TECHNICAL UNIVERSITY OF MUNICH

DEPARTMENT OF INFORMATICS

Bachelor's Thesis in Informatics: Games Engineering

# Acoustic Wayfinding Support in Real Environments without the Sense of Sight

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# Akustische Signaletikunterstützung in realen Umgebungen ohne Sehvermögen

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| Submission Date: | 15.03.2020 |

I confirm that this bachelor's thesis in informatics: games engineering is my own work and I have documented all sources and material used.

Munich, 15.03.2020 Mehmet Dereli

# Abstract

People who have vision impairment or blindness have difficulties with day to day tasks, such as navigating from on point to another or getting to know an unfamiliar environment. The aim of this bachelor's thesis is to create an Augmented Reality system that supports people who are affected by these disabilities by giving acoustic feedback that is generated through different wayfinding support techniques.

# Contents

# 1 Introduction

According to the World Health Organization (WHO) there are at least 2.2 billion people affected by visual impairment or blindness [Org19]. The loss of the dominant human sense, the sight [Eno+19], leads to challenges in everyday activities, such as the avoidance of obstacles or the navigation from one point to another.

There are several aids that are well established nowadays, such as guide dogs and white canes, which help these persons to overcome parts of their daily challenges. Apart from strictly physical aids, there are a few other approaches that make use of smart phones. In doing so, these approaches employ the camera function to identify objects, e.g. Aipoly [Ltd], or to video chat with another person guiding the disabled person to their goal, such as be my eyes [Eye]. However, these assistances only help the user to overcome parts of their daily challenges and are dependent on either another person or an internet connection. Therefore, this thesis proposes another approach, that is based upon the use of Augmented Reality (AR) methods and techniques.

The core idea of the present paper is that of sensory substitution, the conversion of stimuli from one human sensor into that of another. While there are different human sensors that could be used to compensate the loss of vision, this thesis uses stimuli for the sense of hearing. Since the sensor that processes these stimuli is the second most important sensor that humans possess [Eno+19], the information content that can be conveyed is higher when compared to the others.

In order to perceive the environmental stimuli a depth-camera is used. Afterwards, the information are processed by the system, and the resulting sounds are conveyed through headphones. Depending on the current confronted challenge, different modes are provided in order to process the needed information. These modes include user-aswell as environment-centered wayfinding support to accommodate the different challenges. While the user-centered modes try to directly map the visual information into acoustic information, the environment- centered wayfinding mode is based upon 3D user interfaces that are known and used in video games. As they are mainly visual, the underlying concepts are converted from the visual space into the acoustic space.

This paper is divided into eight parts. The first part describes the fundamental element, wayfinding, on which the different modes are built upon. The next part describes the setup of the presented system, before moving to related work that has been made in this area. The main part of this paper is within the System Design chapter, where the idea of each mode is portrayed. After providing insights on the implementation aswell as the pre-study conducted, the results are evaluated, the paper is concluded and an outlook is given.

The research question to this empirical thesis is whether or not sounds can be used to support the wayfinding process.

# 2 Wayfinding

As this bachelor thesis is about wayfinding, the first thing that needs to be explained is wayfinding itself. There exist many definitions for this term, but the fundamental idea of wayfinding is "finding the way". There are several more aspects that are included within this topic, which cannot be explained using a single definition. In the context of this thesis, the following definition is used. "Wayfinding is the cognitive process of defining a path through an environment, using and acquiring spatial knowledge, aided by both natural and artificial cues" [Bow+14a] .
The definition divides wayfinding into two different parts, the acquirement and the use of spatial knowledge. While the acquirement of spatial knowledge refers not only to the structure of the environment, but also the awareness of one's own position and viewing direction, the usage of this information refers to the data processing, which is based upon the particular wayfinding goal. While this process is a cognitive one, it is usually done automatically, due to its regular use in everyday situation.

## 2.1 Wayfinding Tasks

There are several ways to divide wayfinding into tasks. This paper focuses on a mixture of Doug A. Bowman et al. [Bow+14b] and Jan M. Wiener et al. [Wie+09]. Depending on the specific wayfinding goal, the tasks are differently prioritized. Broadly speaking there are three distinctive types that are interesting in regards to this thesis, *Exploration*, *Search* and *Specified Trajectory Movement*. While the first task is categorized as undirected wayfinding, which is wayfinding without goal, the other two are categorized as directed wayfinding, which refers to a wayfinding process with a specific goal.

### Exploration

Exploration tasks deal with gaining spatial knowledge without having a specified goal in mind. It is typically used in new environments where the spatial knowledge is insufficient. An exemplary situation is the movement of a person's residence to another city. The environment is unknown and thus needs to be explored to build up ones spatial knowledge. [ON78]
Jan M. Wiener et al. [Wie+09] made a further distinction in regards to undirected

wayfinding. While exploration can only be done in an unknown environment, someone can still walk around an known environment for the sake of taking a walk. The purpose of such a *Pleasure Walk*, as Jan M. Wiener et al.[Wie+09] refer to it, is not to gain spatial knowledge and takes place in an known environment.

#### Search

Search tasks have a specific goal within the environment, for example the refrigerator in a house or the grocery store across the street. Therefore, search tasks are categorized as directed wayfinding. The process of searching can be done in two ways, naively or primitively. While naive search is about exploring the environment (Exploration Task) until the objective is found, primitive search is about additionally using ones spatial knowledge to find the goal. In comparison, the primitive search fairs better, due to its prior knowledge of the environment.
During the performance of this type of search, spatial knowledge is not only being accumulated but is also used, which is the main difference between directed and undirected wayfinding. [Bow+14c]

#### Specified Trajectory Movement

The last task refers to moving along a specific trajectory which is usually a path. If there is a path that has already been planned, the user can move along that path by using his sensory input. An everyday example would be ones way to the university. Since spatial knowledge has been build up after the first search for it, a path can be planned and followed. On the contrary, if there is not enough spatial knowledge, the path has to be searched first. [Wie+09]
Unlike Search, Specified Trajectory Movement cares about the way that has been taken to a goal. There might be different conditions that have to be fulfilled, such as the use of sidewalks and the avoidance of alleys, or the use of streets and not sidewalks when driving by car. These conditions can be taken into consideration when planing a path. Another factor is the time that takes to reach the goal. The user may want to take the fastest path to the goal or follow a path that lets him see certain places, while the time is irrelevant.
Like in Search and Exploration tasks, spatial knowledge is being accumulated when searching for or following a path.

