful in normal situations where people would like to navigate through the building, but also particularly important in urgent situations of disasters or emergency evacuations [8].

Visualization of Navigation Systems. There exist different approaches in some already existing systems. It can be in various forms such as two-dimensional (2D) maps and three-dimensional (3D) models. A typical 2D-visualization used in navigation systems is a simple map, which shows labeled/unlabeled rooms forming by walls. Other examples are digital maps, such as Google Maps or similar products. Depending on the system, there can also exist additional information shown to the user; for example, a pinpoint indicating the current position of the user or auxiliary information about nearby landmarks. Navigation systems can also be in 3D form that 3D models are used to visualize the environment with even more extra information such as the location of the next doors, etc. [6].

Interaction. The interactions between the navigation system and the users are one of the most important elements of a good navigation system. The interactions can be categorized into system feedback and user input. System feedback is generally used to help the user to navigate. Different techniques can be applied including visual, audio, and haptic feedback. The most commonly-adopted technique is using some displays to show information about the direction visually. The problem with this approach is, however, looking at a screen can impede safety concerns because the users cannot focus on the environment with their full attention. Speech-based systems work by providing audio guidance for the user. They do not require visual concentration, yet they are normally language-dependent. Another option can be haptic-based interfaces, for example, with vibration motors. The drawback of this approach is that the vibration patterns need to be learned by heart, which may increase the perception load of the users. For user input, the common approaches are using push-button, keypad, speech recognition, or touch screen, depending on the used device [6].

2.2 Indoor Localization Techniques

The primary task of building an indoor navigation system is the localization of the devices or users in the environment. [23] has summarized and compared various techniques used for such a task. Although GPS techniques are widely used in outdoor localization, its application for indoor is not promising. Other techniques primarily used for indoor scenarios such as ZigBee, WiFi-, and Bluetooth-based approaches, however, have the accuracy of around 5m levels, which are not sufficient for standalone navigation and are recommended to work as an aid to other techniques. In addition, with the recent development of computer vision and Simultaneous Localization And Mapping (SLAM) technologies, marker-based algorithms are widely used for localization. For example, Hübner et al. [11] used several markers attached to the walls to align the virtual building model with the physical environment. The accuracy of such algorithms can be optimized down to sub-meter levels and are ideal for accurate navigation demands.

Similar to a marker in a physical environment, a spatial anchor (i.e. a point in the environment), whose location is persistently tracked by the system, can be considered as virtual markers in AR applications. As a key shareholder in the market, Microsoft releases public ASA, a cloud-based asynchronous spatial anchor service [14]. With ASA, users can mark precise points of interest, and recall those points from any devices. More importantly, the created spatial anchors can be connected and the coordinates of the anchors are natively registered, no further operations need to be performed. Therefore, it can be used to record the locations in the environment and later used for navigation purposes. For example, Yukun and Yuhang [24] developed an indoor navigation application with ASA in Android. They used ASA to mark several virtual landmarks and the application is able to navigate the users between these landmarks in the building.

2.3 Augmented Reality and Mixed Reality for Navigation

In recent years, AR and MR have gained popularity in various applications including indoor navigation. AR and MR applications augment digital content on top of the real environment enabling more appealing and intuitive user experiences. Especially in indoor navigation applications, the constant instructions provided by AR/MR devices can lead to less memory load and lower mental pressure on users [23]. Taking advantages of AR and MR, much additional information can also be attached to the application, providing further support for the navigation and making the navigation process even more efficient [21].

AR/MR-based indoor navigation systems are generally implemented on handheld AR-supported mobile devices (e.g. smartphones with AR Kits) or head-mounted AR headset (e.g. Google Glasses, Microsoft HoloLens). On the one hand, AR-supported mobile devices have the benefits of low cost, portable and better accessibility. On the other hand, head-mounted AR devices with more advanced sensors and better computation capacity are more reliable in the term of better localization accuracy [11]. Moreover, as the orientation of the AR headsets is usually internally tracked by the equipment, the users' hands can be freed and less user manipulation is required [21]. Microsoft HoloLens, as a typical MR device in the market, its capability of real-time spatial mapping and reasoning has been evaluated to be an off-the-shelf tool for indoor mapping applications [10]; hence it is a good option for the indoor navigation application. Many studies have demonstrate the usability of HoloLens for indoor navigation applications (e.g. [9], [11], etc.).

Chapter 3

Methodology

3.1 Study Area and Data

3.1.1 Study Area

The study area is restricted to one building. In theory, the application should work in any building of interest, yet for the demonstration of this project, The HIL building, ETH Zurich is selected as the study area. The building has a complex shape so it is difficult to orient in particular for visitors who are not familiar with it. The wayfinding in the HIL building is usually supported by floor plans which show every room and their number. The floors are numerate with letters (Figure 3.1).

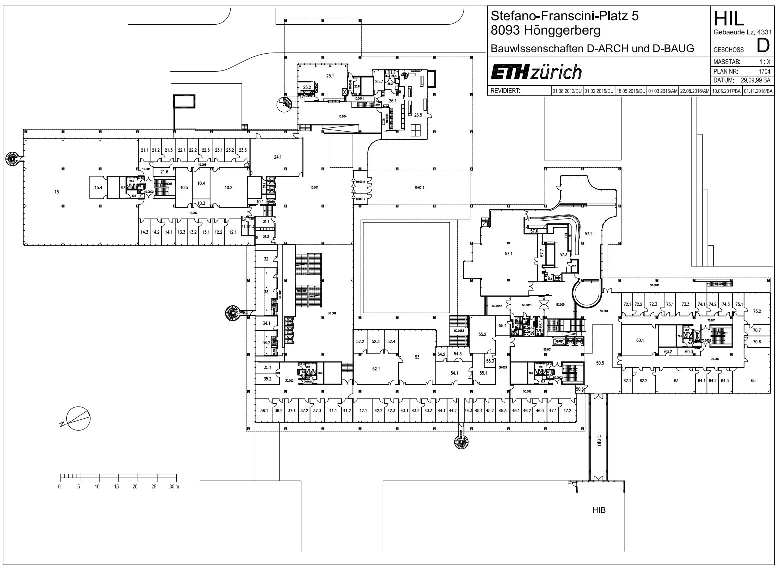


Figure 3.1: Plan of the D-floor of HIL building of ETH Zurich [5]

3.1.2 Data

Self-acquired Data

Landmarks. Landmarks including rooms and some other location of interest (e.g. doors, open spaces, etc.) are manually marked with ASA. The position of every anchor is stored and synchronized to the cloud, which can be used for future navigation. The room number is recorded as the name of the anchor together with its type (e.g. "main" for rooms and "connect" for important connecting points in the study area). These information as well as the ASA ID, which uniquely identifies the ASA are uploaded directly to the table on the Azure Table Storage (ATS) database.

Mini-Map anchors. During the placing of the ASA on the mapping part, a sketch, marking the position of every spatial anchor in the real world, needs to be created to approximate positions on the mini-map with anchors (i.e. game objects) manually on Unity. The choice of this method is argued in Chapter 5.4.

External Data

3D Building model. To make the overview possible on the mini-map, a 3D model of the study area was used to compute different visualization types and make also graphical comparisons possible. The 3D model of the HIL building is abstracted to cubic volumes to approximate the reality (Figure 3.2). A provided 3D model from IKG is used [12]. The model is then sliced and adapted manually using ESRI CityEngine to create a representation of every floor on different layers. Only the floor, which the user is currently on, will be active and the corresponding layers will be enabled and disabled every time the user changes the floor. With this feature, the model can be directly usable for an HoloNav version which supports multi-floor navigations. Other external data source that can be open-source datasets, such as Open Street Maps data. These data are useful yet less precise [13]. The advantage of this source is the easy accessibility of the 3D representations of different buildings and the consistency in visualization.

Symbology. Some symbols like pins and flags are downloaded from the Free3D website [7] in the format of `.obj`. These objects are chosen because they may be similar to users' habits for navigation. The objects are then imported to Unity and the mesh of each object is linked to the corresponding graphical elements. The other graphical elements, such as cubes, stars, and spheres, are directly found in the Unity default meshes.

Figure 3.2: 3D model of the ETH HIL Building (textured) used for the mini-map and Open Street Maps 3D model in background (grey). [12]

3.2 Procedure

3.2.1 Overview

The development of HoloNav relies on the communication between the native HoloLens application and two Azure Cloud Service (ACS): ASA and ATS. Specifically, the native HoloLens 2 application is the graphical UI for both acquiring user input and displaying navigation visualizations. Together with HoloLens 2 and the ASAs, the localization of the user and rooms in the HIL building is achieved. As the query of ASAs requires ASA identifiers (IDs), ATS is used as the back-end of the application to store ASA IDs as well as the auxiliary information about the anchors. Functionally divided, the application consists of two parts: the mapping and navigation process. In the mapping mode, the users create an anchor in front of every door in the HIL building and populate some useful information about the anchor (e.g. name, type, etc.). In the navigation mode, the users select the origin and destination of a route and start a navigation process. The detailed workflow of the two procedures will be explained later in Chapter 3.2.3 and 3.2.4. To compare the effects of different navigation visualizations on the overall performance of the navigation procedure, two versions of HoloNav with two different navigation visualizations and mini-maps are implemented and tested separately (Table 3.1).

Version	**HoloNav 1**	**HoloNav 2**
Mini-map	Hand-invoke mini-map (triggered and oriented by right hand)	Permanent mini-map (stays at the lower right corner in the user's field of view)
Navigation Visualization	Floating arrow pointing to the next position	Transition lines connecting positions on the ground

Table 3.1: Two versions of HoloNav

3.2.2 Application Development Architecture

HoloNav 1 and HoloNav 2 are implemented in Unity Game Engine and the overall design of the application architecture follows the *Project Structure Design* principle. Figure 3.3 depicts the architecture of the application, which consists of five essential elements: the data structures, the game objects, the managers, the controllers, and the UI components.

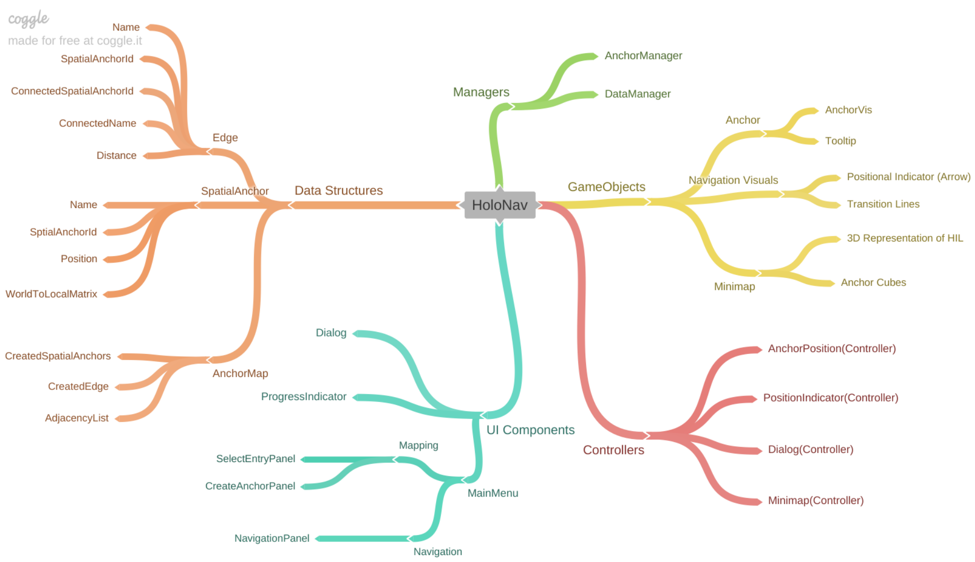


Figure 3.3: Architecture design of the HoloNav

Data Structures

The data structures include three classes used to store anchor related information and also define the schema of tables in the ATS database. The class `Spatial Anchor` contains information about the anchor, including the name, type, ID of the anchor as well as its position in the local frame. The `Edge` class contains information about the edge in the graph, where the information of every two connected spatial anchors, as well as the distance between them, are stored. The `Anchor Map` class contains a reference to the lists of created Spatial Anchor items, and Edge items as well as the Adjacent List, which represents the graph for navigation.

Game Objects

To visualize the navigation guidance, three game objects are created. The `AnchorPosition` game object is a 3D cube with a tooltip indicating the name of the cube and represents the location of every spatial anchor in the environment. For navigation visualizations, the two types of visualizations are implemented: a positional indicator (in the form of a 3D floating arrow), and 3D transition lines. The `Mini-map` game object shows an overview of the routes and consists of both a representation of HIL and anchors that approximate users' position in the building. The `Mini-map` is implemented in both the interactive 3D version for HoloNav 1, which can be triggered by raising the right hand, and the permanent 2D version, which shows constantly in the users' field of view for HoloNav 2.

Managers

The communication of HoloNav and ACS is enabled by the Anchor Manager and Data Manager. In the `Anchor Manager`, the functions used for querying, locating, and creating ASAs are defined. Similarly, the `Data Manager` implements the functions for querying, creating, updating, deleting entries in ATS. Both managers require the corresponding API Keys.

Controllers

In addition to managers, different controllers are implemented to control the interactions of the game objects and UI components. The `Anchor Position` controller is used to change the color of the anchor according to its status. For example, in the mapping mode, yellow denotes the "in creation" status and green represents "confirmed"; in the navigation mode, blue indicates "not yet visited", orange indicates "destination", and green indicates "visited". It also emits events when the user is close (i.e. in a range of 2 meters) to an anchor, which can be used to identify the users' location in the HIL building. The `Positional Indicator` controller constantly updates the bearing of the floating arrow to point to the direction of the next anchor. The `Mini-map` controller manipulates the interaction of the mini-map that initializes the origin and destination of a route with special markers and updates the symbols in the mini-map to approximate the user's position when receiving the event by the `Anchor Position` controller. The `Dialog controller` is used to initiate different popups to notify users with messages.

UI Components

The application also defines several UI components to communicate with users. The main menu can be triggered by the left hand of the user to enter either the mapping or the navigation mode. In the mapping mode, separated panels will be shown and ask users for some useful information about the anchor, while in the navigation mode, a navigation panel with the dropdown menus for the origin and destination of the routes will be shown. As the querying and locating of ASAs sometimes can take a while, a `Progress Indicator` is created to keep the user updated with the loading status. Furthermore, the dialog pop-ups with different messages are shown based on needs.

3.2.3 Mapping

Figure 3.4 shows the workflow of the mapping process. When loading the application, existing tables are automatically queried in ATS by names using the `Data Manager`. If there is no existing table, empty tables will be created and the application will enter the mapping mode directly. A pop-up will also be shown to ask the user to create the first anchor. If there exists a previously created table, a list of created spatial anchors will be returned and the algorithm will populate these anchors to all the dropdowns in the panels and the lists in `Anchor Map` class. The users can enter the mapping mode by selecting it in the main menu. After entering the mapping mode, a panel will be shown to ask the user to select one existing anchor as the entry point to start from. This step is required to connect the new anchors to the existing graph of anchors. Once the entry anchor is selected, the `Anchor Manager` queries the ASA with the respective ASA ID and starts a watcher for ASA. When the queried ASA is successfully loaded to the current scene, the application moves on to the anchor creation process, where new anchor visualization will be instantiated and detailed information will be requested. Every new anchor is uploaded to the cloud and the corresponding record is updated to the table in ATS.

