Sound Reflections

in an audio-based game for visually impaired children

M.C. Bisschop
J.C. Noortman

Delft University of Technology

TU Delft Delft University of Technology

SOUND REFLECTIONS

IN AN AUDIO-BASED GAME FOR VISUALLY IMPAIRED CHILDREN

by

M.C. Bisschop
J.C. Noortman

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Names (Student nr.):	M.C. Bisschop (4171101) J.C. Noortman (4150856)
Supervisors:	dr. ir. R.C. Hendriks S. Khademi, MSc
Thesis committee:	dr. ir. I. E. Lager dr. ir. R. C. Hendriks dr. ir. M. Popov

ABSTRACT

In this thesis a model for sound reflections designed which is to be used in an audio-based game for visually impaired people is described. This project is a part of a three-group bachelor graduation project of six people in total. The other four people create the gameplay and the localization for the audio game [1], [2]. The three groups combined create a working game for visually impaired children, meant to be used to train the user's ears and brain to visualize their surroundings using sound only.

Using the mirror source method, a model for sound reflections in concave 3D rooms is obtained. Important part of this model are the placement of the mirror sources, the calculation of a line of sight and a model for the energy absorption of a wall when sound is reflected off of it. The placement of mirror sources and a model for the wall absorption were successfully implemented. The calculation of a line of sight is only half finished.

The implementation of the model in the game adds a sense of the location and the materials of the walls. The execution time of the model is however too low to run the model completely in real time.

PREFACE

We have submitted this thesis in partial fulfilment of the requirements for the Bachelor Graduation Project of Electrical Engineering at TU Delft. For the Bachelor Graduation Project (*Bachelor Afstudeer Project, BAP*) with a group of six students was worked on a audio based game for visually impaired children. There was worked in three subgroups. This thesis is about the sound reflections of the audio based game. One group was responsible for the gameplay and game integration. The last group worked on sound localization.

It was nice to work two months on one project. We completely got into our subject and worked much to obtain our goal: a working game. We experienced everywhere around us sound reflections while we didn't recognize it before this project. We made the subject of sound reflections ourselves.

In the last few years we learned much in our bachelor Electrical Engineering at the Delft University of Technology. In this project much of what we learned we applied. Mostly signal transformations, linear algebra and project skills did we use.

We would like to thank our supervisors R.C. Hendriks and S. Khademi for their support and assistance. We would also like to thank the other teammembers: T. Coppoolse, W. van Dam, R. Duba and B.W. Kootte. It was nice to work together on such a great project!

M.C. Bisschop
J.C. Noortman
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1

INTRODUCTION

We like singing in the bathroom. Our songs sounds good in there. Our voice has a full sound. It feels like we are a real popstar. We didn't know we could sing that good.
We don't like singing outdoors. Our voice sounds fragile, unstable. We hardly hear ourselves singing.

Sound reflections are all around us. Without thinking about it, our brain processes them unconsciously. From these reflections some properties of our surroundings can be observed. For example, the reflections within an old church sound completely different from those of our bathroom or the outdoors. When a room is completely dark we can visualize it using these reflections.

Imagine, you are visually impaired (or blind). You can not see the room you are in. Finding your way is difficult. You can, however, train your ears and brain to recognize sound reflections, thus obtaining an idea of your surroundings. [3, p. 6–27]

This project is a part of a three-group bachelor graduation project of six people in total. Within this project an audio based game for visually impaired children was created, which can eventually be used to train the user's ears and brain to visualize their surroundings using sound only. These are the three groups:

- Gameplay: creates the user interface and basic game mechanics, see [1]
- Localization: transforms sound in such a way that the distance to and direction of the source of the virtual sound source can be heard, see [2]
- Reflections: models the reflections of different sounds and rooms

This report describes how sound reflections for variable rooms can be modelled. The problem and the requirements for its solution can be found in Chapter 2. Related research is given in Chapter 3, followed by a chapter on the design, Chapter 4. In Chapter 5 the results of the design are presented. The discussion and conclusion of the whole project can be found in Chapter 6 and Chapter 7, respectively. The ethics behind this project are an aspect of this project. The considerations on this are described in Appendix A.

2

PROBLEM DEFINITION

Here, a definition of the problem will be given. The design for the whole game and the part of reflections in it will be explained. Furthermore, the different parts of the reflection model will be given and a list of requirements will be set.

2.1. PROJECT

Figure 2.1 shows the block diagram of the audio part of the whole project: an audio based game for visually impaired children. It can be used as the basics of an audio training game. The game looks a bit like snake. Playing the game, the player has to find the 'food', located somewhere within a room. The player controls movements and receives feedback via a headphone. The software in between the player input and the headphones (see blockdiagram) has to be designed and implemented. Furthermore, some visual feedback is needed for people who are not visually impaired.