## 2.2 Spatial Knowledge

The spatial knowledge that wayfinding tasks use and gather have different levels of accuracy. The quality of wayfinding tasks is tightly connected to the accuracy of this knowledge, because the method that a task can use depends on it. Take for example a student trying to follow a path to the university. This path can be planned, if there is enough accurate spatial information. But if the knowledge is lacking, the path has to be searched. The process of gaining spatial knowledge is called "cognitive mapping" [DS73].

There are three levels of spatial accuracy that have been proposed by Siegel and White [SW75].
The first one is *Landmark Knowledge*. Because it only contains the most outstanding objects in the environment (Landmarks), it has the lowest level of accuracy. It mainly serves the purpose of rough orientation.
The next level of spatial knowledge is route knowledge. It is about the knowledge of paths between specific points. These routes consist of sequential actions, which include instructions such as "turn right at the next point", and are non-metric, meaning that there are no numerical values attached to the instructions.
The third and last level of spatial knowledge is *Survey knowledge* and has the highest accuracy level. It can be imagined as a map-like structure which contains information about the whole topology, this includes positions, distances and orientations.

## 2.3 Reference Frames

Whenever it is talked about positions of objects or directions, the different reference frames play a viral role in it. Reference frames can be split in two types, which are the egocentric reference frame and the exocentric reference frame as seen in Figure 2.1 and have been introduced by Proulx et al. [Pro+16].

The egocentric reference frame provides information and data relative to a person's current position and orientation. This is according to the feeling that we are the center of space.
The other reference frame is called exocentric or allocentric reference frame. This framework describes objects relative to each other, meaning the center of space is external to one's self.
An example is the navigation of people to a location. The instructions in a egocentric reference frame would be "turn left" as it only takes the rotation of the navigated person into account. On the other hand, the instructions in an exocentric reference frame would be "turn north", as it is taking an external point as the center of space.

When people find themselves in a new environment, they try to build up their cognitive

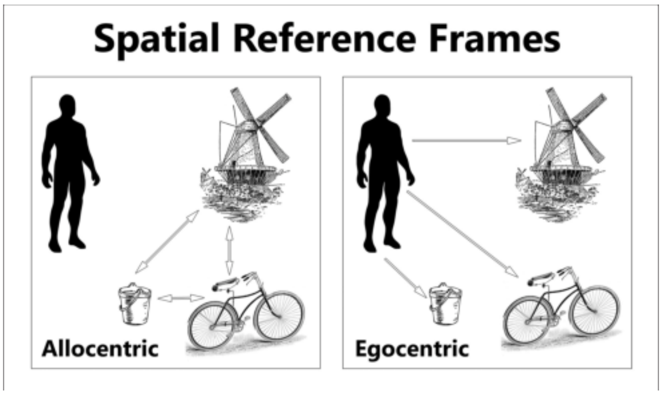


Figure 2.1: The location of objects can be represented in egocentric and allocentric spatial. Adapted from [Pro+16]

map. To do so they use an egocentric framework to identify landmarks and routes, which is due to the position and orientation of the objects being irrelevant in relation to other objects. Only after the second level of spatial knowledge is completed, the exocentric framework becomes relevant, because the required environmental information have to be relative to each other.

## 2.4 Wayfinding Support

The act of wayfinding in its whole is no simple task. As there are many complex and time-consuming processes, such as the buildup of cognitive maps or route planning, there is a certain need for support. Depending on the type of environment that wayfinding is used in, e.g. virtual or real, the aids differ in their operation and quality. The level of support that can be provided in either environment is dependent on the level of control in it. A levitating arrow for example that can be used in video games to represent a direction is not feasible in real life.
The distinction of these environments is less relevant when *Augmented Reality* is included. With its rapid growth in recent years, examples such as the one above are possible and thus create new possibilities.

### 2.4.1 User-Centered Wayfinding Support

When the term wayfinding support comes to mind, one usually pictures an arbitrary external device, such as a map or compass, because such aids are well known in today's society. However, user-centered wayfinding support is not well known. User- centered wayfinding support makes use of the characteristics of human perception. Therefore, the offered support is usually technology oriented. In the following, the different user-centered wayfinding cues are explained.

### Field of View

The field of view (FOV) defines the angle in which information can be collected visually. Humans, for example, have a FOV of approximately 180 degree horizontally and 150 degree vertically [Hei92]. These values are slightly variable due to the facial anatomy of an individual
Depending whether the environment is real or virtual these values can be modified at a great scale. If a first-person video game is taken into account, the FOV does not have to be 180 degree horizontally, but it can be 260 degree. The representation of such big FOV on monitors look different than the human FOV in real environments, thus hindering the wayfinding process due to the visual information overload. On the contrary, FOVs that are too small result in less information than human beings are able to process. As a result, in order to fully scan the environment, the head (the camera in our first-person video game example) has to be moved around to a greater extent. Furthermore, a small peripheral vision leads to the potential miss of motion cues.

### Motion Cues

Motion cues specify whether an object moves, in which direction it moves, at which speed it moves and what its distance to the person of interest is.
Due to the big binocular view field that humans have [Hei92], judging distance is easier than for animals which only have a small field of binocular view. But not every distance judgment is based upon this. When humans are moving, e.g. by car, they can perceive the relative distance of stationary objects by the speed at which their backgrounds moves. Objects that are closer to a person move faster, while those that are further away move slower. This monocular motion cue is called motion parallax. [Fer72]
Another monocular motion cues that is used to judge depth is done through optical expansion. This refers to the optical size change that occurs when an object moves towards a person. [SG86]
Motion cues however are not only visual but vesicular aswell. While in real environments a certain sense of vestibular cues (real motion) is given, there is a lack of it in virtual environments. The vestibular cues in virtual environments can be conflicting with what the user is experiencing in the real environment at the time, thus leading to cybersickness for example [RS91]. This may then result in an aggravated build up and use of the cognitive map. In order to support the vestibular cues in virtual environments there are so called *motion simulators*, which are used in, e.g. simulation games, to match the real and virtual vestibular cues.