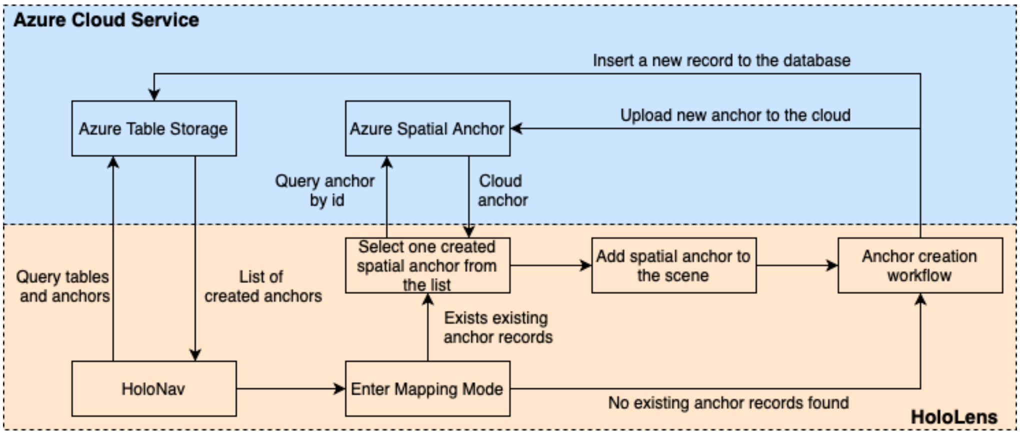


Figure 3.4: The workflow of mapping process

3.2.4 Navigation

In the navigation mode, HoloNav navigates the user between any landmarks recorded in the mapping process with the shortest path. To achieve this function, the ASAs are used not only to form the route until the user reaching the destination but also to estimate the user's temporary position in the environment. The box collider around each anchor allows the device to check whether the user meets with it. It also makes it possible to update the navigation visualizations and terminate the navigation process if the user achieves the destination. After choosing the navigation mode from the main menu, the application will run through three successive phases: the preparation, navigation, and end of the navigation (Figure 3.5).

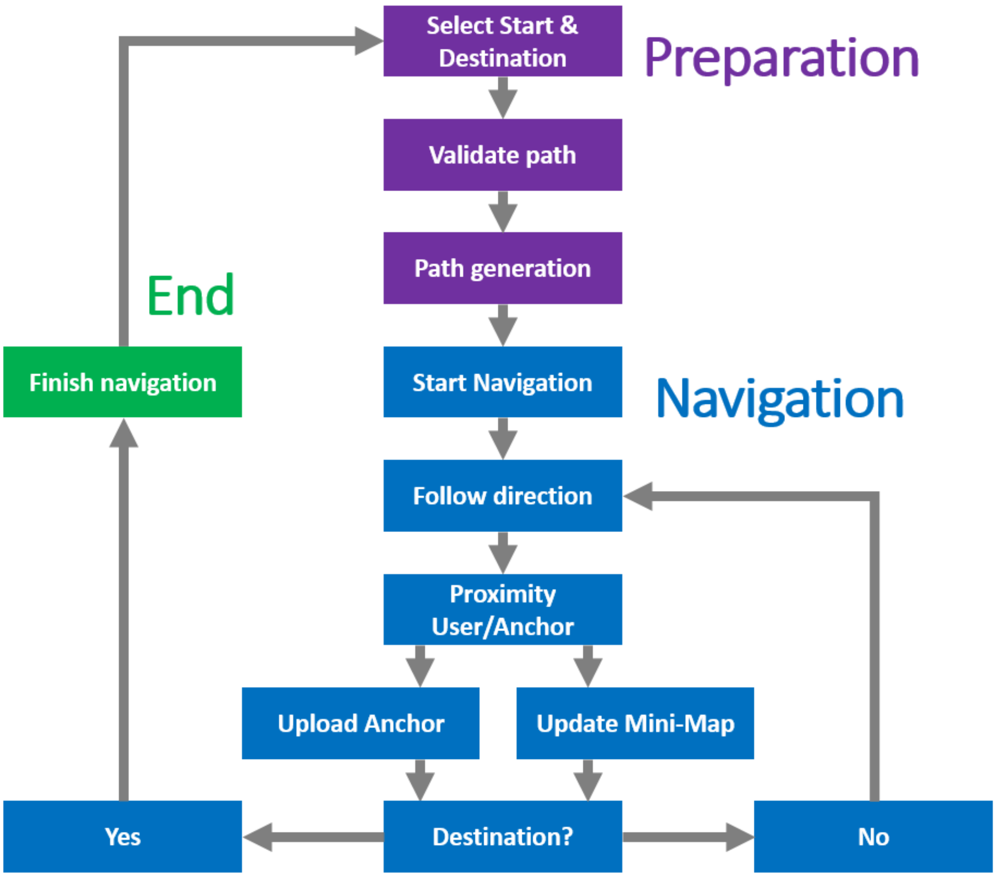


Figure 3.5: Flow chart of the navigation process.

Preparation

During this phase, the route is set up by computing the shortest path between the selected origin and destination, querying corresponding ASAs, and initializing navigation visualizations. One thing to note that the navigation mode in the main menu is only enabled when there are available spatial anchor records in the ATS database. This is checked by the `Data Manager` by the time the application is opened. After entering the navigation mode, the application initializes a panel asking the user to select the origin and the destination point from the dropdown lists. After the confirmation, the `Anchor Map` script computes the shortest path between the two points based on the adjacency list and returns a list of ASA IDs to query. These ASAs are queried by the `Anchor Manager` and added to the scene sequentially. While loading the ASAs, the `Progress Indicator` is invoked. The final step of the preparation is rendering the navigation visualizations. The preparation process is visualized in figure 3.6.

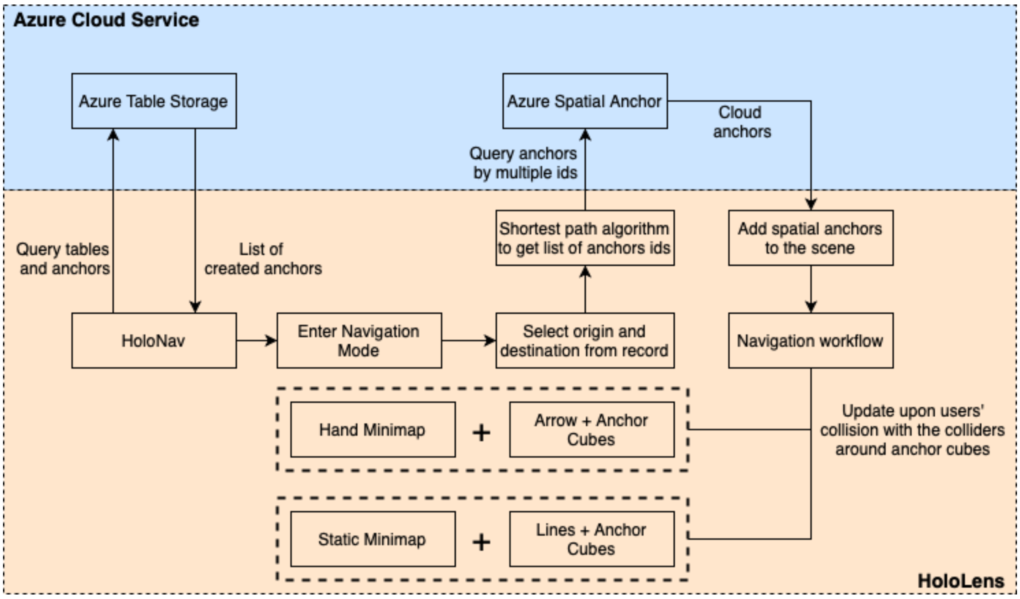


Figure 3.6: The workflow of preparation

Navigation

When the preparation is done, the application is ready to start the navigation, and a pop-up will be shown to ask for the user's confirmation. During the navigation process, the user can follow the navigation visualizations. Each ASA has a hidden box collider. When the user enters the collider, the corresponding anchor and the symbol in the mini-map will update their color indicating the user's progression. To have an overview of navigation, a mini-map is created for users to check the current progress. Every time a box collider detects a collision with the user, the program checks if the corresponding ASA is the destination. If not, the navigation process continues until the final destination is reached.

End of Navigation

When the final destination is reached by the user, the navigation ends and the confetti effects, as well as a pop-up window, informs that the navigation has finished will be invoked. Simultaneously, the positional indicator disappears in HoloNav 1. User has the possibility to choose another route by re-selecting the navigation mode in the main menu.

Different Types of Navigation

On the initial concept, the focus has been on the functionalities of the navigation. For example, how to extend the pre-defined route system to generalized navigation on entire or multiple floors. During the development of the procedures and the first tries, it has become apparent that the difficulties related to the system usability were underestimated. The project planning had to be adapted to change the focus on system usability. This decision can be justified by relation to the time investment to develop new functionalities comparing to the benefits and interests of the new research objectives. According to the actual project objectives, the focus is to compare different navigation systems. For this reason, HoloNav 1 and 2 have been created according to two different navigation concepts. User experiences using various orientation methods, types of interaction for the mini-maps, and graphical elements can also be analyzed and evaluated.

3.2.5 Mini-Map

The mini-map is a virtual mapping element that links the real environment and navigation overview. It is composed of a 3D representation of the building, a set of anchors that indicates the positions of the user in time, and the destination. Inspired by the mini-maps in video games, the mini-map works in an analogous manner and can help the user better orientate herself as well as increasing the user's confidence in navigation by avoiding fears of possible disorientation.

Mini-Map Overview

The mini-map is always active in background. During the preparation phase, when a user chooses a destination, the mesh and color of the destination are updated to the pre-defined style on the mini-map. At the same time, all other anchors are hidden. During the navigation, the mini-map changes every time the user collides with a spatial anchor. The script compares the name of the collided anchor and the names of all anchors created to the mini-map and updates the color of the corresponding anchor. The passed anchors are marked with a different color than the current anchor. The rest of the anchors that have not yet been visited remain invisible. HoloNav adapts the mini-map in the navigation process as shown in Figure 3.7).

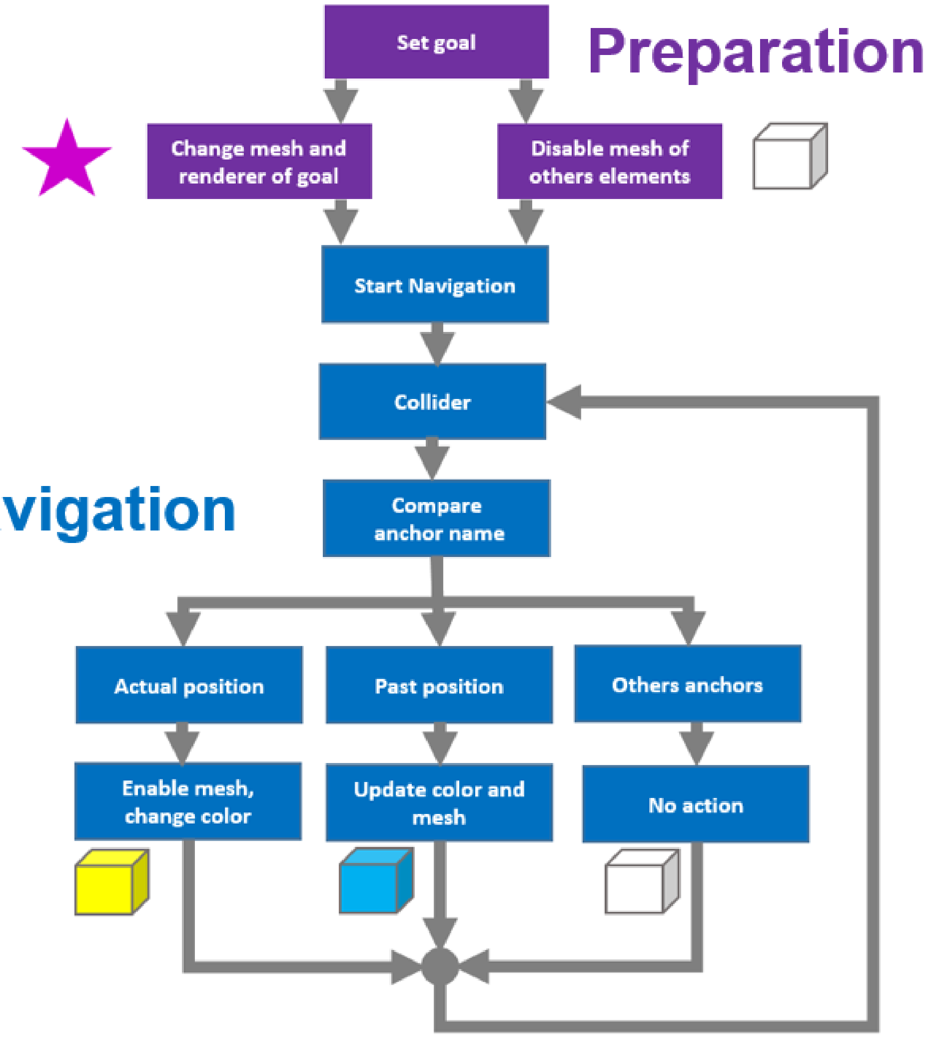


Figure 3.7: Flow chart representing the functioning of the mini-map during the navigation process

Implemented Functions for the Mini-Map

AddDestination. This script is called every time the user chooses a new destination during the preparation phase. The main goal of this function is to initialize the destination point on the mini-map. In achievement of this goal, the selected destination name is compared with the names of all points on the mini-map. If the names match each other, the mesh and the color of that particular anchor are adapted and remain active on the mini-map, while all other anchors are set to invisible.

UpdateMinimap. This function is used during the navigation phase and it is used to update the position of the user on the mini-map. Whenever the user meets a spatial anchor, the point corresponds to that anchor appears on the mini-map and previous points are displayed with another color to differentiate them from the current user location.

CallAnchorScript. This is the parent function that calls AddDestination and UpdateMinimap scripts. It is used for comparing each game object with the current position (actual state of lastest ASA met). It actualizes if a new destination is chosen or if a box collider is met.

ChangeFloor. This function is not used in the current iteration of HoloNav, but the basic idea is to update the 3D mini-map with the actual floor where the user currently is. For the development of this function, a simple button was used. When integrating this function in HoloNav, the floor information can be read out from the names given in the mapping part. Therefore the button can than be replaced.

Mini-Map Structure

The mini-map is composed of different elements that have different parent or child relationship to build a separate unit. It has the following structure (Figure 3.8):

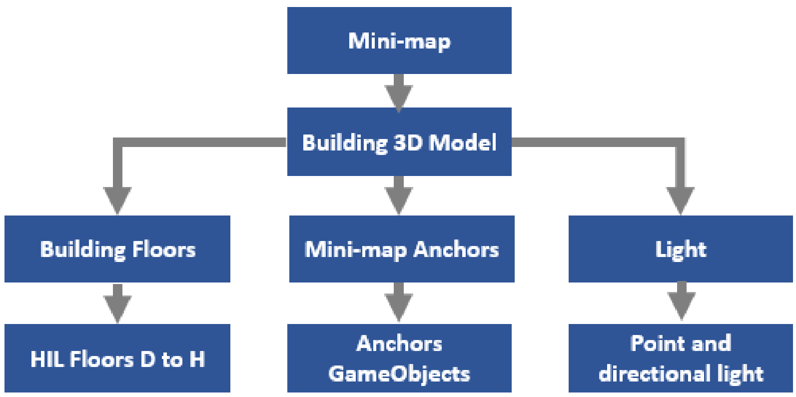


Figure 3.8: Flow chart representing the structure of the mini-map in Unity

An empty game object calling “Minimap” contains the main child element which is the white 3D-Model of the HIL Building with transparency. The 3D-Model contains 3 categories of child elements. The first one are the 5 floors of the ETH HIL Building which can be enabled or disable when the user would change hypothetically the floor during the navigation. Each floor is a box that has a visible material to differentiate it from the translucent volume. The mini-map anchors are game objects which symbolize the ASA on the mini-map. Two different types exist: the connecting points and the destinations points. Each point is double because it can be either a crossing point or a destination. These two classes allow to attach the corresponding script on it and modify only the render or color of one class. Each crossing point has two different scripts attached: "AddDestination" and "UpdateMinimap". Both scripts are needed because "AddDestination" allows making all mini-map elements invisible when the user chooses to confirm a destination. Regarding the destination points, only the script "AddDestination" is attached to show only one target point. The mesh renderer (mesh form and color of the mini-map anchors) are changed according to the navigation needs. Finally, light elements are also a child of the model to avoid the mini-map disparity during a navigation process with natural light variations. One directional light is used and located above the floors. It produces virtual shadows around the mini-map anchors which can be reduced with the help of a directional light that points from the user gaze direction.