The heading and the movement of the playable character are obtained from the input of the player. The block Basics calculates the positions of the playable character, the sound sources and of the walls. The Sound database provides sound for the different sound sources. The Reflections block calculates the positions of the reflection sources and damps the sound due to wall absorption. The Localization block is responsible for modelling sound in such a way that it appears to be located at a specific location. The + block adds the different sound files, given by Localization.

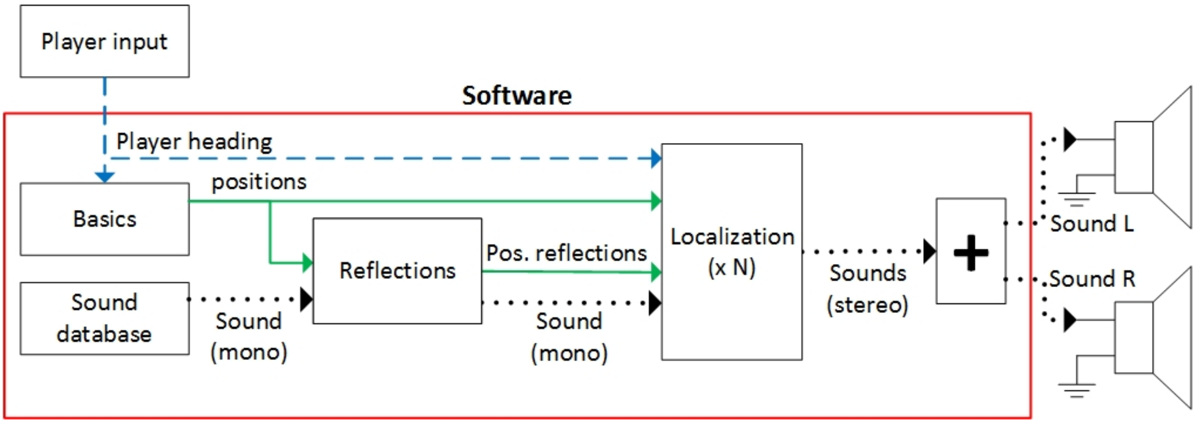


Figure 2.1: Block diagram of the audio based game. The visual feedback is not included in this block diagram.
Black dotted lines: sound (mono/stereo)
Green solid lines: positions of player, sound sources and of the walls
Blue dashed lines: playable character heading/movement

2.1.1. SUBGROUPS

There are three subgroups in this project, all with their own goals and responsibilities:

- *Gameplay*: defines the basics of the game. They create the working game with the integration of the Localization and Reflections blocks. They choose the sounds which will be used, create a visual 2D representation of the game, and implement controls and the user interface. This group implements the blocks Player input, Basics, Sound database and the + block [1].
- *Localization*: is responsible for sound localization and correct spatial audio play by headphones. They implement the localization block and the audio adding block [2].
- *Reflections*: creates the block Reflections. This thesis is about the implementation of this block. We create a model which gives localization a travelled distance and an angle at which it travels towards the receiver for every significant reflection. This will create a realistic sound simulation of a room and will be useful when training spatial cognition.

2.1.2. Boundary systems

The boundary systems are systems with an interface to Reflections. The Reflections block needs to be able to communicate with these systems. The boundary systems are:

- Basics
- Sound database
- Localization

Communication between the gameplay, localization and reflections groups is necessary to make sure these systems work together.

2.1.3. Reflections

Sound traveling through air travels from the source outwards in a radial direction. If this sound encounters a different medium, such as a wall, a car or even a person, most of the sound will be reflected. The rest of the sound will be absorbed by the wall. To accurately model sound, these reflected sound waves need to be modelled too. This will be done by the Reflections block. This block is split up in a couple of smaller blocks. Reflections can be modelled by the mirror source method [4, p. 30-31], where reflections are modelled by virtual sources, or mirror sources. One block calculates the positions for these sources. A second block is called line of sight. This block calculates whether audio from a source can reach the playable character and whether the audio can reach a wall. Another block calculates the sound absorption of the walls and the final block calculates whether an object collides with a wall. The collision block shares a lot of its calculations with the mirror source generating block, therefore it is part of Reflections, instead of of Basics.

2.2. Requirements

[noitemsep,nolistsep]

Here follows a list of requirements. To create a successful model of reflections which can be used in a game for visually impaired people, these need to satisfied.