For the reasons that the system in this thesis is an augmented reality system, the vestibular cues are already existent due to the real environment.

#### Multisensory Output

In order to get as much support as possible, human senses such as hearing and touching can be supported aswell. The presented system focuses mainly on hearing, because it is the second most important human sense and thus the most fitting one to substitute the missing sight[Eno+19]. Hearing can be used to gauge distances and directions. An example would be the beeper that is used in modern cars to signal the distance to the object behind the car when driving backwards. Its support, in the context of wayfinding, is still largely unknown and thus creates an field of research.
Another sense would be the sense of touch. In an experimental system developed by John S. Zelek [Zel05], a glove is being equipped with small motors that create vibrations on different areas. By scanning the environment with a camera, the closest objects are filtered and the different areas of the glove vibrate correspondingly. The closer the user is to an object the stronger the glove vibrates. Even though the feasibility of such systems is still unknown, it presents another field of research.

#### Presence

Another user-centered wayfinding support cue is the feeling of "being there". That feeling is assumed to have an impact on the spatial knowledge, but it is still not very well understood. It is mainly a concern of virtual environments, as the user is feeling a certain distance to the environment. It is assumed that if that distance gets shorter, wayfinding cues from real environments are going to be much more impactful in virtual environments. [Bow+14d]

### 2.4.2 Environment-Centered Wayfinding Support

Apart from wayfinding support that focuses on the user himself, there is wayfinding support for the environment. This support can be in the form of environmental design such as city or building structures, which can hardly be influenced in real environments, or in the form of artificial aids that can be adjusted and tailored to the respective environment to further improve the wayfinding process.

#### Environmental Design

The structure and format of an individual's surrounding can support the process of wayfinding. There are so called *legibility techniques* that help the user to understand

the structure of the environment with only a small number of basic elements. This is the case for environments with a repetitive structure. The individual elements are distinguishable due to their unique characteristics, thus they aid in the build up of the spatial organization. An example for this is the concentric zone model, which is also called Burgess model, which is a city structure model that splits a city structure into rings. Each of these rings have their own characteristics. The outer ring stands for the commuter zone, while the center is the central business district of the respective city. By additionally adding artificial cues in relation to the reference frames, an even more supportive wayfinding environment design is achievable.
Further areas that can be used to support wayfinding are natural environments, architectural design principles or color and texture. Natural environments provide aids in terms of natural characteristics, such as the horizon to judge distances and directions. Architectural design principles help with the placement of lights or with the advantages use of open and closed spaces. Lastly color and textures differentiate objects from each other and group them together. [Bow+14e]

### Artificial Cues

#### Maps

One of the most classic cues that are used to orient a person in the environment are maps. As the time went by, maps have evolved from classical maps in paper form into digital maps on smart phones. Maps are an exocentric representation of the environment and usually provide the user with survey knowledge.
When someone plans a path to a certain goal or wants to learn about the environment itself (Exploration) with a map, this person will first try to find his own position on it. In places, such as subway stations, there are often so called *you are here* maps, which present the current location, in order to help with the described task. When looking at maps, the scale of the map plays a significant role. It is not beneficial to look at a world map but, rather than at a local map, when trying to find the way to the next grocery store. [Bow+14e]
Furthermore, a proper alignment of a map with the environment helps the user reduce the cognitive load for mental rotation. In video games such as *Counter Strike: Global Offensive*, maps are automatically aligned to the player's viewing direction, but in real environments this process has to be done either manually or mentally. Contrary to the classical exocentric maps, the map in the last example is egocentric due to its constant alignment with the user's orientation.

**Compasses**

Compasses provide detailed information about ones orientation. In order to align a map with the environment, compasses are a helpful tool, because of their exocentric framework. The alignment process of a map, is therefore defined as the alignment of the egocentric orientation of the map with the exocentric orientation of the compass.
However, compasses are not very useful when they are used alone, which is why they are usually integrated into modern digital maps. [Bow+14e]

**Signs**

In real environments the usage of signs play a viral role in the context of wayfinding. When thinking about signs in the terms of wayfinding, the most common use cases are directional signs, which are used to guide people in the direction of their goal. But there are three further types of signs. Informational signs are used in combination with directional signs to highlight the place that the sign is directing one towards. The next type of signs are identity signs, which identify the object that they refer to. This is usually done in a written way to ensure that the identification is definitive. The last type of signs are regulatory signs, which are for example used in the form of traffic lights to regulate traffic. [des18]
While the usage of signs in real environments is vast, there is a lack of knowledge about their effectiveness in virtual environments.

**Reference Objects**

Reference objects are placed within rooms or areas where it is difficult to judge sizes and distances. These objects have to be well known in terms of size, so that they can serve as a reference to judge objects around it. [Bow+14e]

**Artificial Landmarks**

Just as regular landmarks, artificial landmarks allow an individual to spatially orient himself in the environment and aid the development of landmark and route knowledge. Furthermore, they are the foundation for distance and direction estimation.
Artificial landmarks can be divided into two categories, global and local landmarks. While global landmarks can be seen from any location due to their distinguishing appearance, local landmark's aid the decision making process whenever a decision point is reached. [SM00]

**Trails**

Trails refer to the path that is placed behind the person of interest. It is useful in terms of backtracking the path left behind, to e.g. get back to a decision point to take an alternative path. Trails can have various forms, such as waypoints or lines indicating footsteps. They are only efficiently in virtual environments, because leaving trails in real life would be more of a hindrance then a help. Another way to use trails in virtual environments is to follow (Specified Trajectory Movement) a trail left by another person in order to follow them. [Bow+14e]

**Audio Cues**

Audio cues are helpful to judge distance and direction. It can be used in the form of word, earcons or spearcons (see Chapter 5 System Design). Audio cues are used in navigation systems to support wayfinding without being dependent on a map. As a result, car drivers can focus their attention on the streets instead of the map. [Bow+14e]

# 3 Setup

This chapter introduces the different hard- and software that are used in this thesis and explains the reasoning behind this setup.