3.2.6 Anchor Visualization

Game Objects: AnchorPosition.

The anchor visualization consists of a cube, which indicates the position of the anchor, and a tooltip, displaying the name of the anchor. By default, the tooltip is hidden. The game object has a box collider around it, which is used to detect whether the user collides with the anchor. The default size of the collider is 0.1m. It is also attached with the `SimpleLineDataProvider` and the `MixedRealityLineRenderer` script, which are used to generate linear transition lines between anchors (Chapter 3.2.7).

Additional Scripts.

Tap to place. The function is included in the MRTK package (Chapter 3.4.3), while enables the user to place the anchor to the desired location. For implementation details, please refer to the documentation of MRTK.

Controller: AnchorPosition.cs.

The `AnchorPosition` script contains a class *Spatial Anchor*, some customized materials from MRTK, and a set of functions that manipulate the interactions of the anchor. The `Init` function links the anchor visualization and the source spatial anchor with all the auxiliary information about this anchor. It also turns on the tooltip object so the name of the anchor is visible. The `AnchorInProgress`, `AnchorConfirmed`, `AnchorNavigation`, `AnchorPassed`, `SetAsTarget` update the material of the anchor to the corresponding ones to indicate different status of the anchor. During the navigation process, to detect the user's position, the box collider around the anchor is enlarged to 2m and the `OnTriggerEnter` function will listen to the event from the box collider in every update and emit an *EnterAnchorPosition* event when the user steps into it. For the anchor object that is set to be the destination, the `OnTriggerEnter` will also raise a confetti effect, which is implemented with the particle system of Unity. The `ConnectAnchor` function takes an additional AnchorPosition game object as input and sets the transform of that object as the endpoint of the `SimpleLineProvider`. This will connect the anchor with the other.

3.2.7 Navigation Visualization

HoloNav 1: Floating Arrow

Game Object. The floating arrow is implemented as a *positional indicator* game object, which is a variant of the *directional indicator* prefab in the MRTK package. The game object has a shape of a chevron and is constantly rotated 90 degrees on the x-axis to ensure a horizontal orientation. The direction to which the arrow is pointing (i.e. the bearing of the arrow) is controlled by the rotation in the y-axis and is computed based on the users facing direction and the position of its target.

Additional Scripts. To compute the bearing of the arrow, the head orientation of the user needs to be constantly tracked. This function is enabled with the `SolverHandler` script in MRTK with "Head" as the tracked target type and "Update Solvers" option always enabled.

Controller: PositionalIndicator.cs. The `PositionalIndicator` script controls the interaction of the arrow. It inherits from the `Solver` class of MRTK with several elements including the target that the arrow points to, the view offset, the distance buffer to activate the arrow. The script receives solver updates in every frame and computes the horizontal angle between the user's facing direction and the position of the target. This angle is then applied to rotate the arrow to the correct direction.

HoloNav 2: Transition Lines

When the origin and destination are selected, Dijkstra's algorithm will return a set of anchors that define the shortest route between them. By looping through all the anchors before the destination anchor, every two consecutive anchors can be connected using the `ConnectAnchor` function (section 3.2.6).

3.3 User Study

To acquire feedback about the HoloNav in terms of usability as well as have a better insight into the research questions, a user study is carried out. Therefore, volunteers are needed to try out the different navigation systems in the pre-defined study area (Chapter 3.1.1 and Figure 3.9). All participants try both HoloNav applications (HoloNav 1 and HoloNav 2) as well as Google Maps, which has the floor plans of the HIL building integrated. For comparative study, three routes were selected. All of the systems will be tested on every route. Every participant will test every system once on different routes. The HoloNav application is started up so that the participants only needed to press start. It was decided to not let the participants select the origin and destination room from the drop-down menus because most of the participants are not familiar with HoloLens 2 and usually have some problems with the clicking. Afterward, the participants tried the navigation with the Google Maps. Because the localization of Google Maps indoors is not that good due to the shading of the GPS signal, the origin of the route is marked with a location marker on the screen.

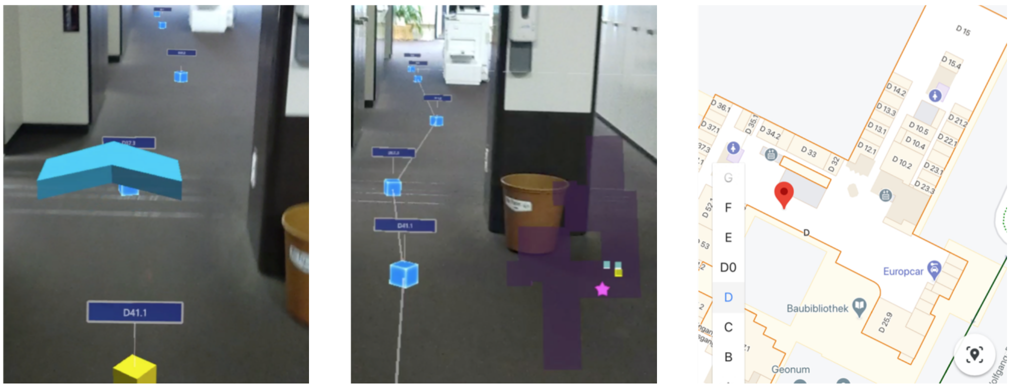


Figure 3.9: This three systems were tested during the user study (from left to right: HoloNav 1, HoloNav 2, Google Maps with location marker in red)

The start of the user study is in the entrance hall of HIL. First, the participants need to read through the instructions of the user study (see Appendix A.1). Then they are asked to read and sign the declaration of consent (see Appendix A.2).

After signing the consent, the real user study can start. The participants first need to fill in a pre-questionnaire, which contains questions about the familiarity with AR/VR-devices (i.e. HoloLens) and the familiarity with the study area. The end of the pre-questionnaire is the Santa Barbara Sense of Direction questionnaire (see Appendix A.3).

The combinations of the systems and routes are randomly assigned so that every system is tested on every route. In principle, the distribution should be somehow balanced. Additionally, the order of the systems to be tested by a participant is mixed so that learning effects will not affect the results.

The setup of the study can be, for example, the participant first tries to reach the selected destination with HoloNav 1, starting at the defined origin, where the investigator helps launch and prepare the application. During the starting up of the application, she introduces to the participant how to use gestures in HoloLens 2, such as clicking and opening up the hand-invoked mini-map. Afterward, the HoloLens 2 is handed over to the participant and she needs to press the start button in the panel. After pressing the button, the environment will be recognized and the ASAs will be loaded. When everything is ready, the participant will see a dialog confirming that she is ready to start the navigation. As soon as she presses the start button, the investigator will start the timer until the participant reaches the destination. During the navigation, the participant walks along with the navigation visualizations and tries to locate the right room. Any wrong turns of the participant are marked on her information sheet (see Appendix A.8). The participant can also have a look at the mini-map for a better understanding of where he is walking. When she arrives at the destination room, the timer must be stopped by the investigator. At this point, the first experiment is finished and the participant and the investigator will head back to fill in a post-questionnaire (see Appendix A.4). The same procedure as described for HoloNav 1 is done for HoloNav 2.

The process with Google Maps is mostly the same. The participant is given an iPhone 6 with a red marker, indicating the position where she has filled in the questionnaires. Any questions about the handling of Google Maps will be answered. Afterward, the participant and the investigator move to the origin of the route, where the name of the destination is given and the participant can then try to locate the room with help of Google Maps. The timer will be started when the participant notifies the investigator that she is ready and will not be stopped until the destination is reached. Similarly, the wrong turns are counted and noted down by the investigator. Again, when the experiment is finished, both will return to fill in the post-questionnaire (see Appendix A.6).

The post-questionnaires include, in the first part, questions about the level of difficulties to find the room and the helpfulness of the system. The second part of the questionnaire is the standard questionnaire for the System Usability Scale (SUS). The third part is to test the ability of the user to memorize the route, where the participants need to cross all images of the environment which they have passed during the navigation. For the post-questionnaires of HoloNav 1 or 2, there are some additional open questions about the UIs and the functionalities of the applications.

After finishing all three navigation processes, the participants need to fill in another questionnaire about the comparison of the two HoloNav applications (see the last page of Appendix A.5), where they can mention which parts of the UI they preferred in HoloNav 1/HoloNav 2 and which mixture would be best. The last questionnaire to be filled in is the comparison of HoloNav and Google Maps (see Appendix A.7), where the participants need to point out which system is easier to understand and which one they would prefer to use in their everyday lives.

3.4 Tools

3.4.1 Software

Unity v2019.4.12f1

The Unity Game Engine is the main development environment for the navigation systems. The different game objects can be directly prepared and displayed on the scene. The corresponding functionalities and gesture interaction scripts can be attached to the game objects. It is also possible to test the functionalities by simulating the MR interactions using an HoloLens 2 Emulator [19] and the computer keyboard. The HoloLens 2 applications can be compiled and built directly in Unity with the Universal Windows Platform selected[16].

Microsoft Visual Studio 2019 v16.5.0

Visual Studio is an integrated development environment with two main roles during the navigation system development. On the one hand, it is used to develop the different classes, scripts using the C# programming language [15]. On the other hand, it is used to deploy the application on the HoloLens 2 device.

ESRI CityEngine 2020.0

The ESRI CityEngine is used to construct the 3D Model of the HIL building with each corresponding floor for the mini-map.

Google Maps - GPS & transports

The iOS version of Google Maps is used on a mobile phone during the user study. The indoor map of the HIL building with the different room numbers is directly available on it.

3.4.2 Hardware

Microsoft HoloLens 2.

For all the experiments, Microsoft HoloLens 2 is used to develop the HoloNav. Both HoloNav 1 and HoloNav 2 are tested in a user study on HoloLens 2.

iPhone 7.

iPhone 7 is only used for the user study to compare the HoloNav systems with Google Maps.

3.4.3 Packages and Resources

Mixed Reality Toolkit (MRTK) v2.5.1

The MRTK is the main building block of the project for UI and some functionalities. Specifically, the interface components of the application are developed with the various prefabs in the MRTK package including buttons, drop-down menus, menus, dialog, etc. as well as customized based on the demo scenes by MRTK. One thing to note is that due to some compiling issues with AMR architecture of HoloLens and the current Visual Studio version, some functions of the earlier versions of MRTK (e.g. the Solver) do not work properly. These issues will be resolved in the next major update of the Visual Studio and the current workaround is to use MRTK later than v2.5.0.

Azure Spatial Anchor SDK for Unity v2.6.0

To integrate ASA in the application, the Azure Spatial Anchor SDK for Unity (v2.6.0) is used. Unlike previous versions, starting from v2.6.0 Azure Spatial Anchor SDK is released and maintained with Unity Package Manager, which needs to be added in the `package.json` file.

Hololens 2 Tutorials on ACS

As the application is based on the two major ACSs, the tutorials on ACSs by HoloLens provides a great source of reference and a good starting point. The tutorial on *Integrating Azure storage* and *Integrating Azure Spatial Anchors* are in particular helpful for the implementation of HoloNav.

ASA Sample Code

Sample codes are provided on the official GitHub repository of ASA and are good demonstrations of various ASA functionalities. Although these codes are written in a simple way and are not suitable for a complex use case as this project, they are a good reference to be familiar with the architecture and function structures.

3.5 Statistical Methods

T-test

To analyze the data from the user study, statistical methods are used to compare the different conditions. The t-test is chosen because it is a standard method for testing whether the mean value of two groups is statistically significantly different. With help of the t-test, it can be seen whether the two groups are significantly different from another. The two-sample assuming equal variances t-test is adopted here because the same participants have used all three applications and the statistics can be grouped by the participants. The two-tailed test is applied to test for the possibility of positive or negative differences. The direction of difference does not matter in this analysis. The p-value is fixed to 5% in this study.

Boxplot

The use of boxplots allows the comparison of the differences between the different conditions visually by showing the median, as well as the different quantile, and the whiskers. That makes it easier to understand whether one system may be better than another.

CHAPTER 4

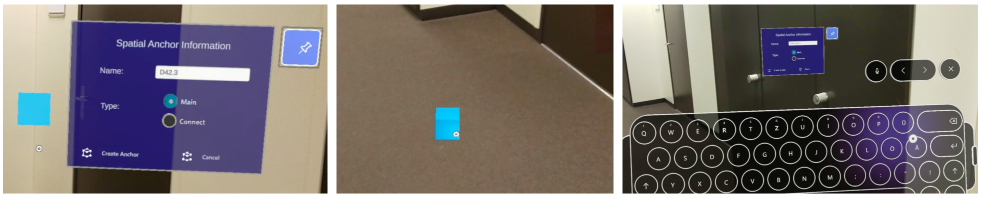
Results

4.1 Application

4.1.1 Mapping

In the study, in total 43 spatial anchors are created. As shown in Figure 4.1, when the user enters the app the first time and no existing spatial anchors can be found on the record, a dialog will show to notify the user to create the first spatial anchor, the corresponding tables will be created automatically. Once the user confirms to create a new anchor, an anchor visualization will be instantiated in front of the user together with another panel for detailed information about the new anchor (Figure 4.2(a)). The user needs to tap the anchor to the corresponding location (Figure 4.2(b)) and populate the information in the panel (Figure 4.2(c)).

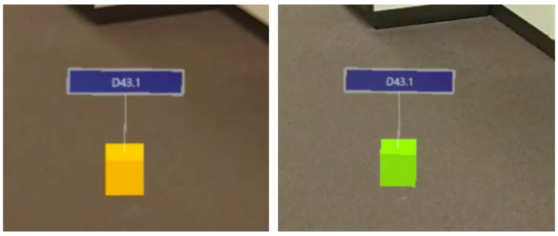
Figure 4.1: The dialog to be shown when no existing spatial anchor created.



(a) Instantiate a new anchor (b) Place the anchor (c) Populate information

Figure 4.2: Procedure for creating a new anchor from scratch

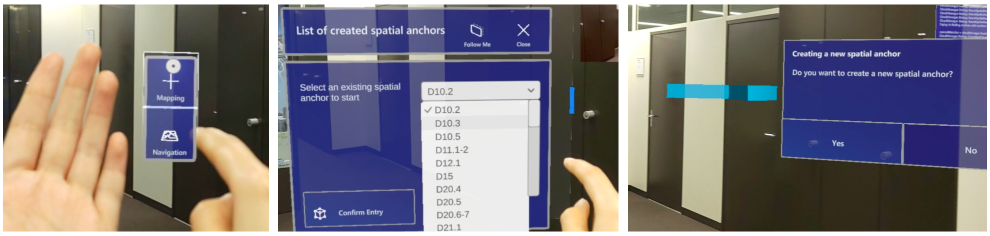
When these steps are done, the user can synchronize the anchor to the cloud by clicking the confirmed button. The color of the anchor will change to yellow, indicating that the process is still in progress (Figure 4.3(a)). The process of creating an anchor in the cloud can take some time. Once the anchor is successfully created as an ASA, the color will change to green (Figure 4.3(b)).



(a) In progress (b) Anchor successful synchronize to the cloud

Figure 4.3: The color change of anchor

If there is already created spatial anchors on the record, however, the user needs to enter the mapping mode from the main menu by reaching his/her left hand and a panel will show to ask the user to select one previously created anchor and load this anchor to the scene as the starting point (Figure 4.4(a)-4.4(c)). An arrow pointing to its location will lead the user to the correct position if the user is not nearby (Figure 4.4(c)). Then the same procedure is needed to create new anchors. The video demonstration of the mapping process can be found here.