Requirements

Req. 1 *The model should be able to calculate reflections for every shape of room*
Req. 2 *Reflections have to create an impression of the size of a room*
Req. 3 *Reflections have to create an impression of the shape of a room*
Req. 4 *Reflections have to create an impression of the materials of the walls of a room*
Req. 5 *The Reflections block has to be compatible with the rest of the game*
Req. 6 *Realistic reflections have to be calculated in less than* 10 ms *on an average computer with a Intel core i7 CPU at 2.00GHz.*
Req. 7 *For the calculation of reflections only* 100 MB *of the RAM (memory) is allowed to be used*
Req. 8 *The system has to be developed in 10 weeks, starting from 20 April 2015*
Req. 9 *Development software available without additional costs has to be used*

Requirement 1 makes sure the model is useful for many different rooms, which adds variety to the game. Requirements 2 to 4 are about the value added by reflections in the game. The reflections block is part of a bigger project, so to make it integratable there is requirement 5. The computer we can use in this project is a limiting factor, its limits described in requirements 6 and 7. Requirements 8 and 9 are about the limitations of the bachelor graduation project.

3

RELATED RESEARCH

This chapter is about the research done prior to creating a model for reflections. First a short explanation of sound will be given, followed by a section on how humans perceive sound, known as psychoacoustics. After this the effect of reflections when localizing a sound source will be explained. After this comes an extensive section on how to model reflections. Finally, the sound intensity and wall absorption are explained.

3.1. SOUND

Sound is a vibration that propagates as a typically audible mechanical wave of pressure and displacement, through a medium such as air or water. Any sound wave can be modelled by a superposition of simple plane waves. The wave equation for sound in free space in three dimensions is described by Equation (3.1) [5, p. 8].

$$c^2\nabla^2 p = \frac{\partial^2 p}{\partial t^2} \tag{3.1}$$

Here, p is the sound pressure, c the speed of sound and t is time [5, p. 8].

Sound traveling through air travels from the source outwards in a radial direction. If this sound encounters a different medium, such as a wall, a car or even a person, most of the sound will be reflected. The rest of the sound will be absorbed by the object. Depending on the material and shape of the object, much of the sound is reflected back to the receiver by these objects, making reflections a significant part of the sound heard by the receiver. In addition, sound heard in corners or near walls can sound louder than the same sound heard from the middle of the room [6, p. 44].

3.2. PSYCHOACOUSTICS

The interaural time difference (ITD) is an important cue in localising sounds. In Figure 3.1 it is shown that there is a difference in path length from the source to the left and right ear and thus a difference in the arrival time. There is a distance of around 18 cm between the human ears. Due to this, an arrival time difference occurs when the sound source is not straight in front or behind the person. The brain can interpret this and is able to localise the sound source [7], [8, p. 96-100].

The interaural level difference (ILD) is another important cue when localizing sound sources. Besides a time difference the human head causes a level (or intensity) difference as well [7] [8, p. 100-102].

The ITD and ILD are useful when determining whether a sound is to the left or to the right. The shape of the ear and the movements of the head are useful for determining where a sound source is located in the midsagittal plane, whether it is in front or behind and above or below you [7], [8, p. 102-104].

The precedence effect is described in [8, p. 104-105], [9, p. 73-93] and [10]. This effect is also called the Haas effect or the law of the first wave front. It is the phenomenon that the first arrived sound wave dominates our impression of where sound is coming from. This is normally the direct sound from the source. After first hearing a sound, for a short period of around 30 ms, that specific sound will be filtered out by the brain. This period is called the “fusion interval”. Therefore people are unaware of fast reflections. Spatial cognition is gained when the delay between direct sound and single reflected sound is at least 10 ms. About 20 ms is the delay for a room that would be classified as intimate. Reflections arriving after around 30 ms will be perceived

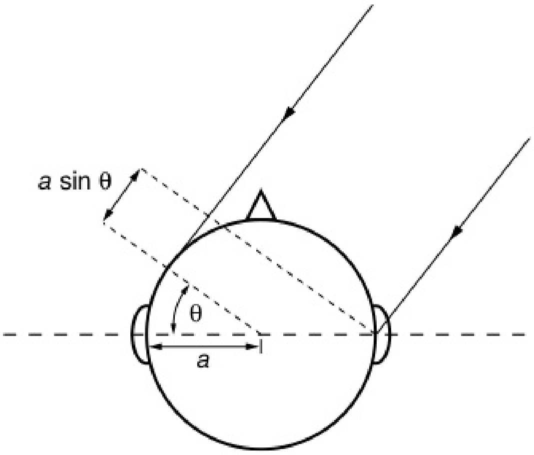


Figure 3.1: Difference in distance causing the Interaural time difference (ITD)
source: `http://neuromorphs.net/nm/wiki/sound_localization`; Visited 11-06-2015

as echoes. In Figure 3.2 these times are shown.

People like to listen in reflective spaces, not outdoors, is shown in studies. The perceived width of the sound sources together is the apparent source width (ASW). This is associated with the level of early lateral reflections. Early reflections are those that are heard within 80 ms of hearing the direct sound. The sense of being surrounded by a diffuse array of sound images is called the listener envelopment (LEV) and is associated with reflections arriving after about 80 ms. Spatial cognition is the recognition of a spatial environment by sound only. The level of spatial cognition is high when hearing reflections with a delay of more than 10 ms but does not increase with more delay [9, 95-111].