## 3.1 Hardware

### 3.1.1 ZED Mini

The camera that is used in this thesis is the ZED Mini, developed by Stereolabs. It provides real-time depth and motion sensing aswell as environment mapping. The two sensors that can be seen on the ZED Mini in Figure 3.1, mimic the human eyes. Together the two 720p RGB sensors span a FOV of 110 degree. [Laba]


Figure 3.1: ZED Mini. Adapted from https://www.vrnerds.de/zed-mini-verwandelt-rift-und-vive-in-hochwertige-ar-brillen/ (Mar. 2020)

The decision for taking this camera, is mainly based on its spatial mapping function. It provides the functionality of reproducing the environment in the Unity Game Engine as one connected mesh. Thanks to this function, 3D calculations can be made in real time.

### 3.1.2 LEAP Motion

The hardware that is being used to interact with the system is the LEAP Motion, which is developed by Leap Motion, Inc.. It is a small USB device that uses two infra red (IR) cameras and three IR LED's to scan a space of approximately 1m in front of it. The data is then utilized to track hand and finger motions. [Wei+13]

Figure 3.2: LEAP Motion Adapted from https://www.robotshop.com/de/de/leap-motion-controller.html (Mar. 2020)

Usually the LEAP Motion, seen in Figure 3.2, is placed upright on a table under a person's hands to track their movements. In this thesis however, the hands are tracked from top down, due to the LEAP Motion being mounted on a Oculus Rift together with the ZED Mini as seen in Figure 3.3.

## 3.2 Software

### 3.2.1 Unity

Unity is a game engine that has been developed by *Unity Technologies*. It can not only be used to create games, but also to develop Augmented Reality, Virtual Reality, 2D aswell as 3D applications. Due to its versatility and user friendly interface, it is the engine of choice. Applications build with Unity can be ported on different platforms such as computer or PlayStation. In this thesis however, most of the tests are done within the editor.

The game engine itself is written in C++, while the scripting API that is being offered is C Sharp (C#). C# is a general purpose, functional object oriented programming language. The engine offers physics calculations aswell as visualization components, that make the User Interface clean and user friendly. Furthermore there are already a API's that can be used to integrate the ZED Mini and the LEAP Motion into the game engine.

Figure 3.3: ZED Mini and LEAP Motion mounted on a Oculus Rift Source: Mehmet Dereli

# 4 Related Work

This chapter describes Augmented Reality, its current state-of-the-art and its connection with the presented system. Furthermore, several approaches of wayfinding support without the sense of sight are portrayed.

## 4.1 Augmented Reality

When the term *Augemented Reality* (AR) comes to mind, a lot of people already have a vague idea of what it is. The reason behind this is that, a lot of applications, such as Snapchat or Pokémon Go, are based on AR. While these applications have in common that they make use of AR, they differ in the way of incorporating different AR aspects. Snapchat, for example, tracks faces and makes it possible to change the physical appearance, by using filters on an individual's face. On the other hand, Pokémon Go uses the location of the player and overlays the current environment, shown on the mobile phone, with a Pokémon that the player can then catch or interact with.

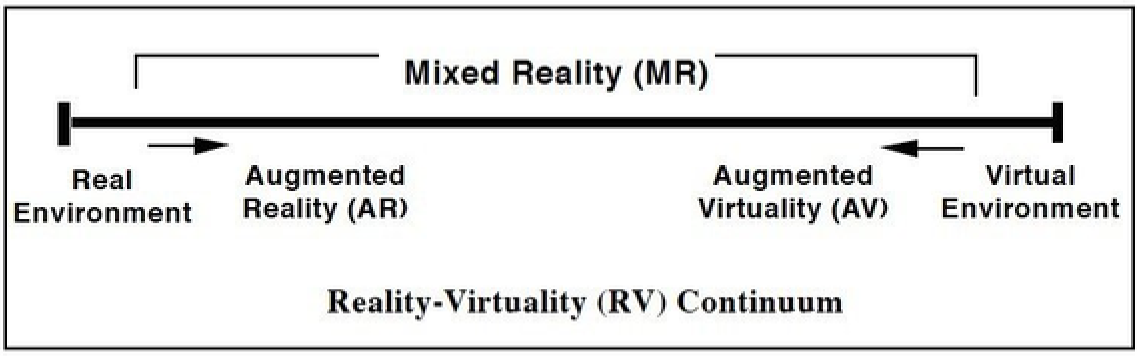


Figure 4.1: Reality-Virtuality-Continuum, Adapted from [Mil+95]

Milgram et al. [Mil+95] describe AR as the "augmentation" of the real-world-environment with virtual objects. Furthermore, it has been placed right next to "Real Environment" in the Reality-Virtuality(RV) Continuum seen in Figure 4.1, as it is closer to the real

environment then to the virtual one. [Mil+95]
In order to utilize of AR, several different SDKs exist. Due to the use of the ZED Mini, the corresponding SDK "ZED SDK" is used to map the real environment and augment it.

## 4.2 SWAN: System for wearable audio navigation

THE SWAN is a system, that intends to accomplish the same goal as the system introduced in this thesis. SWAN stands for *System for wearable audio navigation* and has been developed by Jeff Wilson et al. [Wil+07]. The hardware used is custom made and can be seen in Figure 4.2.

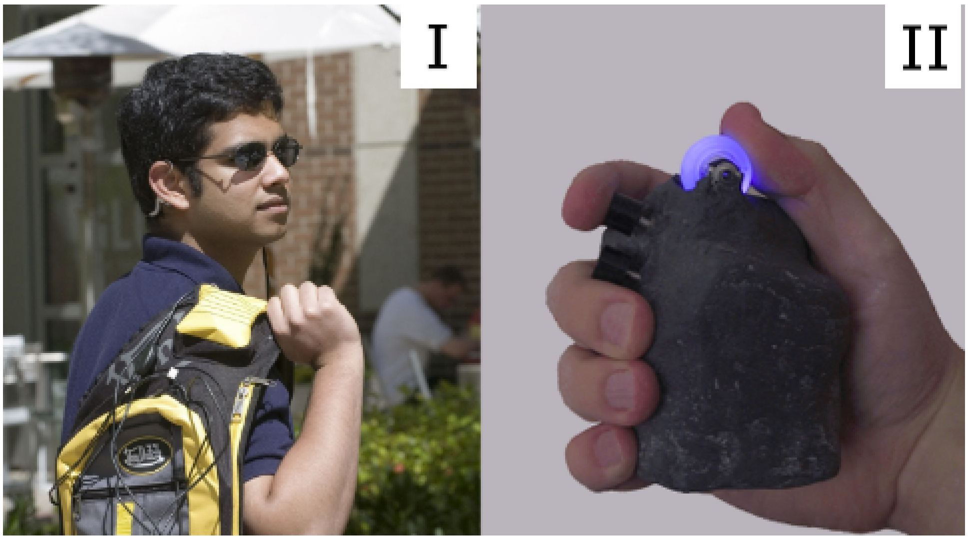


Figure 4.2: (I.) A SWAN developer is shown testing the SWAN system. (II.) Manual controller for the audio menu interface is shown in use. Adapted from [Wil+07]