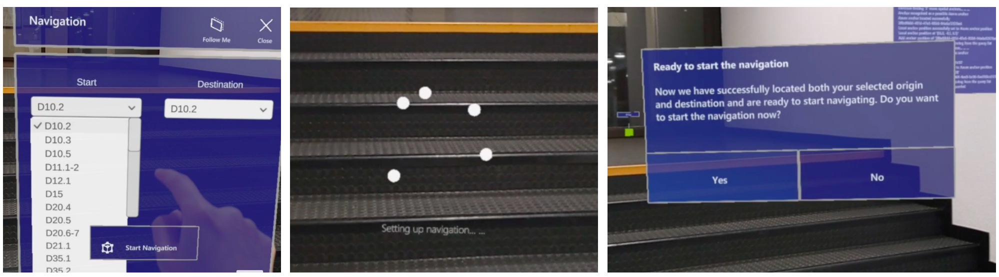


(a) Choosing the mapping mode (b) Select an existing anchor from the list (c) Arrow guide to the selected anchor

Figure 4.4: Procedure for creating a new anchor when there are existing anchors in the record

4.1.2 Navigation

Similar to the mapping mode, users can enter the navigation mode in the main hand menu and a panel with the dropdown menus for selecting the origin and the destination of the route will be popped up (Figure 4.5(a)). All the names of the created main anchors will be populated automatically to the dropdown menus, while the names of the connecting anchors will be ignored. Once the user has confirmed the route, the app will find the shortest path in the graph using the Dijkstra's algorithm and query these anchors consecutively. A progress indicator will be shown until all the anchors are successfully loaded to the scene and a popup window will be shown to notify the user when the navigation is ready (Figure 4.5(b) and 4.5(c)). Two different navigation visualizations will be set up on the two versions of the HoloNavs (Chapter 4.1.5). The navigation process will start after the user confirms in the dialog. During the navigation process, the anchors will update their colors according to the user's position. When the user reaches the destination, a visual effect of confetti and a dialog will be shown, notifying the user of the end of the journey (Figure 4.8). For video demonstration for both HoloNav versions, please refer to the link for v1 and v2 respectively.



(a) Select the origin and destination (b) Progress indicator (c) Dialog to confirm the start of the navigation

Figure 4.5: Procedure for creating a new anchor from scratch

4.1.3 Mini-Map

To compare and evaluate navigation experiences, two different mini-maps are used for the applications HoloNav 1 and HoloNav 2. The main differences are in the user interaction with the mini-map and also in the conceptual design.

Mini-Map for HoloNav 1

After the first navigation experiences, it appeared that a permanent mini-map could disturb the navigation. For HoloNav 1, the mini-map is appearing directly on the hand of the user according to the needs. The mini-map is fixed on the hand using a HandConstraintPalmUp [18] of the MRTK v.2.5.1. To make it appears, the user has to put the right hand in front of the HoloLens device (Figure 4.6). The advantage of this characteristic is that mini-map can be really detailed, more complex and highly visible because it is not permanent and the position can be adapted with the hand. In this version, a color set using clear pink, yellow, white, and red was used to create an impactful mini-map. The chosen meshes of the points are pins for crossing points and flags for destinations. This choice is based on the habitude of using other navigation system's markers like on Google Maps or Tomtom [22]. The main practical disadvantage of such a mini-map is that the user has to stop to consult it, which can be a waste of time. And if the user is familiar with the system there is a risk that the user may use it while walking. This fact can be a security problem because the user could lose attention to the navigation.

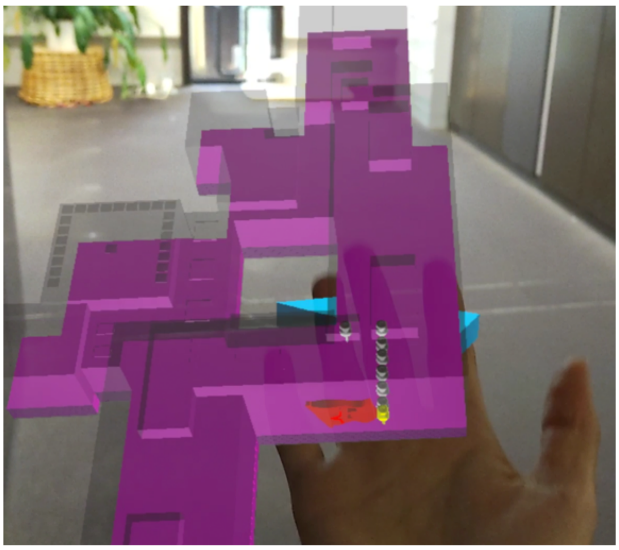


Figure 4.6: Hand mini-map in the system HoloNav 1
Mode

Mini-Map for HoloNav 2

The mini-map for HoloNav 1 could be a stress factor for some users. If the mini-map is not permanently visible, it can be an inconvenience during the navigation because the progress of the walk cannot always be checked. And when the user makes the mini-map appears, the link between the environment and the mini-map model cannot be understood clearly. In this context, a permanent mini-map for HoloNav 2 was tested. This variant is fixed to the gaze position and off-centered on the field of view (Figure 4.7). If the mini-map is a child element of the main camera, it can be a problem to read the attached scripts afterward. In this case, the Unity “ParentConstraint” component can be used. It gives the mini-maps the same position as if the main camera is a parent of the mini-map. The problem with this positioning system is that the mini-map always move because of the gaze changes. To solve this problem, the constraint can be released from the Y-axis (up-down) which can give more flotation to the mini-map. The issue with this solution is that when the user changes his altitude, the mini-map height stays constant. Concretely, in the HIL-Building, when the user walks upstairs, the mini-map is staying down. For this reason, all constraint axes are used in the final product. In the future, a solution to compensate the height could be an interesting issue. Regarding the map design, a simplification using a 2D mini-map was used. It is actually the same mini-map structure as in HoloNav 1 but without transparent volume. Only the floors are displayed perpendicular to the user gaze. The color set for this version is more discrete because the user has permanently information during the navigation. The floors are still transparent purple but in a more discreet tone with transparency. The form of the map elements is also simpler with squared forms for crossing points. This choice was made to create an evident link between the ASA (cubes on the floor) and mini-map anchors (squares on mini-map) with also a unique color code. The destinations are represented by pink stars to notify clearly where the goal is. The position of the mini-map was chosen on the lower right side to follow simultaneously the transition lines on the floor and the overview with the direction of the user glance. This solution makes a comparison possible between the first system and a more classical approach.

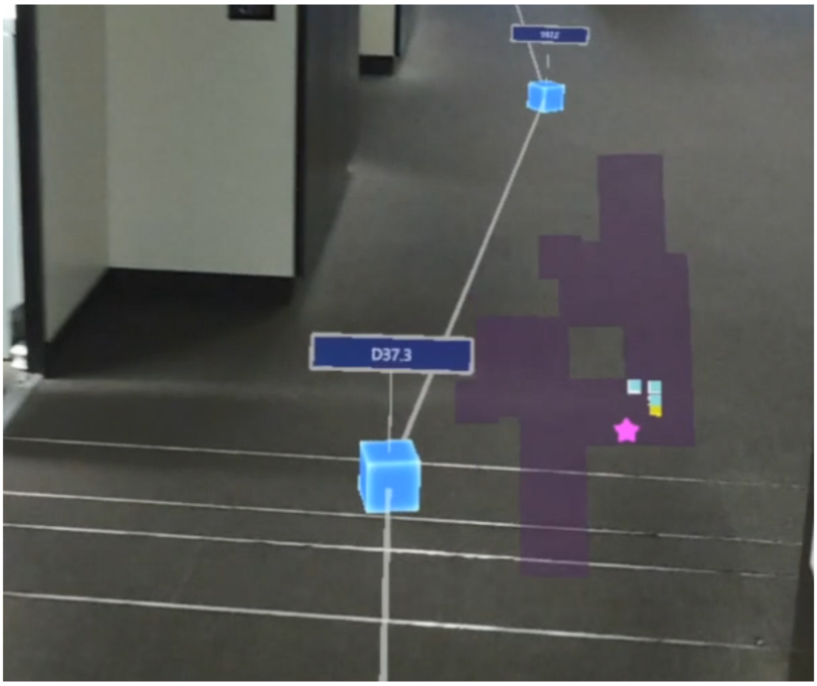


Figure 4.7: Permanent mini-map in the system HoloNav 2

Comparison between Mini-Map Types

Those two types of mini-maps allow understanding of which design would be preferred by the user and why. It is also interesting to study which level of interaction and graphical styles the user expects from the mini-map. The results of the user study can thus give a lead to follow for future MR mini-maps concepts.

4.1.4 Anchor Visualization

The anchor visualization (Figure 4.8) is showing the state of the user. The blue color of an ASA shows that it is not passed yet. If the user enters the box collider of an ASA, the color of the anchor will turn yellow. This means that the anchor is already passed. The destination anchor can be recognized by its orange color. If the destination anchor is reached the color will turn yellow as well and a small firework of confetti is generated. This should help the user to visually see if he is doing a good job.

(a) cube when ASA is not passed (b) cube when ASA is passed (c) cube if it is the destination ASA (d) cube with confetti if the destination is reached

Figure 4.8: Color styles of the cube changing during process

4.1.5 Navigation Visualization

HoloNav 1: Floating Arrow

The navigation visualization of HoloNav 1 is a floating arrow that is constantly showing to the upper front of the users' field-of-view (Figure 4.9). To reduce the level of complexity, the arrow is orientated horizontally and the direction of the arrow always points to the next anchor position, which the user needs to head to. The bearing of the arrow is computed based on the user's head direction and the position of the next anchor position. Hence, if the user is facing another direction relative to the target position, a larger bearing will be applied to the arrow. When the user is facing the target directly, the arrow will point straight outward in the environment.

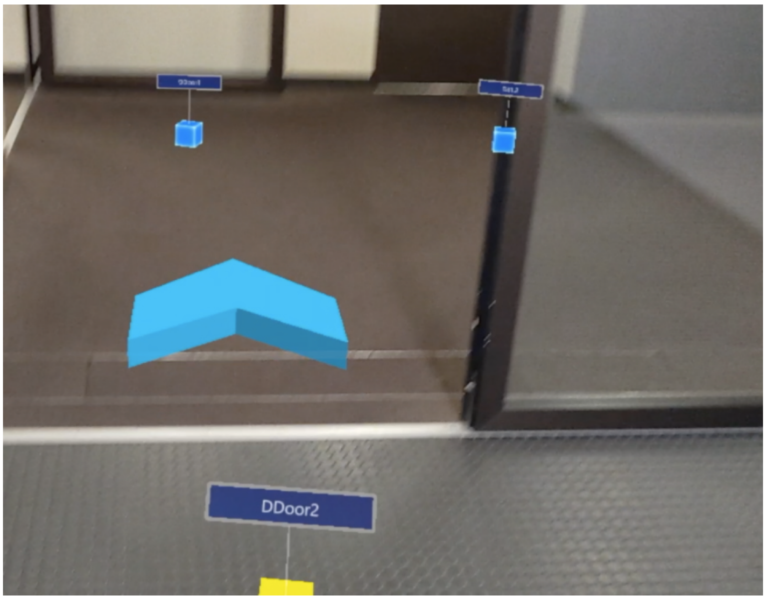


Figure 4.9: Floating arrow showing the direction to walk for HoloNav 1

HoloNav 2: Transition Lines

Different from HoloNav 1, the navigation visualization of HoloNav 2 consists of segments of transition lines connecting consecutive anchors. Users need to follow these transition lines by themselves. The direction of the routes is clearly depicted with this type of navigation visualization and users can see the directions of positions further away. Users are not forced to follow the transition lines and can adapt their own paths if needed (e.g. avoiding obstacles) while roughly following the same directions (Figure 4.10).

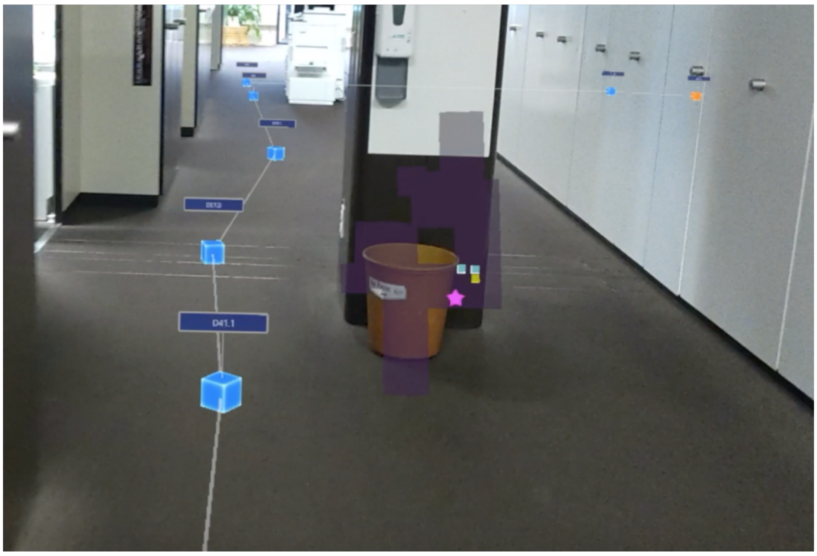


Figure 4.10: Transition lines showing the direction to walk for HoloNav 2

4.2 User Study

22 participants (9 females) participated in this user study (avg. age 25.59 yrs). Participants were equally and randomly assigned to different routes (A, B, C) for each navigation system (HoloNav 1, HoloNav 2, Google Maps). The three routes should have at minimum one turn and be in different corners of the building, that there is no learning effect from the room numbers (Figure 4.11).

With all participants, the Santa Barbara Sense of Direction Scale was done for analyzing the navigation skills of each person. There the mean-value was a score of 81.5. More information can be taken from the boxplot (Figure 4.12). It can be seen there, that mostly all have a good sense of direction, but there are as well some with not that good sense of direction (min. value 3).

Figure 4.11: The three routes A (green), B (orange), C (blue) in HIL Building from ETH Zurich [5]

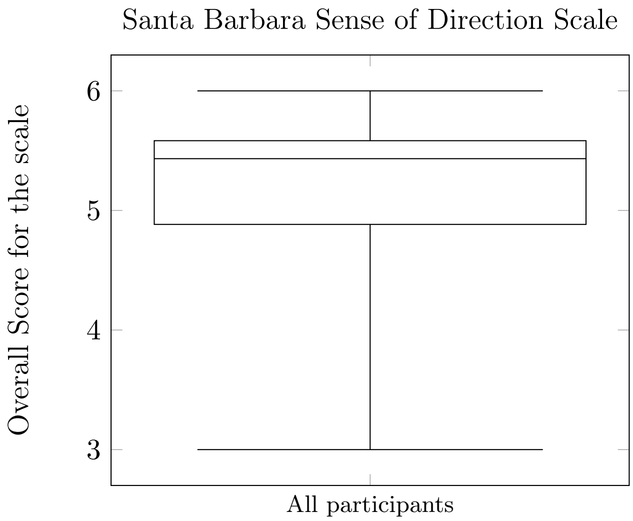


Figure 4.12: Score of the Santa Barbara Sense of Direction Scale from all participants of the user study

As already discussed in Chapter 3.5 the two-tailed t-test is chosen for analysis. In the next sub-chapters, the hypotheses are discussed with help of analyzing the results obtained from the questionnaires of the user study.

4.2.1 Hypothesis 1: HoloNav has a Good System Usability

To analyze the the standardized questionnaire was used after every use of the different applications. Therefore can be done a comparison between these values. As it can be seen in the boxplot (Figure 4.13) all of the three systems have mostly the same mean value for the SUS. It also can be seen that for Google Maps the standard deviation (SD) is the smallest. The maximum value is the smallest in the case of Google Maps. The mean values of both HoloNav systems are mostly the same (HoloNav 1: 77.5; HoloNav 2: 78.8). The SD from HoloNav 1 is smaller, but there are a lot bigger whiskers to the smallest value than in HoloNav 2.