3.3. LOCALIZATION WITH AND WITHOUT REFLECTIONS

In an anechoic room sound sources are easy to locate. In a reflective room with early and late reflections this is different. The ratio between reflected sound and direct sound is important here. This ratio has to be more than a certain level. For the "out-of-head"-perception this ratio is similar. A lack of reflections is a reason for people to perceive sound inside their heads. An out-of-head perception is the perception that the sound is located in the space around the receiver. For modelling reflections both are important [11], [12].

Early reflections with the same azimuthal angle as the direct sound aid with localization. In reverberant rooms, which are large rooms with walls that reflect most of the incident sound [9, p. 45], the early lateral reflections make localization of sound more difficult [11].

Localization accuracy drops with an increase in reverberation, the persistence of sound after a sound is produced. Reverberation is caused by late and diffuse reflections. Reflections of sound are mostly disturbing for localization [7], [11].

In the human ear the interaural time difference (ITD) and interaural level difference (ILD) are important for the localization of sound. However, reflections might degrade localisation performance. Sound reflecting in walls, ceiling, and objects degrades the sound localization. The ITD depends on coherence between the signals in the two ears. Reverberated sound does not contain useful coherent information. The ILD is less degraded by reflections, because the level changes at both ears in the same way. Addapting audio per ear different is called binaural. If the signals are binaurally coherent (perfect aligned) doesn't matter for the binaural comparison of level. Only the intensity matters [7].

3.4. MODELING REFLECTIONS

In a rectangular room, solutions of the wave equation can be found by adding boundary conditions. If an impulse creates vibrations in a body, in this case the air in a room, this body will, after a relatively short transient behavior, keep vibrating at only its resonance frequencies. A set of eigenvalues can be obtained, describing the behaviour of the sound at these frequencies. These eigenvalues show that resonant frequencies create

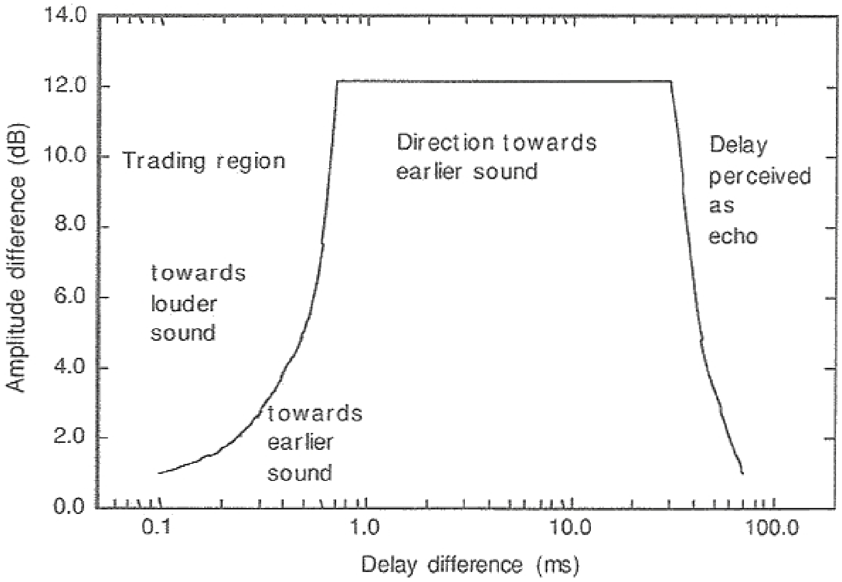


Figure 3.2: Delay versus intensity trading
source: `http://www.feilding.net/sfuad/musi3012-01/html/lectures/008_hearing_III.htm`; Visited 11-06-2015

standing wave patterns. The amplitude of a standing wave is dependent on position. At frequencies below about 150 Hz these become noticeable [9]. Low frequencies have long wavelengths. This results in large distances between the minimum and maximum amplitude of the standing wave. At high frequencies, resonance frequencies are more numerous and are additionally more closely packed. This makes them negligible [9, p. 199], [6, p. 44]. When considering only low frequencies, this set of eigenvalues is manageable. When trying to model the behaviour of sound with frequencies ranging from 20 to 20.000 Hz, the amount of calculations needed become incredibly numerous [6, p. 38]. There are however other ways to model the behaviour of sound than just with the wave equation. These methods model sound as a particle, instead of as a wave and are called geometrical models.

When a sound source reflects in a wall, the total sound can be modelled as a superposition of the original sound with that of its virtual mirror image. This is called the mirror source method. It is very accurate, but the 'visibility test,' whether or not a line of sight can be found from a source to its next point of reflection or to the receiver, takes up much computing time for many reflecting surfaces [4, p. 30-31], [13, p. 873-943], [14]. In [13, p. 873-943] an algorithm for the mirror source model is given.