The system is based on a combination of a GPS sensor and a digital compass, to estimate position and direction. It uses speech and non speech sounds to signal directions. The most significant feature is its path following function. A path is represented by nodes which emit different sounds. After passing one path segment by reaching the corresponding node, the node of the next path segment emits its sound and thus guides the user to the respective goal. Furthermore, the system signals relevant objects that are in the user's vicinity, such as benches or bus stops. It also recognizes points of

interest, detects objects and even detects surface transitions, such as the change from the sidewalk to a descending stairway.
The drawback of this system is characterized by the path planning part. The nodes used for the path representation, must be dropped by the user himself during the build up process of the cognitive map. The nodes can then be used as the start or end of ones path.

## 4.3 Object Detection Featuring 3D Audio Localization for Microsoft HoloLens

As the previous system is more focused on path following, the system introduced by Eckert et al. [E+18] focuses on object detection. The system of Eckert et al. [E+18] uses the *Microsoft Hololens*, due to its compact incorporation of the necessary hardware. It is able to capture images, to use its microphone, to play 3D audio and to detect basic hand gestures.
The corresponding architecture is a client server architecture. For detecting objects, a RGB image is taken by the Hololens and send to the server. Next the server uses a pre-trained model of YOLOv2, as part of its deep learning approach, and detects objects in the form of (x | y) coordinates. These coordinates are then conveyed to the Hololens, which calculates the 3D coordinates accordingly with the help of the virtual 3D Model it creates via spatial mapping. Lastly, detected objects are signaled to the user as 3D sounds. The system can be interacted with via voice commands or the hand gestures that the Hololens provides.

## 4.4 RFID Based Indoor Navigation with Obstacle Detection Based on A* Algorithm for the Visually Impaired

As the previous systems are focusing on either path following or object detection, the system introduced by Sanchez et al. [SYC15], incorporates both features.
Sanchez et al. [SYC15] use passive radio-frequency identification (RFID) tags, to mark a path for the user. Similar to the nodes in SWAN, the user is guided towards these tags via speech based instructions, such as "walk forward" or "turn left". The hardware that is used by the user is a white cane, which has a RFID reader, a micro controller for RFID validation, an ultrasonic obstacle detection sensor, ZigBee modules to communicated with a laptop, and a mp3 decoder.

First, the user chooses a destination tag with a laptop, which is responsible for the calculation of the path via A* algorithm. Then, the user is guided from tag to tag, which have to be scanned by the cane, until he reaches his destination tag. Whenever the user leaves the calculated path, a new alternative path is calculated for the user to ensure the shortest possible path. The calculation of an alternative path is also being done whenever an obstacle is found by the ultrasonic obstacle detector. These obstacles are incorporated into the system, thus updating the cognitive map of the system, by blocking paths between tags.

In comparison to SWAN , the paths that can be generated and followed are rather short because of the necessary environmental preparations. The idea of dropping nodes instead of mounting physical tags on the floor is faster and thus reduces the time needed to build up the cognitive map of the system.

# 5 System Design

Since all relevant aspect are covered, the system presented in this thesis is introduced in the following. As it is wanted to cover more than just a single area of wayfinding, the system offers several different modes that make up the system. Overall, it can be divided into the two types of wayfinding support that are described in chapter two, user-centered and environment-centered wayfinding support.

## 5.1 User Centered Wayfinding Support

The absence of the sense of sight causes a hole in the wayfinding process. Usually the process consists of the eyes collecting visual information of the surroundings, which are then being processed by the brain. Because the human sensor that collects these visual information is absent in the context of this paper, the collection is done by the ZED Mini. To convey this information to the user, a fitting method of translating this visual information into acoustic information must be chosen. This translation process is done by the following two modes, which are presented in the following.

### 5.1.1 Scan Mode

The Scan Mode has been developed with the purpose of directly conveying the environment to the user. By conveying the user all of the points of interest (POI) around him through 3D sounds, the environment is painted. This basic idea is characterized by several issues. POI's are defined as 3D coordinates of points in the environment and are an upgraded version of camera pixels in terms of versatility.

The major issue, in the context of sensory substitution is that of information overload, as the human brain is only capable to process a limited amount of information and sound concurrently. An exemplary solution to this problem has been proposed by Peter Meijer in his system "The vOICe" [Mei92]. Here a picture is taken and the pixels are converted into corresponding sinus waves that are composed of pitches, which represent heights, and loudness, which represents brightness. The sinus waves of each pixel in a column are merged together, which serves the purpose of conserving as much information as possible. This information is delivered to the user by sound waves.

Unlike the previous approach, the system within this thesis does not attempt to preserve all information regardless of their importance. The environment is scanned in an 210 degree angle. This angle is broader than the FOV that a human's FOV and therefore it can collect more information about the surrounding than human eyes. First of all, the POI's are divided into horizontal sections. In each of those sections the POI with the highest interest is filtered out. To avoid the overlapping of sounds, they are played one after another. This prevents information overload and the challenge of distinguishing each sound. Because as accurate as the human ear may be, there are still limits to it and to the capabilities that a headset has.

### 5.1.2 Pointer Mode

This mode has been developed to complete the Scan Mode. Unlike the scan mode, which solely signals the user a set amount of points within his surroundings, depending on the user position, the pointer mode allows for more freedom.
Instead of filtering all available POI's, the user can choose and move the POI's by himself. By using his index finger as a pointer, the POI that emits a sound is moved. This enables a more accurate representation of the environment due to the finer distinction.

When comparing the two modes, they both lack certain aspects individually. The scan mode makes for a rather easy scan of the environment but has a low level of accuracy, while the pointer mode has high accuracy, but takes longer to gather the necessary information. However, when both modes are used in combination, they supplement each other by making up for the downsides.