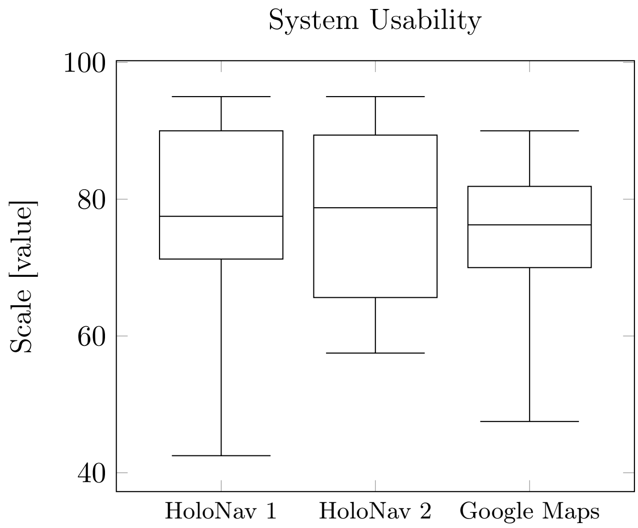


Figure 4.13: SUS of the three different systems

It can be said, that systems with a score above 68 have good system usability. 68 is the average score a system is reaching with the official SUS questionnaire [1]. Therefore it can be said, that all of the tested systems have good system usability, which is noticeable over the average score.

To compare HoloNav 1 and HoloNav 2 statistical, a two-tailed t-test in done. For each system 22 observations have been done. The result of the test is $P(T<=t) = 0.91 > .05$. Therefore it can be said, that there is no significant difference between these two systems.
These comparison is also done the same way with Google Maps for both HoloNav systems. For HoloNav 1 vs. Google Maps $P(T<=t) = 0.38 > .05$ is the result. For HoloNav 2 vs. Google Maps $P(T<=t) = 0.43 > .05$ is the result. As well there is no significant difference between the system usability in this cases.

The question of which system HoloNav 1 or HoloNav 2 the user preferred was asked. The answers are mostly balanced (HoloNav 1: 10 users; HoloNav 2: 11 users; Irresolute: 1). A mostly similar question is asked to choose out of HoloNav or Google Maps as the preferred system. Here 19 users would choose HoloNav as the easier to understand navigation system (Google Maps: 3 users). But the questions, which system they would like to use in their everyday life Google Maps wins by far (Google Maps: 18; HoloNav: 4). Users tell that the handling of HoloNav is easier because it was clear what the system is showing and what is expected of the user that he does. Google Maps is preferred for everyday use because most of the users are not familiar with HoloLens and do not like to wear glasses only for navigation reasons, whereas the mobile phone with Google Maps is always in their bag and thus ready to hand.

The p-values clearly show that there are no significant differences between the systems. However, both systems, HoloNav 1 and HoloNav 2 are clearly above the mean of the SUS, which is why it can be said that both systems do well here. The hypothesis can therefore be verified.

4.2.2 Hypothesis 2: HoloNav is Better than Google Maps in Terms of Efficiency

To compare the efficiency of the different systems the time is stopped during the wayfinding. Because there exist 3 different ways, time needs to be considered beside them. Therefore in the next few boxplots (Figures 4.14, 4.15, 4.16) the time for each route and system is displayed. This should help to see differences visually.

As we can see (Figures 4.14), the mean value is the smallest in HoloNav 2 (51 seconds). Google Maps and HoloNav 1 has almost the same mean value. The big difference here is, that Google Maps has a bigger SD than the other two systems. As well the whisker for the maximum value is big compared to the others.

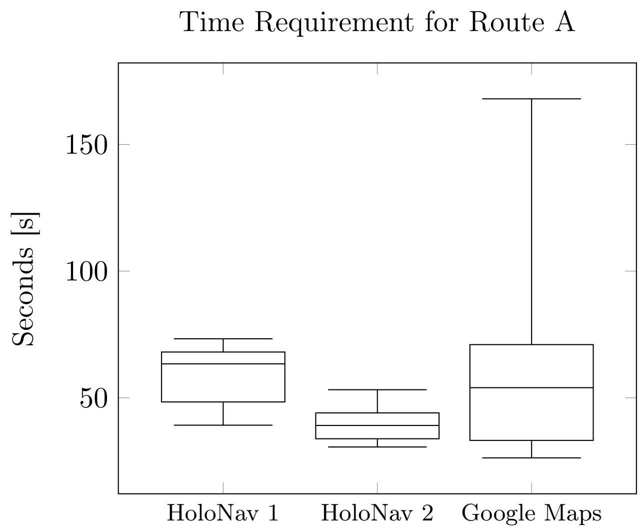


Figure 4.14: Requirement of time in seconds for route A

As it can be seen in figure 4.15 the mean values for the required time are mostly similar in all three systems. HoloNav 1 usually took the most time. The average value is above those of the other systems. HoloNav 2 and Google Maps are mostly the same, there are some users which were faster using HoloNav 2, and some users were a bit slower with Google Maps. The SD is slightly bigger for Google Maps than for HoloNav 2.

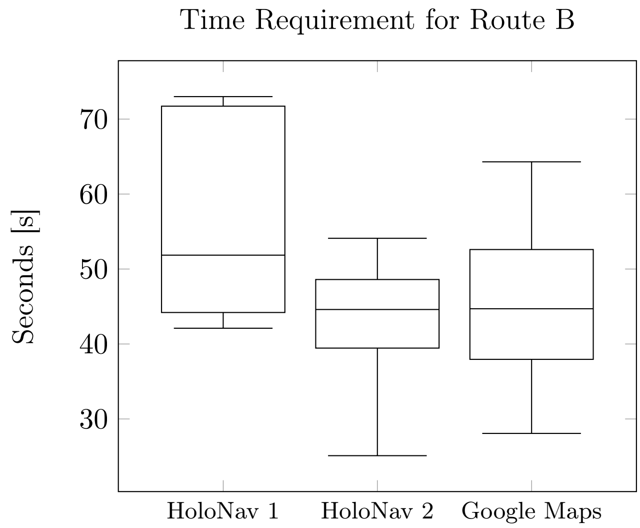


Figure 4.15: Requirement of time in seconds for route B

The destination of route C was clearly fasted found with the help of HoloLens 2 (Figure 4.16). Both, HoloNav 1 and Google Maps sometimes needed a lot of time to find the right destination. But in mean, Google Maps was better than HoloNav 1.

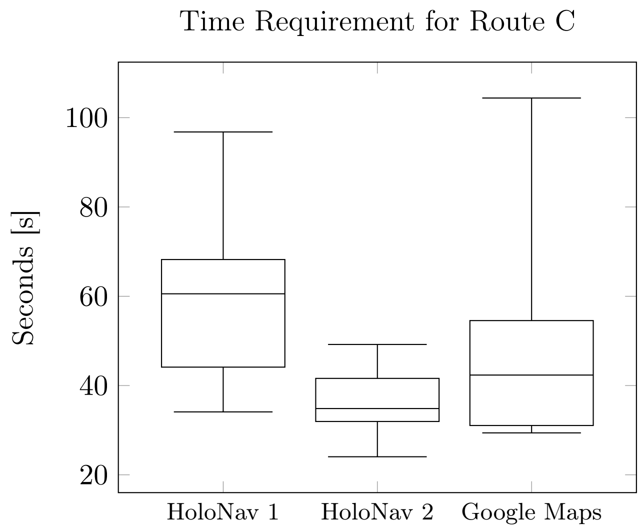


Figure 4.16: Requirement of time in seconds for route C

To summarize, one can say here, that always HoloNav 2 was the fastest system to find the destination, no matter if in route A, B or C. The navigation with HoloNav 2 does not show a big SD, mostly all participants needed almost the same time. The SDs of the other two systems are mostly noticeable bigger. Google Maps shows often a large SD and big whiskers.

By comparing the results from the t-test of the time requirement (Table 4.1) it can be seen that the hypothesis can not be reject. It is not a significant difference between the time consumption between HoloNav 1 or HoloNav 2 compared to Google Maps. It would need to have an analysis with larger distances, more difficulties on the wayfinding or a bigger sample size.

P(T <= t) two-tailed			
	Route A	Route B	Route C
HoloNav 1 vs. Google Maps	0.80	0.14	0.48
HoloNav 2 vs. Google Maps	0.18	0.66	0.20
HoloNav 1 vs. HoloNav 2	0.01	0.05	0.01

Table 4.1: Results when comparing HoloNav to Google Maps in time requirement

4.2.3 Hypothesis 3: HoloNav is Better than Google Maps in Terms of Correctness

To compare between the correctness of the systems the investigator is counting the wrong turns a user is doing during the wayfinding. Wrong turns are if the user forgot about doing a turn or if she walks in the false direction.

Because the counted values are between 0 and 2 (integer only), boxplots do not help to see differences visually. Therefore only the t-test is made for comparing. The results of the t-test (Table 4.2) are not significant. Therefore here it can not be said, that one system is totally better than another.

P(T <= t) two-tailed			
	Route A	Route B	Route C
HoloNav 1 vs. Google Maps	0.41	0.33	0.32
HoloNav 2 vs. Google Maps	0.71	1.00	0.03
HoloNav 1 vs. HoloNav 2	0.27	0.33	0.33

Table 4.2: Results when comparing HoloNav to Google Maps in wrong turns

Although it can be seen some differences if the mean values for wrong turns for every system are compared. In Table 4.3 the mean values can be seen. Analyzing them it can be said, that HoloNav 2 was always correcter than the other systems. Google Maps do not have one route which none of the participants had no faults.

Both HoloNav systems were able to navigate to one room without wrong turns on one route across all participants.

	Route A	Route B	Route C	Mean
HoloNav 1	0.43 (SD = 0.49)	0.00 (SD = 0.00)	0.25 (SD =0.66)	0.23
HoloNav 2	0.14 (SD = 0.35)	0.14 (SD = 0.35)	0.00 (SD = 0.00)	0.10
Google Maps	0.22 (SD = 0.42)	0.14 (SD = 0.35)	0.67 (SD = 0.75)	0.34

Table 4.3: Mean values of wrong turns for every route as well as the mean value per system overall

4.2.4 Analyzing of Memorability

The goal of a navigation system should be, to show the user the way to the right destination. An additional plus would be if the user would later be able to navigate to the room by knowing the route by heart. Therefore 9 pictures were given to the participants which they could have passed during the wayfinding (Figure 4.17). For route A two images should be crossed, for route B three images and for route C there are as well two images to cross. For every cross or not-cross which is correct, the user gets a point. In total 9 points could be reached. A percentage is calculated out of them.

Analyzing the t-test (Table 4.2.4) it can be seen that between the different systems there is no significant difference to be mention. Therefore it can be said, that probably it does not matter if the user is walking with HoloLens 2 on their head or with a mobile phone in the hand through a building. Neither HoloNav 1 nor HoloNav 2 influence the recognition of the real world more.

P(T <= t) two-tailed	
HoloNav 1 vs. Google Maps	0.19
HoloNav 2 vs. Google Maps	0.26
HoloNav 1 vs. HoloNav 2	0.80

Table 4.4: t-test results by comparing the achieved percentage of memorability

Looking at the boxplot (Figure 4.18) one can see that Google Maps mostly achieves the best percentage. But there is not a huge difference between HoloNav 2 and Google Maps. The median is in HoloNav 2 88.89%, whereas the median of Google Maps is 100%, this can not be seen clearly in the boxplot.

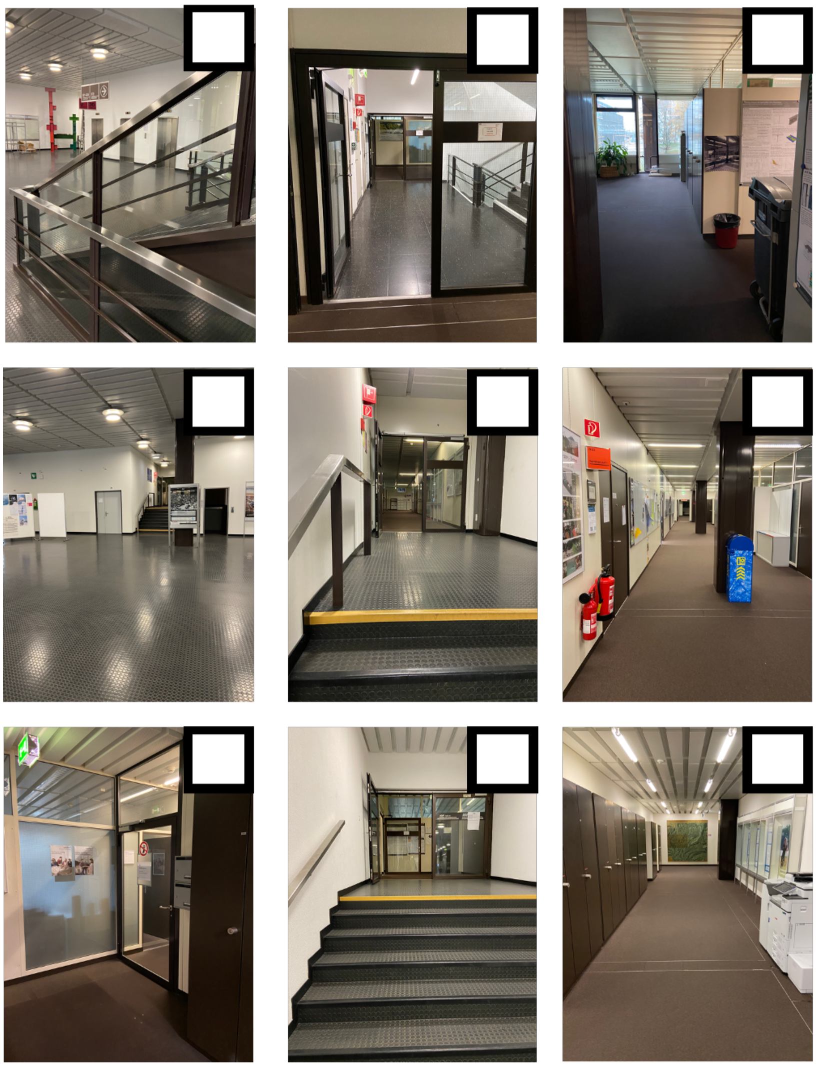


Figure 4.17: 9 different photographs from the HIL building where the routes where placed

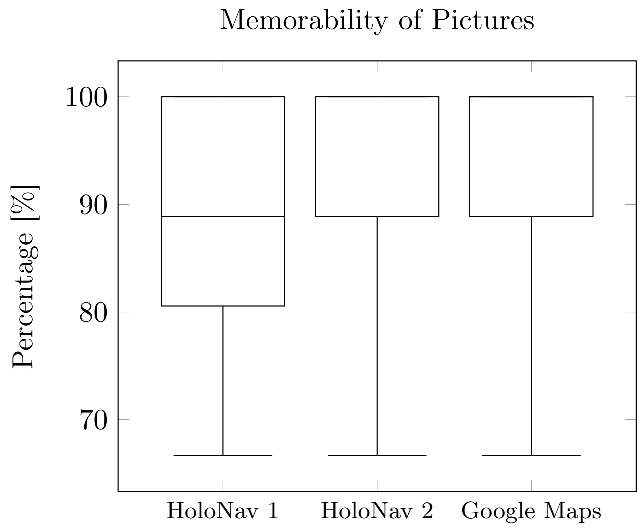


Figure 4.18: Memorability of the pictures of parts of the route during wayfinding

4.2.5 Analyzing of Visual Aspects

Participants were asked to chose between the different visualizations given in HoloNav 1 and HoloNav 2. Here just a short listening of the preferred visualisation should be given (Tables 4.5, 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11).

In total both systems are mostly voted the same amount. There is not a significant difference to see if users like more HoloNav 1 or HoloNav 2 in general (Table 4.5).