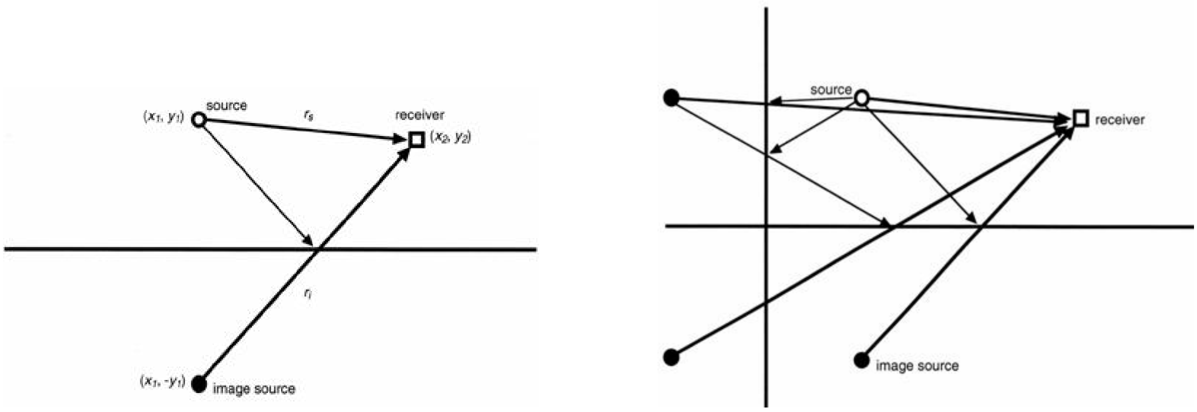
This superposition principle isn't always applicable. Sources could be out of phase with each other. In a superposition of these the sound will damp. In [13, p. 913-923] a second principle of superposition is given. Sources has to have a sign for their phase. This calculation could be implemented in the mirror source method.

When a sound wave reaches an object, the law of reflection states that the angle of incidence is equal to the angle of reflection to the normal on that object. [15, p. 513-516]

Figure 3.3 shows the principle on which the mirror source method is based. In Figure 3.3a a source is mirrored in the wall. When drawing a line between the mirrored source and the receiver, the line intersects with the wall at the exact point the sound from the original source would reflect to reach the receiver. The path length of the source and the mirror source to the receiver are the same as is the angle at which they reach the source. A situation with two walls and more reflections is depicted Figure 3.3b. Here, two first order and two second order reflections are drawn. The dot in the lower left corner is a double second order source here. Both the first order sources mirror to this position.

The ray tracing method releases many particles in a room and calculates a path for each particle. This is not very accurate. This method is however good at calculating the reflections from curved objects. The hybrid method first finds possible reflections with ray tracing, then uses mirror source modeling [16]. Both of these methods are pretty accurate for high frequency sound, where the length of the wall is large in comparison to the wavelength of the sound.

With a room impulse response, the acoustic properties of a room in terms of sound propagation and reflections for a specific setup of microphones and sources can be described. For multiple rooms and multiple



(a) A situation with one wall

(b) A situation with two walls

Figure 3.3: Basic principles of mirroring sound sources.
Source: Sonification of sound `http://web.arch.usyd.edu.au/~densil/sos/`; Visited: 10-06-2015

source and receiver setups, multiple impulse responses are necessary. Depending on the accuracy of the room impulse response, it models a room accurately for both low and high frequencies. The room impulse response method is a faster method than the mirror source method. [17],[18]

3.5. Sound intensity

The radiated power of a isotropic sound source spreads equally in all directions. The sound intensity is the power per unit area (P/m^2). When the sound reaches the receiver in a free field at distance r, the sound intensity is:

$$I = \frac{P}{(4\pi r^2)} \tag{3.2}$$

The intensity decreases with r^2. It is an inverse square law [8, p. 16-22], [19, p. 28-36].

Sound reflections cause serious deviations in the inverse square law. In highly reverberant rooms, the sound intensity does not depend on distance at all. The equation describing the intensity in reverberant rooms is:

$$I_r = \frac{4P}{R_c} \tag{3.3}$$

Here, R_c is the “room constant”. This constant is approximately equal to the total room surface S multiplied by the average absorption coefficient α and divided by $1-\alpha$ [8, p. 244-250], [19, p. 36-39]:

$$R_c = \frac{\alpha S}{1-\alpha} \tag{3.4}$$

Where α describes the amount of energy absorbed by a wall.