## 5.2 Environment Centered Wayfinding Support

The second part of the system is made up of environment centered wayfinding support. The system creates artificial wayfinding cues in the form of audio cues to signal a path.

### 5.2.1 Path Following

Artificial cues are used in both real and virtual environment. In real environments however, there are certain limitations that restrict its utilization, in comparison to virtual environments. However, in this mode those limitations are lifted.
This mode makes use of existing path following approaches in video games and additionally transforms them into audio cues. Path following has been used in video games in a variety of manners. Examples are the following of Non-Player-Characters

(NPC), which lead the way from a point A to another point B, or in the form of trails, which then must be followed by the player. Nevertheless, the cues used in both examples are visual. So, the problem of how to turn them into acoustic cues results.
The approach that the presented system takes, is the placement of 3D audio cues at nodes that are spread along a path. The closest node to the user emits a sound. Whenever he closes the distance to the current closest node, the sound moves to the next node, and thus leads the way along the path.

## 5.3 User Interface

There are different proposals on how to interact with a non-visual system. One approach is integrating controllers for user input, which is used by the SWAN system [Wil+07]. Another one is to use speech based input through microphones.
Whilst the former User Interface (UI) requires the user to carry around a controller at all times and thus hinders the use of at least one hand for other activities, the later one can be uncomfortable in public spaces. Furthermore it might cause speech recognition problems.
The approach within this thesis makes use of the LEAP Motion to track and recognize hand gestures. Due to the low number of modes that are in the presented system, the amount of gesture possibilities are enough to cover all modes. There are four movement patterns included within the available API. Those are, circling a finger, swiping with the hand, key tapping and screen tapping. A number of more gestures can be added, as a result of the devices recognition of extended and non-extended fingers.

## 5.4 Sounds

The use of sound plays a major role within the context of this thesis. While there are several distinctions that can be made in regards to sound, like the harmony of sounds or their pitch, the use of sounds in this thesis focuses more on their feasibility in the context of 3D localization.
The biggest distinction that has to be made when it comes to sounds, is that of words against sounds. Several systems exist that use words to convey the user its destination, when it comes to path following and menu navigation. However, this thesis is going to use earcons [BSG89] for the modes themselves.
Earcons are a wide spread technique used to signal specific events with short and distinctive sounds. An example is the beep tone that is made whenever a error occurs on a computer operating system. The distinguished sounds that each mode produces, is thereby used to signal 3D positions and the mode itself to the user as an aspect of

feedback.
In order to grasp the stand alone feasibility of loudness to signal distance, no other acoustic cues, such as frequency, are provided. When multiple indicators of distance are added onto the same sound, the complexity increases, which is what this system wants to avoid. Furthermore, the sounds are supposed to supplement the environmental sounds and not overwhelm them. This might happen, if the sound frequency increases and distracts the user's attention.

# 6 Implementation

In this chapter we are going to look at the implementation of the system.

## 6.1 Spatial Mapping

The foundation of every mode within the system presented, is the *Spatial Mapping* function, that is provided by the ZED Mini Unity SDK [Labb]. Anyhow, there are no information on how this function has been accomplished by Stereo Labs. Therefore, no insights about the implementation can be provided. The spatial mapping is used to create a 3D mesh of the given environment and to update it at runtime, in accordance to the information that is gathered from the current FOV of the ZED Mini.
The depth and accuracy of the environmental model can be adjusted according to the available computing power. An exemplary mesh can be seen in Figure 6.1.

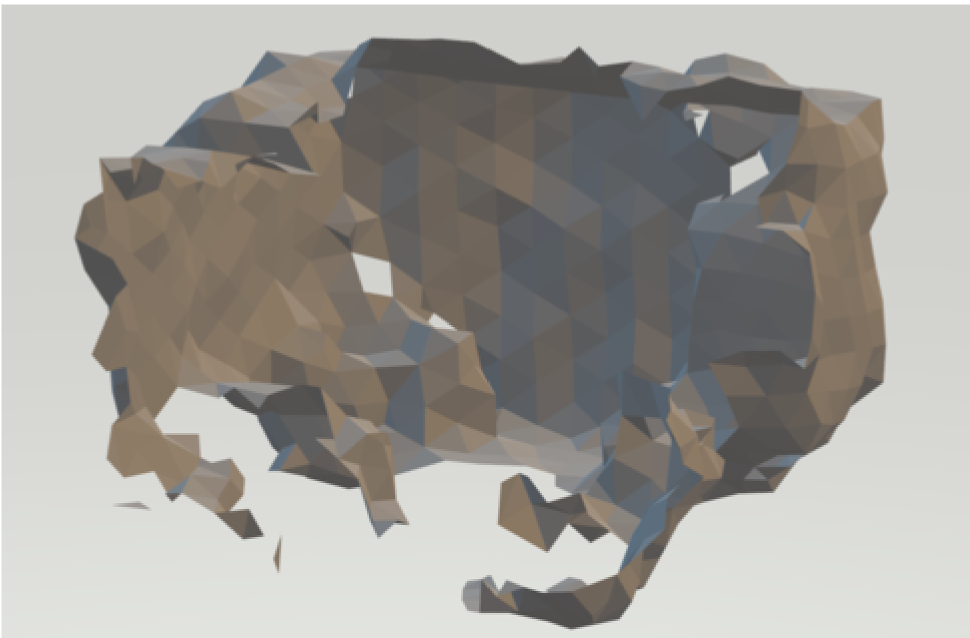

Figure 6.1: ZED Mini Spatial Mapping Mesh Source: Mehmet Dereli

## 6.2 Scan Mode

The scan mode has a rather different implementation than the other systems, introduced in chapter four, in terms of scanning the environment. Here, the generated mesh and the physics raycast that is provided by unity are made use of instead of a depth picture. As seen in the following code, a width x height grid of raycasts with an additional angle is spanned. After each raycast is shot, the 3D coordinates are saved within the corresponding list.

**Algorithm 1:** Scan Mode

```
Result: List of Map Reduced Raycast Hits
for i = 0; i < width; i+ = gap do
    for j = 0; i < height; i+ = gap do
        HitList.add(ShootRay(i,j,angle));
    end
    angle += rotation;
end
MapReduce();
```

After all raycasts have been shot and the hits are added into the HitList the function MapReduce(), selects the one POI with the highest interest for each section.
Afterwards, there is only a single hit left in each section of the scan. Then, the sounds are then played one after another at the 3D position of each of the map reduced hits.