More likely system in general	
HoloNav 1	10
HoloNav 2	11
Irresolute	1

Table 4.5: Sum of persons who liked HoloNav 1 or 2 more in general

People think it is easier to navigate if they see a transition line on the ground (HoloNav 2). The arrow (HoloNav 1) was only liked by approximate ⅓ of all users (Table 4.6).

more easy for navigate	
HoloNav 1	6
HoloNav 2	16
Irresolute	0

Table 4.6: Sum of persons who think one system is easier than another

The UI with the guiding arrow and the hand-invoke mini-map (HoloNav 1) was liked more than the one with the permanent mini-map and the transition lines (HoloNav 2) (Table 4.7).

more attractive UI	
HoloNav 1	15
HoloNav 2	7
Irresolute	0

Table 4.7: Sum of persons who found one UI more attractive than the other

The same result as in table 4.6 can be seen here. People are more secure to navigate if they have transition lines (HoloNav 2) (Table 4.8).

indicator for direction	
Transition Line	16
Arrow	6
Irresolute	0

Table 4.8: Sum of persons who liked one directional indicator more than the other

Almost ⅓ of the user liked it more if the mini-map can be shown if needed (HoloNav 1) and not all-time-shown (HoloNav 2) (Table 4.9).

mini-map	
Permanent	7
By hand	14
Irresolute	1

Table 4.9: Sum of persons who liked the mini-map more permanent or hand-invoked

Almost ⅓ do not remember the different symbolizations for the mini-map. And the rest of the probands like almost ½ to ½ the cubes (HoloNav 2) and the pins (HoloNav 1) the same way. Here no significant difference can be seen (Table 4.10).

Symbolization for mini-map	
Cubes	7
Pins	9
Do not remember	6

Table 4.10: Sum of persons who think one Symbolization is better than another

Same as the symbolization also the color style was not remembered by the users. Mostly they do not mind which color the mini-map has. A bit more likely was the transparent purple used by the permanent mini-map (HoloNav 2) (Table 4.11).

Color style for mini-map	
pink (clear)	4
purple (transparent)	8
Do not remember	10

Table 4.11: Sum of persons who think one color style is better than another

To conclude it can be said, that in this chapter no significant differences between the different visualizations can be seen. It would need a larger group of participants and maybe as well longer time periods wearing the HoloLens.

Chapter 5

Discussion

5.1 Interpretation of Results

As is derived from the statistics of the user study, there is no significant difference in the usability of the different navigation systems. Nevertheless, there are some thrilling findings from the user study. In this section, the results found in Chapter 4.2 will be interpreted.

5.1.1 Hypothesis 1: HoloNav has Good System Usability

As shown in Chapter 4.2.1, the mean values of the SUS scores for all three systems (HoloNav 1, HoloNav 2, and Google Maps) are above the average score (i.e. 70) of a good system ([2]). Therefore, all of them are considered to have good system usability and could be used for navigation. Thanks to the analysis of the open question asked during the user study, the advantages and disadvantages of HoloNavs are conveyed.

One disadvantage of the HoloNav systems (both 1 and 2) is, that HoloLens is not used in commonly used. Although some already have some experience (but in most cases less than 15 minutes) with HoloLens, the handling of this device is not yet familiar. Because the handling of the applications on HoloLens 2 was not that easy, the user experience may be less promising. By contrast, Google Maps is well-known and used by almost all people sometimes in their lives, it is clear that the users are more familiar with Google Maps. It is not clear though if all participants were answering the questions with the considerations of Google Maps used for indoor spaces. The regardlessness of this context may have biased the results.

The advantage of the HoloNav systems, on the other hand, is that that it is totally clear for the users how the system is working and what is expected from the users. The transition line is a bit more known from traditional navigation systems (like car navigation systems) than the floating arrow. Therefore, it can be argued that users like transition lines more. But both visualizations were in most cases rated as quickly comprehensible by the participants. Whereas the visualization of Google Maps for indoor space is not that clear: the location point which should have shown the actual position and orientation of the user, is usually floating around randomly because of the unreliable GPS signal. This causes confusion.

To summarize, it can be said that it is still an open question which system is the best one. The answer seems to be depending on the frequency of the users using the devices or the systems, the general acceptability of the hardware, and how quickly the users get used to new things. In general, the user study has shown that all of the systems (HoloNav 1, HoloNav 2, and Google Maps) have good system usability. Therefore, it can be concluded that the systems already work well enough for the user, although some revision and more research on this topic need to be conducted in future studies.

5.1.2 Hypothesis 2: HoloNav is Better than Google Maps in Terms of Efficiency

After analyzing the result from Chapter 4.2.2, it can be concluded that there is no significant difference between the systems in terms of efficiency. In most cases, all three systems have similar mean values for the time-of-arrival in each route. However, it can be clearly seen that the variance and the mean value of HoloNav 2 are always the smallest among the three, indicating that HoloNav 2 has great potentials for efficient navigation. It also noticeable that there exists a big difference from the highest quantile to the box for Google Maps. One possible explanation can be although some people are more familiar with Google Maps and know how to navigate with it, if they are not familiar with the building structure of HIL, they needed much more time for finding the destination.

HoloNav 2 has a small variance, which means most participants were the same fast finding the destination. This suggests that this system is the one which suits best all users. It does not matter if people are familiar with the building, the device, or the application. HoloNav 1 has often needed the most time. It is worth mentioning that during the navigation with HoloNav 1, the users are required to invoke the hand mini-map to test the usability of it, this would have a negative effect on the time-of-arrival evaluation. In fact, many users have also reported that the mini-map is not a must to arrive at the destination with HoloNav 1, the floating arrow itself may be sufficient for the task. The results of Google Maps usually depends on how often users use it in their daily lives, and how well the users know about the building and can locate themselves without help from GPS signal.

Although this hypothesis can not be rejected (i.e. HoloNav is not significantly better in terms of efficiency than Google Maps), the study shows that HoloNav 2 always is the fastest. Therefore, though it can not be concluded that HoloNav systems are better than Google Maps, it is interesting for future work, to have longer distances for wayfinding and some routes with a higher difficulty, to see which system is faster then.

5.1.3 Hypothesis 3: HoloNav is Better than Google Maps in Terms of Correctness

By counting the wrong turns that the user made during the process of navigation, we can analyze the correctness of navigation systems. As well as in the other hypothesis, the difference between the tested systems are not statistically significant, yet both HoloNav 1 and HoloNav 2 have less mean values over all three routes; hence, they are better in terms of correctness than Google Maps.

From the observations, if a user has problems finding their position on the map of Google, the probability of the user walking in the false direction initially is higher. Different from the Google Maps, the problem of wrong turns with HoloNav is different. Mostly it is the problem with refreshing or re-scanning of the environment and therefore it can not render the direction immediately. Another problem that can be noticed is that the floating arrow changed its direction too late and the users walked straight ahead instead of making a turn. The users usually realized it after some meters, leading to more time consumption. These findings may also contribute to the reasoning of hypothesis 2.

To sum up, one can conclude that both HoloNav systems have on the chosen routes the higher correctness than Google Maps. Nevertheless, the routes selected in this study is relatively short and only with a limited number of participants. For a comprehensive study of the correctness of navigation with HoloNav, it is recommended to conduct more concrete tests on longer routes and in a building that is not known by anyone.

5.1.4 Memorability

In general, the environment is more remembered when people need to be actively looking at it to orient themselves as it is needed for the navigation with Google Maps. In contrast, if the users wear the HoloLens 2, they do not need to think about their way and only follow the visualizations on the screen. It is not necessary then for the users to constantly concentrate on the environment. Due to these reasons, it is as expected that the memorability of routes with Google Maps is a bit higher than that with HoloNav. However, the differences between the two systems are too small to have a significant result here.

5.1.5 Visual Aspects

As seen in Chapter 4.2.5, there is not a concrete conclusion on which visualization is the best for navigating. It usually depends on personal taste. Therefore, it would be best if the users can choose which visualization they want by themselves. A combination of some UI elements from both HoloNav 1 and HoloNav 2 may be a good practice for that. For most users, it was easier to follow the transition line than following the floating arrow. This may because transition lines are one of the most commonly used visualizations in all navigation systems. The solution could also be integrating the transition lines with the arrows showing the directions.

The more preferred mini-map was the non-static version (i.e. hand-invoked mini-map). However, the use of such a mini-map may be a bit more time-consuming because people need to explicitly stop and have a look at the map. In this sense, it may not work seamlessly while walking, whereas the permanent one is easy to read while walking. Here an option could be to have two possibilities ready and allow the users to choose the mini-map individually. Both mini-maps have their advantages and disadvantages. A next step could be to orient the mini-map in the same direction as the user is walking towards. Many users have mentioned that the mini-map would be easier for them to understand with this function.

The color style and the symbolization for the mini-map do not matter, as seen from the approximately ½ for one versus the other possibility in each case. Lots of participants did not even remember which color or symbolization they liked more.

5.2 Discussion of Results under the Given Related Work

As seen in Chapter 2, computer vision is one of the most often used methods for indoor positioning systems and can be used to recognize landmarks, like stairs, pillars, etc. In this study, a MR navigation system was successfully implemented. The operating platform is HoloLens 2, which is one of the most advanced head-mounted MR headsets with many state-of-art technologies enabled. With the native spatial mapping capability as well as the technique of ASA, landmarks can be labeled and recognized with virtual markers (i.e. spatial anchors) in a physical environment. It makes the recording of the precise locations of landmarks and the retrieval and recall of such locations possible. Together with some useful navigation visualizations, these spatial anchors can be used later for navigation. The study demonstrates a feasible workflow for designing and implementing a MR-based navigation system. Compared to the traditional paper-based maps, the system has visually pleasing interfaces, a good user experience, and efficient performance on navigation. This project can be considered as a foundation for other MR navigation systems for future work.

5.3 Consequences

The indoor navigation system using ASA and MR gives raises many interesting perspectives. Through the interactive way of navigation, it can be a complement to the existing approaches and also help users with difficulties using the traditional navigation systems in the market. A critical point is, however, the scale of the environment where such navigation systems will be used and the size of the audience. On the one hand, to develop the virtual landmark network, a significant number of ASAs need to be created manually to cover as many landmarks inside buildings as possible. Intensive human works are required for a usable system on a large scale. On the other hand, the system can also be used for a small number of target locations with a limited number of users; for example, in a museum, only a few landmarks at locations of interest are needed and the mapping part of the navigation system is easily achievable by the staff. In this context, the work to build a navigation system that can guide a person interactively in the building is feasible. As it is analyzed from the user study, it is also very important that the system can be personalized in terms of the ways of interactions and the visualizations. This can increase the user experience by enhancing satisfaction during navigation. In a nutshell, it is feasible to develop a MR indoor navigation system with ASA on MR devices as HoloLens 2 for applications with limited user quantity and offer a plurality of perspectives for the future.

5.4 Limitations

5.4.1 Application

Dropdown Menu in MR

During this project, it is observed that the usability of such UI type in HoloLens 2 requires some previous experience from the user. For one reason, the support for dropdown lists is still under development by MRTK, the design of such component is not yet fine-tuned for HoloLens 2. The main problems are that to acquire a sense of how far each element in the dropdown list to be pushed, a lot of practices are required to be able to precisely pick the desired one. In addition, the user needs to find the exact contact point with her index to click and move the scrollbar. Pre-defined buttons with the names of elements may be more user-friendly for people with less experience with HoloLens 2.

Mini-Map Development

At the beginning of the mini-maps development, the focus was on the functionalities and interactions. On the HoloLens 2 Emulator in Unity, the goal was to develop as many functions as possible. After the first navigation, the initial plan was to implement a rotating mini-map and show some routing information directly on it. But after the first deployment on the HoloLens 2 device many difficulties appear in the field of usability. In detail, the mini-map was taking too much space in the limited field of view of the HoloLens 2 device in the first versions and it could be problematic for the security and user experience during the navigation. But if the mini-map size is too small, this element becomes useless and not enough visible. Some lighting issues when the user of the gaze was in front of a window were problematic too and some lighting solutions in Unity have to be found and each time tested on the device. The symbolization, textures, and color styles have also to be researched for intuitive use without instructions and optimal navigation experiences. All those issues need to find some compromises. And to find them, a lot of deployment and live tries have to be done. It means that the time invested for this part has not to be underestimated. Each application build, deployment on the device, live test, and correction could take at minimum 15-20 minutes. If the time, personal and financial resources of such a development are limited, the usability part of the mini-map could have an impact on the project, in particular for the other functionalities, if the planning is not realistic. Special attention must therefore be paid to these aspects.
For the HoloNav application, the actual state of functionalities for the mini-map still has room for improvement. On one hand, it is not problematic because the new HoloLens 2 users may have difficulties interacting with elements and information. And this is why the system has to remain simple. On the other hand, the fact that the mini-map does not rotate can lead to comprehension problems during the navigation. Priority functionalities to be implemented in the future are also those which increase the intuitiveness of the systems and not the complexity.

Mini-Map Anchors

To make the link between the mapping data which are created in the real environment and the mini-maps modeling, several solutions can be considered. One approach consists to read the ASA coordinates on the ATS and transform them into the mini-map coordinate system. This method is profitable if the number of spatial anchors is big and some changes are done in the database. But it can be problematic if the user is not the administrator of the ATS database and does not have access to some information. Given that the navigation system is used for one floor only and for some pre-defined routes only and that less than 50 spatial anchors were needed, another approach was preferred to spare time. All representations of the mini-map anchors were created manually. This method has the advantage that it is possible to use a certain leeway to display spatial anchors with human interpretation and modeling. For example, if two spatial anchors are too close to each other to differentiate them, it is possible to find a compromise between the reality and the modeling and space them out to a certain extent. The big disadvantage of this method is that when new changes in the database are made, then the mini-map anchor state does not correspond to the ASA state anymore.

Multiple Floors

The HoloNav system can technically be extended to more floors. Some potential technical difficulties can be present. For example, during the preparation part of the navigation, the shortest path calculation has to take into account the elevators. In the graph, a short-cut using different resistance values has also to be prepared. During the navigation, some issues could be present with long stairs (repetitive and linear elements) which could make the HoloLens 2 device lost in the environment. The same problem may appear if the floors are too similar. In this case, the device could maybe not recognize anymore which floor is the current one. Therefore, it is important to do some tests and take into consideration these elements.

Environment Scanning

An HoloLens 2 device scans the environment continuously to get the user position. If the volume of the building is too large (like for example in the main entrance of the HIL), it may happen that the scan quality is not good enough to get a correct position. This phenomenon could appear too along regular long corridors. Such an issue may cause navigation to fail. And then user satisfaction can be directly impacted. To improve this, one possible solution would be to force the device to scan. If this can be done, it is possible to regain control of the position quality by scanning in a smaller or more favorable environment.

5.4.2 External

Drift of Anchor Location

During our experiment, it is possible that some drifts of anchor locations may happen. One possible reason for such drifts is the repetitive structures in the route (e.g. a long corridor). As the structure of the corridors in the HIL building can sometimes look quite similar, it may confuse the HoloLens's spatial mapping that there are the same [17]. The placement of some spatial anchor can be wrong. To mitigate such a problem, attaching unique markers such as QR codes or several small markers to the environment may help HoloLens better recognize a similar-looking structure.

The inaccurate localization of the spatial anchors can also attribute to the long distance between the spatial anchor and the user's location. When a longer route is selected for navigation, it is possible that the HoloLens will initiate a scanning process in the middle of the navigation because the HoloLens has detected a new unknown environment. The same problem also can happen when the HoloLens is passed to another user and the environment is forced to re-scan for some reasons. This would cause an inaccurate shift of the loaded spatial anchors. Similar issues have been reported by some other users in the forum and no existing solutions have been proposed. These shifts may be caused by the re-scanning of the environment by HoloLens. Unfortunately, the process of re-scanning the new environment is controlled by HoloLens and cannot be stopped by the application. The only possible solution is to pre-scan and cache the environment beforehand. However, this may raise another problem with the memory with HoloLens, which needs to be thoroughly considered and carefully handled in the future.