3.6. Wall absorption

When a sound wave strikes a wall, a part of the sound energy will be reflected, the amplitude and phase of which differ from the incident wave. Both waves interfere with each other and form, at least partially, a standing wave. The changes in amplitude and phase are described by Equation (3.5) [5, p. 35-38], [13, p. 127-128].

$$R = \frac{Zcos(\theta) - \rho_0 c}{Zcos(\theta) + \rho_0 c} \tag{3.5}$$

R is the reflection factor, Z is the impedance of the wall, in Pas/m^3, θ is the angle of incidence, c is the speed of sound and ρ_0 is the volumetric mass density. $c\rho_0$ is the characteristic impedance of air. The wall impedance is dependent on the angle of incidence and the frequency of the incident sound wave. The part which is not reflected is dissipated as heat in the wall.

The pressure and velocity of an incident wave travelling along the x-axis can be described by Equation (3.6). Then, if there is a wall perpendicular to the wave at x = 0, the pressure of a reflected wave is described by Equation (3.7). The only differences between the two are the travelling direction and the factor R.

$$p_i(x,t) = \hat{p}_0 e^{i(2\pi f t - kx)} \tag{3.6}$$

$$p_r(x,t) = R\hat{p}_0 e^{i(2\pi f t + kx)} \tag{3.7}$$

Here $\hat{p}_0$ is the maximal pressure, f is the frequency of the sound wave, t is time, k is the angular wave number and x is the location of the wave. The quantity of energy dissipated is described by the absorption coefficient of the wall, which is described in Equation (3.8).

$$\alpha = 1 - |R|^2 \tag{3.8}$$

Here, α is the absorption coefficient. This coefficient can be any value from -1 to 1 [5, p. 35-38], [13, p. 127-128]. Other ways in which walls have an influence on the reflected sound are the roughness and the length of the wall. If a wall has protrusions or irregularities which are not much smaller or much larger than the wavelength of a sound, the reflected sound will be completely or partially scattered. Such a wall is called a diffusely reflecting wall [5, p. 59-61]. When the dimensions of a room are of the same order of magnitude as the wavelengths of sound, standing waves become noticeable. For a frequency of 20 Hz, the wavelength is about 17 m.

4

DESIGN

To meet the requirements given in Section 2.2, a model has to be designed. This design is described in this chapter. We will first choose a reflection model method. After this the design for the reflections model in both 2D and 3D will be described. Our model consists of source placement, the validation of these sources and the wall absorption. The algorithm which calculates whether an object within the room collides with a wall is also described here.

4.1. REFLECTIONS MODEL METHOD

It is clear from Chapter 3 that the mirror source method is a good way to model reflections. It has a more manageable number of calculations than the wave equation model [5, p. 101] and it is accurate, though for complicated shaped spaces computing the visibility of sources takes time [20]. The impulse response method requires an impulse response for every room we would like to model and every combination of source and receiver location. It is easier to calculate reflections from curved walls with the ray tracing method. Computer calculations however are much more efficient when using only linear surfaces, thus using curved walls is unattractive [6, p. 99-104]. Therefore,+ the mirror source model was chosen.

There are two main design topics in modelling reflections:

1. Positions of reflection sources
2. Wall absorption

These are the main topics in this chapter.

4.2. POSITION OF REFLECTION SOURCES

The design of the algorithm to calculate the positions of mirror sources with the mirror source method will be described in this section. It first explains the two dimensional (2D) design for a rectangular room. A generalised design for three dimensions (3D) and all possible room shapes follows after this.

4.2.1. 2D DESIGN

FIRST REFLECTION

Calculating mirror sources in a 2D rectangular room is straightforward. Calculating the coordinates of the mirrored sources in each vertical wall is possible by using the following formulas:

$$x_{reflection} = x_{wall} - (x_{source} - x_{wall}) \tag{4.1a}$$

$$= 2 \times x_{wall} - x_{source} \tag{4.1b}$$

$$y_{reflection} = y_{source} \tag{4.1c}$$

Here, $x_{reflection}$ is the x-coordinate of the mirrored source, x_{wall} is the x-coordinate of the wall, x_{source} is the x-coordinate of the original source, $y_{reflection}$ is the x-coordinate of the mirrored source and y_{source} is the y-coordinate of the original source. In Figure 3.3a, a visualisation of these formulas can be seen. Calculating this for both vertical walls gives us two sources outside the room. Replacing x by y and y by x in Equation (4.1) gives the coordinates for the mirror sources mirrored in the horizontal walls. This also gives two sources outside the rooms. This sums up to four mirrored sources for a rectangular room.

SECOND AND HIGHER ORDER REFLECTIONS

Calculating the positions of the second order reflections works the same. In Equation (4.1), however, the position of the source is not that of the original source, but it is the position of a first order mirror source. By mirroring a first order source in each of the walls, four reflections will be obtained. One of these will be a back reflection. A back reflection is a reflection which reflects back to its original source. This reflection is only valid if there are two parallel walls and both the source and receiver are on a line perpendicular to these walls. Reflections of these sources in other walls are invalid, since the angle of incidence has to equal the angle of reflection, which is 90°. For simplicity's sake, these back reflections are cancelled. Because these sources don't exist this doesn't matter for sound quality. Thus, three second order sources are created per first order source. Each source, except for the original source creates a number of mirror sources equal to the number of walls -1. This sums up to a total of twelve second order sources for a rectangular room. Each second order image corner room contains two image sources mirrored to the same position. This occurs for every rectangular room. The number of mirror sources for different orders of reflection is shown in Table 4.1.