**Algorithm 2:** MapReduce()

```
Result: List of Map Reduced Raycast Hits
List<Hit> closestHits;
Hit sectionClosestHit;
foreach Hit h_i ∈ HitList do
    if h_i.distance < closestHit.distance then
        sectionClosestHit = h_i;
    else if closestHit == null then
        sectionClosestHit = h_i;
    if Section ends then
        closestHits.add(sectionClosestHit);
        sectionClosestHit = null;
    end
end
```

## 6.3 Pointer Mode

In difference to the Scan Mode, the pointer mode does not filter any sounds, but enables the user to move a single sounds to their own liking by pointing in the wanted direction. Which is achieved by shooting a raycast from the tip of the index finger.
As seen in Figure 6.2, the hand model possesses individual fingers, a middle hand and forearm bones to allow humanoid movement.

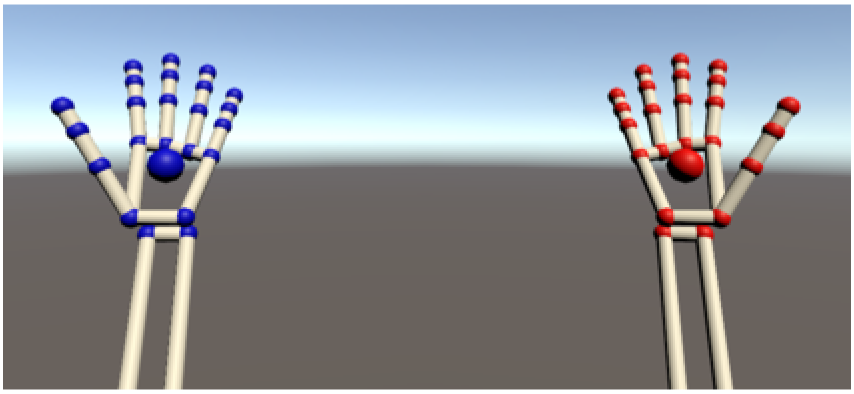

Figure 6.2: LEAP Motion Hands Source: Mehmet Dereli

## 6.4 Path Follow

Lastly, there is the path following mode. This mode is the single environment centered wayfinding support mode in the system. In order to find a path through the mesh, a custom wayfinding system is implemented.
First of all, the environment is divided in a grid of cubes, with each cube representing a node. The path from an user to a specific goal is defined by a sequence of adjacent nodes. Every time the user moves from one node into another, the A* (or Dijkstra) wayfinding algorithm calculates the next node in accordance to the new position. The continuous update of the path ensures that even if the user deviates from the calculated path, he is always guided along the shortest path possible.
The guidance of the user along the path is achieved by placing a 3D sound within the next node, so that whenever the user walks into another node and the new path is calculated, the sound moves along with the user.

# 7 Pre-Study

The following section deals with the conducted pre-study and is split into three parts. The first part entails the preparations made for the study. The next one describes the tests aswell as their execution, while the last part contains the evaluated results.

## 7.1 Preparation

In order to ensure a safe execution of the study, the room in which the study was conducted was cleaned out and a space of approximately 4 square meters was prepared. The system was connected to the computer and the application was prepared for the study. Due to the setup, in which the system was connected to a non-portable computer via cables, the test space was right in front of the computer.
For the participants of the study, an information sheet with all the necessary aspects of the study was written. It included the purpose of the study, its risks, the usage of the collected data and aspects of data protection. Furthermore, a standardized consent form from the Research group of AR was prepared.
Lastly, the questionnaire for the pre-study was written. It includes several demographic questions ,to group people together and categorize their potential affinity towards the system, and questions about the tests conducted, which are further elaborated on in the following.

## 7.2 Execution

Before the tests are conducted, the different documents mentioned in the previous section are read out loud, to ensure the participant is aware of the necessary information. After the letter of consent is signed, the tests are conducted. The pre-study consists of three different tests in total.

The first test is about locating 3D sounds. The metric used for the localization consists of a direction and a distance. The direction is split into left, front-left, front, front-right and right, while the distance is categorized into close, middle and far.
There is a total amount of seven sounds, which are played indefinitely until an answer

is given. After the user gives his answer about distance and location, the next sound is being played from a different location. It is allowed for the user to turn his head, in order to locate the direction of the sounds. The answers are written down by the instructor as they are given.

The second test is about orienting oneself in an unknown environment and trying to analyze it in regards to its structure. In order to do so, the scan and the pointer mode are provided to the participant.
The user is positioned in the middle of the room and three pillars are placed around him in the virtual environment. The challenge is to locate the position of all those objects. In the first half of the test the user is only allowed to use the scan mode, while in the later half he can use the pointer mode aswell.
After the user confirms the location of the objects, he is asked to mark their position. For this purpose, a target with 2 rings and 8 uniform sections, is provided within the questionnaire.

The last test checks the feasibility of path following through sounds. The user is given the task to follow a path based on the 3D sound that is being played from the next node within the path. Because of the cables connecting the system with the computer, the path is limited to a length of approximately 4 meters. The difficulty of following the path is defined by the corner that the participant has to walk around without bumping into it.

After each test is conducted, the participant is asked to fill out the corresponding questions.

## 7.3 Results

### 7.3.1 Study population

The pre study was conducted with a number of five participants, who are all studying Informatics: Games Engineering at the Technical University of Munich. Four of the participants were male and the fifth one was female. The group was on average 22 years old and had little to no experience with audio systems. Furthermore, four participants were either wide or short-sighted. All them managed to conclude the study without any sort of complications.