Quality of Spatial Anchor in Homogeneous Environment

One of the pitfalls of spatial anchors, as a computer-vision-based method, is that the quality of the anchor position heavily relies on the visual features in the environment. However, in some large spaces in the HIL building such as hallways, open spaces, study areas, etc., it is possible that no sufficient visual features can be found. These situations generally lead to very long scanning times or inaccurate localization of the anchor. Similar to the solutions to repetitive structures, manually adding some features to the environment may help.

Effect of Internet Connection

A good internet connection is required for the HoloNav to communicate with the ACS. During the user study, it happened one or two times that the application did not function well due to poor network connection. Therefore, for applications in large buildings as HIL, reliable internet connection needs to be guaranteed or the application should be designed in a way that the users are properly notified when such situation happens. For example, a popup dialog with useful information will help the users better identify the problems.

Chapter 6

Conclusion and Outlook

6.1 Achievement of Objectives

At the beginning of the project, the following three main objectives are defined:

1. Develop and compare different effective and visually pleasing interaction concept for navigating indoors
2. Create a routable 3D representation of the ETH HIL Building
3. Create a meaningful and effective interactive mini-map visualizing the current location

For the first objective, the medium solution is achieved and two navigation visualizations are implemented in the two HoloNav systems respectively. For one system, the transition lines are used; for the other, a floating arrow is showing the right direction to walk. The usability of these two kinds of visualizations is compared in the user study. So far, the arrow is not integrated to the ground to form the transition markings and voice commands are not yet supported. At the current state of work, the arrow is floating at a height that is visually pleasing to the user's field-of-view, yet a comparison between the current setup and the integrated version on the ground would be a good idea. Voice commands could help remind the users to avoid risky situations, like falling over stairs, crashing on glass-doors, etc. More intelligent voice commands which keep updating the users the remaining distance till the next turn could also be added.

The second objective is reached as well till the medium solution. The system is working for almost the whole D-Floor from HIL. Only one corner of the floor is not labeled with the ASAs, which could easily be added in a next step without any adjustment in the application itself. Users are allowed to choose freely their origin and destination from the list of rooms with the room-numbers. At this point of the study, it is not yet possible to navigate across multiple floors or use the elevators and changing floors. While, it is worth mention, that the current work already support some stairs (sub-floors) in the environment, yet because of the adjoining corridors, they are still considered the same floor. In theory, the project can be generalized to multiple floors scenarios, while some adaption is needed.

The third objective is to implement a mini-map. This mini-map is showing the origin and destination position at the beginning of the navigation. Afterward, it is updating the anchors which are already passed. Therefore, it can be seen as an overview of the whole route. Until now, road-maps are not available in the mini-map, which would show rooms and corridors clearly. The implemented mini-map supports change floors. Nevertheless, to be able to orient the mini-map according to the user's walking direction, as described in the maximal solution, further adaptions need to be made.

To conclude, that the maximum solutions for the three objectives are set a bit too ambitious given the effort and time-frame of the study. Moreover, as a new device on the market, there are only very limited resources for many issues with HoloLens 2 and have to be solved individually. Indeed, it took a lot of time to solve the version issues with ASA SDK, MRTK, and HoloLens 2 at the beginning of the study and the schedule of the project was thereby hindered. As the focus of the study was set to the implementation of a workable navigation system for testing in a user study. Therefore, some maximum solutions, such as creating anchors all over the HIL Building, would not boost the output of the study extremely; hence, were not in the priority. The study thus focused more on creating pleasant UIs, which should help the user to operate with the system and improve the overall user experience.

6.2 Overall Conclusion

6.2.1 Application

In the study, the HoloNav, a MR-based indoor navigation application on HoloLens, is successfully realized. The application provides two major functions: 1. the mapping function, which can be used to record any locations of interest in buildings; 2. the navigation function, which supports routing between any locations on the record. Two types of navigation visualizations are implemented: one with an arrow and hand-invoke mini-map, one with transition lines and permanent mini-map. Both versions of HoloNav are tested on the D-floor of the HIL building with in total of 43 virtual landmarks created.

6.2.2 User Study

22 participants took part in the user study, where 3 systems were tested. On the one hand, there were two different visualizations of a navigation system for HoloLens 2, named HoloNav 1 and HoloNav 2. On the other hand, the well-known application Google Maps is tested. Participants tried all of the three systems on three different routes. The routes to the systems as well as the order of using the system were randomly assigned.

After analyzing the results of the user study it can be said, that there can be seen tendencies, which system works better for indoor navigation. But there are no significant results. Some effects like familiarity with the building and familiarity with mobile phones but not with HoloLens 2 can not be neglected. To answer the research questions three hypothesises were made and analyzed.

6.2.3 Research Questions

The first research question is: *What kind of visualization is preferred in Mixed Reality navigation systems?*. The analysis of the comparison between the two HoloNav systems brings some insights. It can be seen, that following a transition line was the faster navigation system. A lot of participants mentioned that it is clearer to follow a transition line than a floating arrow. Therefore, lines should be integrated into a MR navigation system. An option would be to add arrows to the line so that the direction of walking is clear. One can see by the results that the hand-invoke mini-map was liked more than the permanent one. Even if it is more time consuming, it was more appealing in the UI than having a permanent mini-map always in the field of view. The color style (clear pink or transparent purple), as well as the symbolizations (pins and flags or cubes and stars), does not matter for the mini-map. Most people do not remember it afterward, or do not prefer one or the other. To conclude it can be said, that a combination of HoloNav 1 and HoloNav 2 would be a good solution. The transition lines should be adapted with arrows showing the direction. The mini-map could be non-static or available per button to be permanent.

The second research question to answer is: *What are the benefits of a Mixed Reality navigation system compared to traditional navigation systems for wayfinding in indoor spaces?*. As it can be seen during the interpretation the probability that HoloNav 2 is the fastest option for wayfinding is really high. Users do not need to be familiar with the system to navigate fast and correctly. Mostly they do not have some wrong turns. So benefits are the speed as well as the correctness. If a user is walking in the wrong direction she will recognize it quickly. Furthermore, system usability is rated rather high, which means that HoloNav 1 and HoloNav 2 are already good to use. A disadvantage was mentioned by the proband of the user study, that in everyday life they would not like to wear HoloLens 2 for navigating. At the moment it is common to have a mobile phone with oneself all the time. People can not imagine now to wear HoloLens 2 for normal. This may change if more useful applications are available for HoloLens 2 which motivates people to wear HoloLens 2 as a standard. Then users say they would like to use HoloNav more than the traditional Google Maps on their phones.

6.3 Potential Future Work

The identified limitations during this project for the navigation systems provide opportunities for future development. The actual HoloNav application state can be improved to have a system more adapted to the user requirement or needs of the market. It could also offer a better user experience in terms of functionalities, graphical aspects, interactions and plurality of device types. Some suggestions are formulated below:

1. Multiple floors: One further step consists to develop the HoloNav for multiple floors. The database structure has to be adapted and some tests have to be done to keep a high quality of positioning during the navigation. A solution to adapt the shortest path algorithm has also to be developed to take into account the stairs and the elevators time speed differences during the navigation. Some functionalities can be also developed on the mini-map to optimize the overview of the navigation inside of the building.

2. Multiple devices: A complement to the actual MR navigation application using HoloLens 2 could be an extension to other supports using AR, like smartphones or tablets. It could be an interesting way to make the application more accessible and possibly increase the number of users to densify the network of ASA faster.

3. Interdisciplinary navigation: the MR indoor navigation system could be combined with other existing systems to integrate more functionalities. The navigation can be completed to propose more information to the user regarding the environment. Or vice versa it is also possible that another existing system can be completed by the navigation to get some information about actual position and orientation. A possible application of an interdisciplinary development is to use such a system in a museum. MR navigation can guide the user through the museum building. And at each point of interest, an artwork for example could be augmented through MR interactions according to a defined concepts [25]. The advantages of such a system could be to better distribute the visitors during peak periods and make the user experience unique.

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Glossary

2D	Two-dimensional
3D	Three-dimensional
ACS	Azure Cloud Service
AR	Augmented Reality
ASA	Azure Spatial Anchors
ATS	Azure Table Storage
ID	Identifier
MR	Mixed Reality
SD	Standard Deviation
SLAM	Simultaneous Localization & Mapping
SUS	System Usability Scale
UI	User Interface

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

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For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Appendix A

Forms for the User Study

In this chapter of appendix, all forms used for the user study can be found. It includes the introduction sheet, the declaration of consent, all questionnaires, and the notepad for the investigator.

A.1 Introduction

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HoloNav: A Mixed Reality Indoor Navigation System

1 Introduction

Thank you very much for your willingness to participate in this study for our interdisciplinary project (IPA).

You will be participating in a study which will test indoor navigation systems. You will wear HoloLens 2, which are MR-Glasses. The application should be able to help you in finding the right way to a specific room.

We are especially interested in how helpful the system is and if it is understandable. You can provide feedback afterwards.

2 Experiment

At the very beginning, you need to sign the consent form to be able to participate in the study.

Afterwards you need to fill out a questionnaire with some questions about yourself.

Then we will provide you a short explanation of the possible and needed gestures for HoloLens 2. Try to repeat and learn them, then it will be easier afterwards to navigate with the HoloLens.

Next you will get the HoloLens 2. Your goal is to find a specific room as quick as you can. If you wear the HoloLens 2 you can start the navigation by clicking. Please tell us, when you were able to start. You will then navigate to the described room. If you think you have reached it, please give us a note.

We will then return to the place of origin. Here a short questionnaire about wayfinding with the help of the Application on HoloLens 2 has to be filled out.

You will repeat the same procedure (Navigate with HoloLens 2 + Questionnaire) with a slightly different application.

For ending up you will get a mobile phone with Google Maps. With help of this navigation tool you have to find as quick as possible the described room. Same as before, give us a note if you think you have reached it.

If you want to stop the experiment early, please let us know.

3 Legal notice and privacy

To participate in this experiment, you must be at least 18 years old. Furthermore, you should be in full possession of your mental and physical strength and not be under the influence of drugs, medication or alcohol.

4 Risks

The provided devices may cause some pressure marks on your head. Prolonged usage of the devices may lead to tiredness and headaches.

5 Right of withdrawal

If something is unclear, please ask without hesitation. You may stop the study at any time without specifying reasons and without any consequences.

6 Data protection

The obtained data will be stored safely and reported in an anonymous form. The data will only be used for scientific purposes and could be used in a publication. The data is primarily needed for our IPA. Furthermore, the data will be made available to the Institute of Cartography and Geoinformation (IKG). So, the data will be stored on the servers of the IKG.

7 Contact

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Master in Geomatics	Master in Geomatics	Master in Geomatics
brunnerx@ethz.ch	schalaur@ethz.ch	wuti@ethz.ch

8 Supervision of the IPA

Fabian Göbel, Tiffany C.K. Kwok, Luis Lutnyk, Dr. Peter Kiefer, Prof. Dr. Martin Raubal

Institute of Cartography and Geoinformation

ETH Zürich

E-Mail: goebelf@ethz.ch

Dr. Martin Oswald

Computer Vision and Geometry Group

ETH Zürich

A.2 Declaration of Consent

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Please read this form carefully and ask the investigator if you do not understand something or want to know something.

Title of the study: HoloNav: A Mixed Reality Indoor Navigation System

Place of the study: ETH Hönggerberg, HIL

Investigator (name and first name): Brunner Xavier, Schalbetter Laura, Wu Tianyu

Proband (name and first name): . . . .

⇒ I participate in this study on a voluntary basis and can withdraw from the study at any time without giving reasons and without any negative consequences.

⇒ I have been informed orally and in writing about the aims and the procedures of the study, the advantages and disadvantages, as well as potential risks.

⇒ I have read the written information for the volunteers. My questions related to participating in the study have been answered satisfactorily. I can receive the written information and a copy of my written consent upon request.

⇒ I was given enough time to decide about participating in the study.

⇒ With my signature, I certify that I fulfill the requirements for participating in the study stated in the information for the volunteers.

⇒ I agree that the responsible investigators and the Institute of Cartography and Geoinformation (IKG) have access to the original data under strictly observed rules of confidentiality.

⇒ I am aware that during the study, I must comply with the requirements and limitations described in the information for volunteers. In the interest of my health, the investigators can, without mutual consent, exclude me from the study.

Place, Date	Signature of Investigator
Zürich, ...	. . . .
	. . . .
	. . . .

Place, Date	Signature of Proband
Zürich, ...	. . . .

A.3 Pre-Questionnaire

Questionnaire to User Study

IPA - HoloNav: A Mixed Reality Indoor Navigation System

Test Person ID.: _______

1 Personal Questions

1.1 **Age:** ________ years

1.2 **Gender:**

☐ Male ☐ Female ☐ Other: ________________

1.3 **I have used VR or AR-Device at least once before.**

☐ Yes ☐ No

1.4 **I have used Microsoft HoloLens 1 or 2 before.**

☐ Yes ☐ No

1.5 **If yes (Questions 1.4): On what occasion? For how long (hours; minutes)?**

____

1.6 **I know the floors and rooms of the HIL-Building of ETH.**

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.7 **Why do you know the HIL-Building? (choose the best possible answer)**

☐ I am currently studying/working there.
☐ I had been studying/working there.
☐ I was there often.
☐ I was there sometimes.
☐ I was there once.
☐ I do not know this Building (Question 1.7 was answered with 7).

1.8 **Which of the following navigation tools do you use the most often (overall)?**

☐ Paper Maps
☐ Car Navigation System
☐ Apps

1.9 **How many hours/minutes do you use navigation tools (paper maps, car navigation system, apps) on average per week?**

☐ Max. 1h ☐ 1h - 10 h ☐ More than 10 h

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2 Self-assessment Questions

This questionnaire consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

1. I am very good at giving directions.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

2. I have a poor memory for where I left things.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

3. I am very good at judging distances.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

4. My "sense of direction" is very good.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

   strongly agree 1 2 3 4 5 6 7 strongly disagree

6. I very easily get lost in a new city.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

7. I enjoy reading maps.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

8. I have trouble understanding directions.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

9. I am very good at reading maps.

   strongly agree 1 2 3 4 5 6 7 strongly disagree

10. I don't remember routes very well while riding as a passenger in a car.

    strongly agree 1 2 3 4 5 6 7 strongly disagree

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11. I don't enjoy giving directions.

strongly agree 1 2 3 4 5 6 7 strongly disagree

12. It's not important to me to know where I am.

strongly agree 1 2 3 4 5 6 7 strongly disagree

13. I usually let someone else do the navigational planning for long trips.

strongly agree 1 2 3 4 5 6 7 strongly disagree

14. I can usually remember a new route after I have traveled it only once.

strongly agree 1 2 3 4 5 6 7 strongly disagree

15. I don't have a very good "mental map" of my environment.

strongly agree 1 2 3 4 5 6 7 strongly disagree

A.4 After First HoloNav Experience

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Questionnaire to User Study – HoloNav 1

IPA - HoloNav: A Mixed Reality Indoor Navigation System

Test Person ID.: _______ Route ID: _______ System ID: _______

1 Questions for the Study

1.1 I think I would have found the room without help.

Strongly agree Strongly disagree
1 2 3 4 5 6 7

1.2 I think the application helped me to find the right way.

Strongly agree Strongly disagree
1 2 3 4 5 6 7

1.3 I think I understood, what the system showed me to do.

Strongly agree Strongly disagree
1 2 3 4 5 6 7

1.4 I was confused by the visualizations of the application.

Strongly agree Strongly disagree
1 2 3 4 5 6 7

1.5 I found it helpful to see the real environment.

Strongly agree Strongly disagree
1 2 3 4 5 6 7

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2 System Usability Scale

This is a standard questionnaire that measures the overall usability of a system. Please select the answer that best expresses how you feel about each statement after using the HoloNav today.