4.2.2. MULTIPE SOURCES, ONE LOCATION

The number of mirror sources and the number of their unique locations in rectangular 2D rooms are shown in Table 4.1. The same numbers in rectangular 3D rooms are shown in Table 4.2. By mirroring a source in a wall, it often has a location one or more other source(s) also mirror to. It would be more efficient to calculate these locations only once.

Table 4.1: Reflection sources per order and total reflection sources in a rectangular 2D room. Here, w is the total amount of walls (four in a rectangular room) and o is order.

Order	Extra Sources	Double	Unique locations	Total unique
1	4	0	4	4
2	12	4	8	12
3	36	24	12	24
4	108	92	16	40
5	324	304	20	60
o	$w \cdot (w-1)^{o-1}$		$w \cdot o$	$w \cdot \text{sum}(o)$

Table 4.2: Reflection sources per order and total reflection sources in a rectangular 3D room. Here, w is the total amount of walls (six in a rectangular room) and o is order.

Order	Extra Sources	Multiple	Unique locations	Total unique
1	6	0	6	6
2	30	12	18	24
3	150	112	38	62
4	750	684	66	128
5	3750	3648	102	230
o	$w \cdot (w-1)^{o-1}$			

The sources at the same location do exist multiple times, see Figure 4.1. Source S has double image source S". Both exist because there is one possible line in two directions (the red thin line inside the room). This is in two directions so there are be two sources. Taking the width of the red line in the limit to zero (just in the corner) and make it vanish in the blue thick line from the image source. Both of the ray traces take the same path but in different direction, just in the corner between the walls. This phenomenon always happens with perpendicular walls.

While multiple sources are all important, the locations of the multiple sources are important too. It would be more efficient to copy the location without calculating it every single time. This particular effect of perpendicular walls is not used in the design, because it could only be used there and it would have to be checked

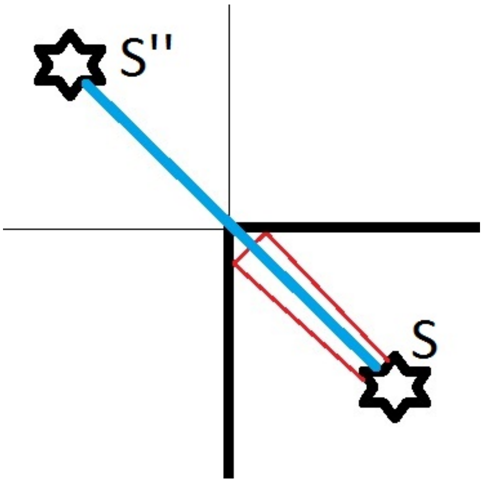


Figure 4.1: Image source S" of source S is a double sound source.

whether the walls of the room are perpendicular. In Tables 4.1 and 4.2 it is shown that the idea of copying the locations is most valuable with high orders of reflections. In most rooms high order reflections are not needed (see Chapter 3), because they are not audible due to wall absorption and air damping.

4.2.3. 3D DESIGN

ADDING FLOOR AND CEILING

Adding a floor and a ceiling to the rectangular 2D room makes it three dimensional. In Equation (4.1) the z-coordinate has to be added and there are two more 'walls' to mirror the source in. This is a basic 3D room, which is still rectangular.

CONCAVE ROOMS

In [13, p. 873-943] a basic script in pseudo code for mirror source scouting in concave rooms can be found. In concave rooms all corners are less than π. This section explains how this script results in a design for mirror source position calculation.

The maximum amount of sources calculated by the mirror source method is:

$$\text{sources} = w \cdot (w-1)^{o-1} \tag{4.2}$$

with w the amount of walls and o the order of the reflection. When a source is found invalid, either by being too far away or by not being within the line of sight of the previous source, next order sources will not be calculated for this source.