### 7.3.2 Test 1

The results of the first test can be seen in Table 7.1. Each row represents one sound that was played, the direction from which they were played, their distance, aswell as the correctness of each users answer.
There are several things that can be confirmed when looking at the results, such as the accuracy of different directions. While the diagonal directions were the ones that the majority got wrong, their accuracy nonetheless improved over time, as the participants got more used to the sounds. This indicates that a finer distinction can be achieved with training. This can be seen when the direction results for the sounds two and four are compared to sound six. The three general directions front, right and left were all guessed accurately form the start, without the need for a learning period. This indicates that even without any training at all, a certain level of directional distinction is given by the participants.
A similar learning curve can be found in regard to the distance. While only three of the first 15 distances were guessed correctly, they provided references for later sounds. 11 out of the last 15 directions were guessed correctly, meaning the accuracy improved.

| Participant | | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| Sound 1 | Direction | Front | √ | √ | √ | √ | √ |
| | Distance | Far | X | √ | X | X | X |
| Sound 2 | Direction | Front-Right | X | X | X | √ | X |
| | Distance | Middle | √ | √ | X | X | X |
| Sound 3 | Direction | Front | √ | √ | √ | √ | √ |
| | Distance | Middle | X | X | X | X | X |
| Sound 4 | Direction | Front-Left | X | X | X | √ | √ |
| | Distance | Far | X | √ | √ | X | √ |
| Sound 5 | Direction | Right | √ | √ | √ | √ | √ |
| | Distance | Far | √ | X | X | X | X |
| Sound 6 | Direction | Front-Right | √ | √ | √ | √ | √ |
| | Distance | Far | √ | √ | √ | √ | √ |
| Sound 7 | Direction | Front | √ | √ | X | √ | X |
| | Distance | Close | √ | √ | √ | √ | √ |

Table 7.1: Test 1 Results

Additionally to the first test, the participants were asked how confident they were in their answers. Four out of the five participants stated that they are confident in regard to directions. However, in terms of distances they questioned themselves. This indicates that even though the accuracy of both direction and distance rise over time, loudness does not seem to be an effective stand alone indicator when it comes to judging distances.

### 7.3.3 Test 2

Table 7.2 represents the results of the second test. The table consists of the three objects that were placed in the virtual environment and the rightness of the answers given.
With an accuracy of 10 out of 15, it can be said that the directions are rather consistent overall. On the other hand, distances had a accuracy of 6 out of 15, which is bad. Just like in the previous test these results indicate that using loudness as a stand alone indicator for distance is not fairing well.

| | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Object 1 | Direction | X | √ | √ | √ | √ |
| | Distance | X | X | √ | X | √ |
| Object 2 | Direction | √ | √ | √ | X | √ |
| | Distance | X | X | X | √ | √ |
| Object 3 | Direction | √ | X | √ | X | X |
| | Distance | X | X | √ | √ | X |

Table 7.2: Test 2 Results

The feedback that was given by the participants favored the pointer mode more then the scan mode. The participants remarked that they were not feeling confident in the sounds provided by the scan, because of the lack of feedback. On the contrary they stated that the pointer mode and its input felt very intuitive. The immediate feedback, aswell as the intuitive estimation of the direction, made them feel confident in the sound. One user further remarked the accuracy of which the objects can be identified with the pointer mode.
When asked if they would have preferred voice input over the Leap Motion, the majority was siding with the hand gesture input. Two participants would have preferred voice input when it comes to the scan mode.

### 7.3.4 Test 3

The last test was about following a given path. All five participants were able to complete the path without any complications. The time it took to complete the test differed for every participant, but was on average 30 seconds. Four of the participant remarked that they felt more confident in gauging distances, because the sound volume changed with their movements. It has to be noted that every participant turned their heads around in order to better identify the sound direction. This behaviour was observed throughout all the tests with every participant.

# 8 Conclusion

The purpose of this empirical research is to determine the feasibility of using sound to support for the wayfinding process. While the hardware and the design of the system have deficits, the pre-study and its evaluation are still a valid indicator in regards to the research question.

The setup used for the system turned out to have its flaws. Mounting the Leap Motion on an "Head Mount Device"(HMD) and tracking hands from upside down with an additional angle, made the hand tracking challenging. While a simple gesture, such as a hand with spread finger for the scan mode, was easily detectable, the accurate tracking and orienting of fingers was harder. Although the horizontal directions are accurate, the vertical rotation is inaccurate overall. The users nonetheless remarked the intuitive UI, which was particularly the case for the pointer mode.
The spatial mapping function of the ZED Mini, which is used as the foundation of the system, had infrequent challenges with accurately mapping the environment, as it detected objects in empty spaces. The overall results however, were still satisfying the required accuracy.

The results of the pre-study strongly hint that sounds can indeed be used to signal distance and direction. While the study population already had an strong intuitive grasp of the directions of the provided sound cues, distances were challenging, when using the sound volume as a sole indicator for distance. The sound volume did not produce the wanted results, as users did not feel very confident in their ability to gauge distances. The question as to whether or not an additional change of sound frequency and pitch provide the necessary cues can not be answered within this thesis.

As to whether or not the research question can be verified, it can be said that the results in this thesis strongly indicate that sound can indeed be used for wayfinding support.

The results produced within the pre-study are not definitive. They are indicators to get a first idea of the feasibility of sound in regards to wayfinding support. In order to get more conclusive results, an in depth user study has to be conducted.

# 9 Outlook

While the system in this thesis fulfills the requirements needed to answer the research question, it is still very basic in its design. There are several ways to further improve upon the system and increase the support that it offers.

One way to improve the system is to change the sounds used. As stated in the conclusion, the user feels insecure when gauging distances, which might be improvable when sound frequency and pitch are added. Furthermore, we only used sounds in the form of earcons within our system. The article "Spearcons (Speech-Based Earcons) Improve Navigation Performance in Advanced Auditory Menus" [WNL06] proposes the usage of speech-based earcons (spearcons) to improve upon the auditory menu. This might provide the necessary feedback that was remarked during the pre-study.

Another way to improve the wayfinding support is to include text detection into the system [JKJ04]. As stated in the wayfinding chapter, signs are used in order to support wayfinding. The information that signs provide are usually in writing, which is why text detection and the conversion of the written into sounds is needed. Because signs are a widely spread way to navigate, their inclusion into the system would immensely increase the wayfinding support offered.

Another way to improve upon the wayfinding support is to add color detection. The ZED Mini provides a texturing function together with the spatial mapping. By filtering out the color when using the pointer mode for example, additional information can be provided.

Because the system is designed to add supportive sound to the already existing environmental sound, a function to adjust and cancel environmental sound could improve the system. This could be archived by adding microphones to the setup which pick up the environmental sounds from each direction and display them to the user via the headphones.

# List of Figures

# List of Tables

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