	Strongly Disagree	Some-what Disagree	Neutral	Some-what Agree	Strongly Agree
1. I think I would like to use this tool frequently.	☐	☐	☐	☐	☐
2. I found the tool unnecessarily complex.	☐	☐	☐	☐	☐
3. I thought the tool was easy to use.	☐	☐	☐	☐	☐
4. I think that I would need the support of a technical person to be able to use this system.	☐	☐	☐	☐	☐
5. I found the various functions in this tool were well integrated.	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in this tool.	☐	☐	☐	☐	☐
7. I would imagine that most people would learn to use this tool very quickly.	☐	☐	☐	☐	☐
8. I found the tool very cumbersome to use.	☐	☐	☐	☐	☐
9. I felt very confident using the tool.	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going with this tool.	☐	☐	☐	☐	☐

How likely are you to recommend the HoloNav to others? (please circle your answer)

Not at all likely Extremely likely

0 1 2 3 4 5 6 7 8 9 10

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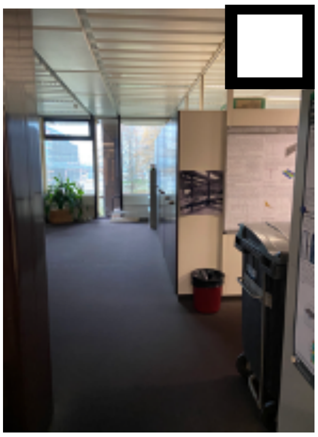
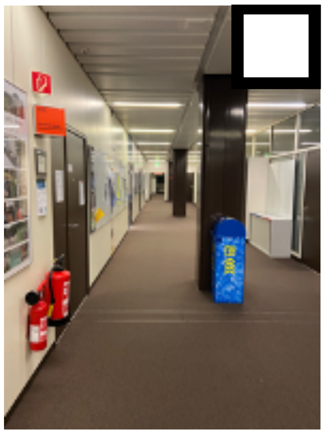
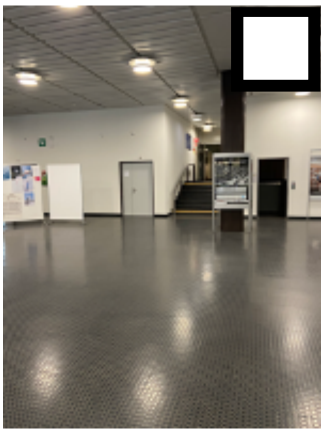
3 Remembering

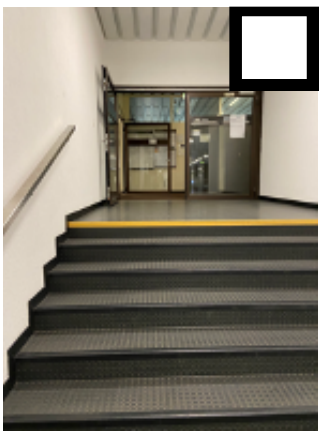
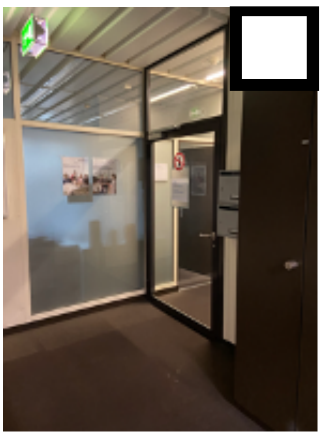
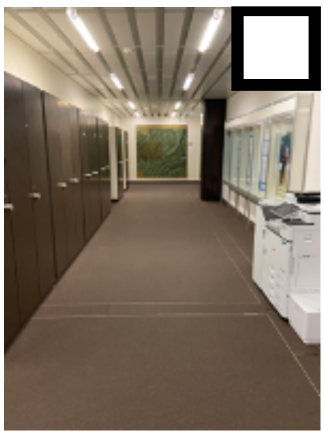
During the navigation you have passed some of the following photographs. Please mark all photos which you have passed during this navigation. Therefore, make a cross in the field.

Example: I have passed this environment | I have not passed this environment







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4 Open Questions

4.1 What do you think was helpful to find the right way?

____
____
____

4.2 What has irritated you?

____
____
____

4.3 What would you change in the user interface?

____
____
____

4.4 Which functionality was missing?

____
____
____

4.5 Do you want to say something else?

____
____
____
____
____
____

A.5 After Second HoloNav Experience

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Questionnaire to User Study – HoloNav 2

IPA - HoloNav: A Mixed Reality Indoor Navigation System

Test Person ID.: _______ Route ID: _______ System ID: _______

1 Questions for the Study

1.1 I think I would have found the room without help.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.2 I think the application helped me to find the right way.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.3 I think I understood, what the system showed me to do.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.4 I would not have found the way without the application.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.5 I was confused by the visualizations of the application.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

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2 System Usability Scale

This is a standard questionnaire that measures the overall usability of a system. Please select the answer that best expresses how you feel about each statement after using the HoloNav today.

	Strongly Disagree	Some-what Disagree	Neutral	Some-what Agree	Strongly Agree
1. I think I would like to use this tool frequently.	☐	☐	☐	☐	☐
2. I found the tool unnecessarily complex.	☐	☐	☐	☐	☐
3. I thought the tool was easy to use.	☐	☐	☐	☐	☐
4. I think that I would need the support of a technical person to be able to use this system.	☐	☐	☐	☐	☐
5. I found the various functions in this tool were well integrated.	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in this tool.	☐	☐	☐	☐	☐
7. I would imagine that most people would learn to use this tool very quickly.	☐	☐	☐	☐	☐
8. I found the tool very cumbersome to use.	☐	☐	☐	☐	☐
9. I felt very confident using the tool.	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going with this tool.	☐	☐	☐	☐	☐

How likely are you to recommend the HoloNav to others? (please circle your answer)

Not at all likely Extremely likely

0 1 2 3 4 5 6 7 8 9 10

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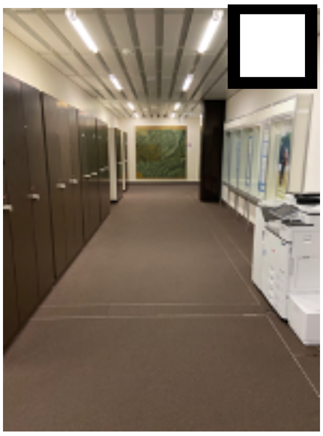
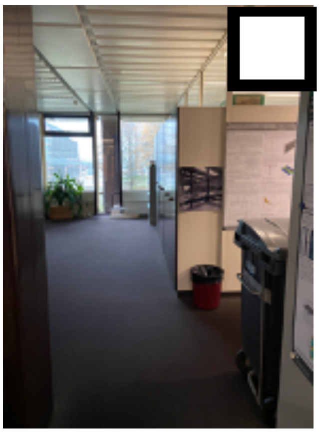
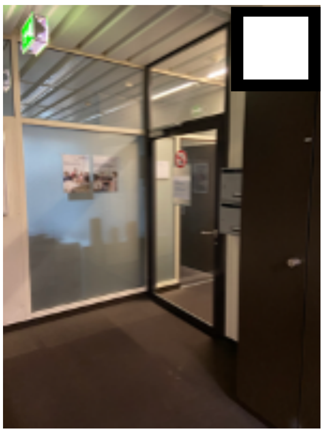
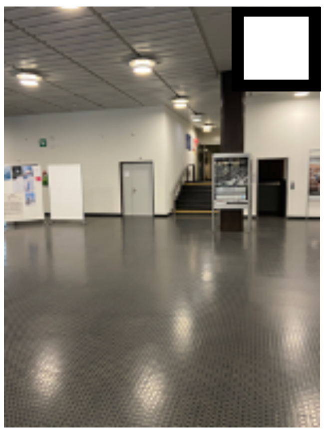
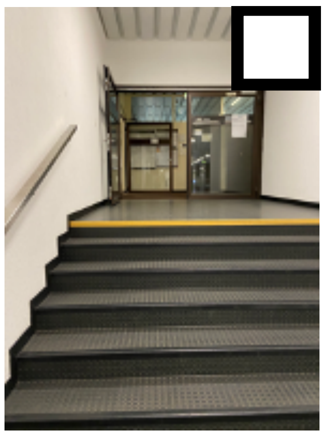
3 Remembering

During the navigation you have passed some of the following photographs. Please mark all photos which you have passed during this navigation. Therefore, make a cross in the field.

Example: ☒ I have passed this environment ☐ I have not passed this environment



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4 Open Questions

4.1 What do you think was helpful to find the right way?

____
____
____

4.2 What has irritated you?

____
____
____

4.3 What would you change in the user interface?

____
____
____

4.4 Which functionality was missing?

____
____
____

4.5 Do you want to say something else?

____
____
____
____
____
____

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5 Comparison between the two HoloNav-Systems

5.1	Which system do you liked more in general?	☐ First	☐ Second	
5.2	Which HoloNav was easier?	☐ First	☐ Second	
5.3	Which User Interface was more attractive?	☐ First	☐ Second	
5.4	Which indicator for direction was more clear?	☐ Lines & Cubes	☐ Arrows	
5.5	Which type of mini-map do you liked more?	☐ Static	☐ Hand	
5.6	Which symbology do you prefer on the mini-map?	☐ Cubes	☐ Pins	☐ Do not remember
5.7	Which color style did you prefer for the mini-map?	☐ First	☐ Second	☐ Do not remember
5.8	I have noticed a learning effect on the second application.	☐ Yes	☐ No	

5.8 How important was the interaction with the mini-map for you ?

First HoloNav System:

extremely important ... extremely unimportant

1 2 3 4 5 6 7

Second HoloNav System:

extremely important ... extremely unimportant

1 2 3 4 5 6 7

5.10 What was it, which made the system chosen in 5.1 better?

____

____

5.11 Would you like to have a mix out of this two Systems? If yes, which functionalities would you wish to have?

____

____

A.6 After Google Maps Experience

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Questionnaire to User Study – Google Maps

IPA - HoloNav: A Mixed Reality Indoor Navigation System

Test Person ID.: _______ Route ID: _______

1 Questions for the Study

1.1 I think I would have found the room without help.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.2 I think Google Maps helped me to find the right way.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.3 I think I understood, what Google Maps showed me.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.4 I would not have found the way without Google Maps.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

1.5 I was confused by the visualizations of the Google Maps.

Strongly agree						Strongly disagree
1	2	3	4	5	6	7

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2 System Usability Scale

This is a standard questionnaire that measures the overall usability of a system. Please select the answer that best expresses how you feel about each statement after using Google Maps today.

	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
1. I think I would like to use this tool frequently.	☐	☐	☐	☐	☐
2. I found the tool unnecessarily complex.	☐	☐	☐	☐	☐
3. I thought the tool was easy to use.	☐	☐	☐	☐	☐
4. I think that I would need the support of a technical person to be able to use this system.	☐	☐	☐	☐	☐
5. I found the various functions in this tool were well integrated.	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in this tool.	☐	☐	☐	☐	☐
7. I would imagine that most people would learn to use this tool very quickly.	☐	☐	☐	☐	☐
8. I found the tool very cumbersome to use.	☐	☐	☐	☐	☐
9. I felt very confident using the tool.	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going with this tool.	☐	☐	☐	☐	☐

How likely are you to recommend Google Maps to others? (please circle your answer)

Not at all likely Extremely likely

0 1 2 3 4 5 6 7 8 9 10

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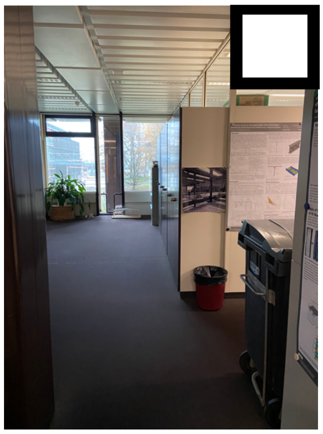
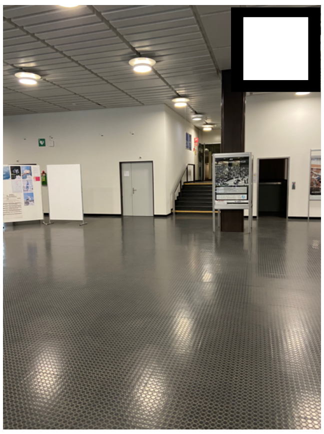
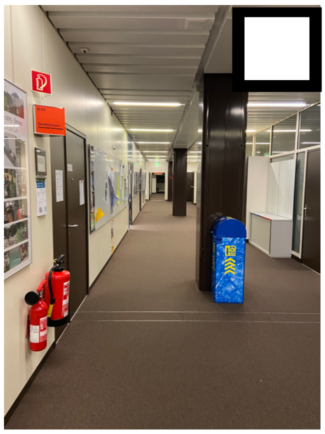
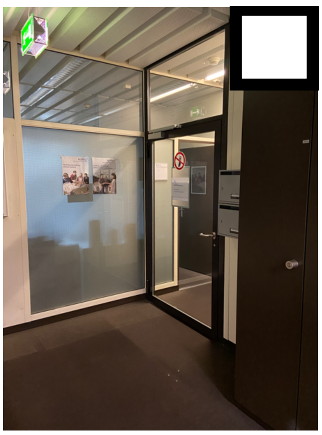
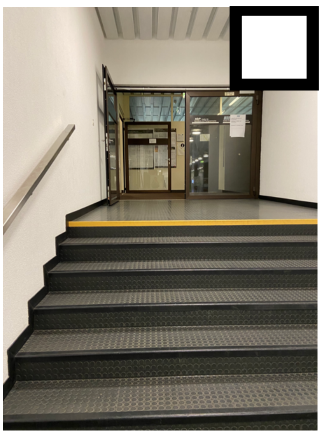
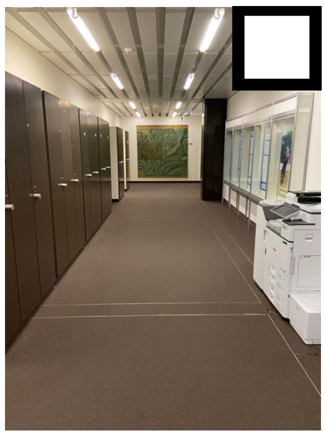
3 Remembering

During the navigation you have passed some of the following photographs. Please mark all photos which you have passed during this navigation. Therefore, make a cross in the field.

Example: ☒ I have passed this environment ☐ I have not passed this environment



A.7 Questionnaire for Comparision Between Google Maps and HoloNav

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Questionnaire to User Study – Comparison

IPA - HoloNav: A Mixed Reality Indoor Navigation System

Test Person ID.: _______

1 Comparison between HoloNav and Google Maps

1.1	Which navigation tool do you liked more in general?	☐	HoloNav	☐	Google Maps
1.2	Which navigation tool would you rather use in your everyday life?	☐	HoloNav	☐	Google Maps
1.3	Which navigation tool was clearer to understand?	☐	HoloNav	☐	Google Maps
1.4	Which navigation instrument was more satisfactory?	☐	HoloNav	☐	Google Maps

1.5 Why have you chosen this navigation tool in question 1.1?

____
____
____
____

1.6 Why was this system clearer (question 1.3)?

____
____
____
____

1.7 Do you want to say something else?

____
____
____
____

Thank you for your participation!

A.8 Sheet for Investigator

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Route:
A : D42.2 – D55.3
B : DDoor 1 – D21.2
C : DDoor 2 – D35.1

Systems:
H1 : HoloNav 1
H2 : HoloNav 2
G : Google Maps

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Measurement User Study

Test Person ID	System 1	Route 1	Time 1 (sec)	Wrong Turns 1	System 2	Route 2	Time 2 (sec)	Wrong Turns 2	System 3	Route 3	Time 3 (sec)	Wrong Turns 3