INPUTS AND OUTPUTS

As is simplified shown in the block diagram (Figure 2.1) there are several inputs for the reflections block:

- omax: maximum order of reflection that needs to be calculated
- dmax: maximum distance of image source to reciever
- sourcePos: position of source (x,y,z)
- playerPos: position of player (x,y,z)
- wallPos: positions of walls. Matrix with two dimensions:
    1. wallNumber: number of the wall
    2. list of wall edges and type:
        - xmin: the minimum x-coordinate of the wall (edge)
        - ymin: the corresponding y-coordinate
        - xmax: the maximum x-coordinate of the wall (edge)
        - ymax: the corresponding y-coordinate
        - wallType: the type of the wall: important for the wall absorption (see Section 4.3) :
            - ◇ 0: stone
            - ◇ 1: wood

    - ◇ 2: curtains
- h: height of room (hmin, hmax)
- x: input sound. Vector with a samplefrequency (Fs) and length (blocksize)
- blocksize: size of a sound block

And some outputs:

- tab: table with lists per order and source. With three dimensions:
  1. order: the order of the reflection in a range from 0 to maximum order (omax)
  2. sourcenumber: the number of the source in a range from 0 to maximum amount of sources (sourcemax)
  3. list with coordinates of source and some specifications of the source:
     - x: x-coordinate, see in this section Calculating mirror sources
     - y: y-coordinate
     - z: z-coordinate
     - wallNumber: number of the wall
     - distance: between the source and the receiver player
     - vp: vision of player on source, 1 stands for visible, 0 stands for not visible, see in section Line of sight
     - flag: if the source is valid this is a 1, invalid is a 0, see in section Valid source
- y: matrix with output sound, with three dimensions:
  1. order: the order of the reflection in a range from 0 to maximum order (omax)
  2. sourcenumber: the number of the source in a range from 0 to maximum amount of sources (sourcemax)
  3. sound: the output sound vector

4.2.4. CALCULATING MIRROR SOURCES

To calculate the position of a mirror source, the orthogonal projection of a source on a wall is needed. This projection is called a footpoint. By multiplying the coordinates of this footpoint by two and reducing it with the position of the source, the position of the mirror source is calculated, see Figure 4.2 [13, p. 928].

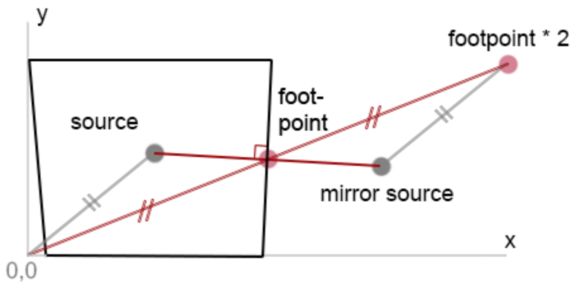


Figure 4.2: Calculation of a mirror source

LOOPS

Every position of the mirror sources has to be stored in a three dimensional matrix: reflPos[order,index,coordinate]. The first dimension is for the order of the reflection. The second dimension is for the index number of the source. The third dimension is the (x,y,z) coordinate. This is done this way because the system stays scalable and clear to understand.

This is implemented in a nested structure, it has 3 loops:

1. Order: when calculating mirror sources with order o, the sources with order $o-1$ are read out. These sources of order $o-1$ are called the mother sources. The loop is in range from 1 to the maximum order (omax). Order 0 is the original source.

2. Index: for a certain order each mother source will be evaluated.

3. Walls: each of the mother sources will be mirrored in every wall except for the wall in which the mother source was mirrored. The sound of the mother source will be adapted for wall absorption and stored, see Section 4.3.

The mother source is stored in reflPos[order-1, index, coordinates]. The newly found mirror source will be stored in the same matrix, but at a different place: reflPos[order, index*walls+w, coordinates]. Here, w is the number of the wall wherein the reflection was calculated.

In Chapter 3 it is made clear that mirror sources has to have a sign for their phase. This calculation is not implemented because it takes a lot of computational power [13, p. 913-923].

VALID SOURCE

There is a check if the calculated image source is valid. There are two conditions which have to be checked to see whether a source is valid. The first one is distance. If a mirrored source is further away from the receiver than a predetermined value, dmax, its sound will be damped so much it will no longer be audible. If this source is mirrored in another wall, this distance to the receiver will only increase, therefore, this source is invalid. The second condition is visibility. If a direct line, a line not crossed by other walls, cannot be drawn from a source to wall, the source cannot 'see' the wall. A sound cannot directly reflect to this wall. This source does not necessarily have to be the original source. Mirror sources also need visibility. The details on this are described in the next section.

LINE OF SIGHT

There are two lines of sight that need to be calculated. There is the line of sight between the mirrored source and the player and the line of sight between a source and the wall in which it possibly creates a mirror image. The first line of sight determines whether the player can hear this reflection. Even if the player cannot hear this reflection, it could still hear reflections of this reflection. The source is still valid. The second line determines whether a new source is valid at all.

A receiver can receive sound from the direct source if there are no obstructions between the two of them. A mirrored source can only be received if a direct, unobstructed line, can be drawn between the receiver and the source and if the receiver lies within the field angle. The wall in which the source was reflected does not count as an obstruction. This case is referred to as 'having a line of sight.' The field angle is the angle between the source and the two corners of the wall in which it was mirrored. An example can be seen in Figure 4.3. In this figure, the lowermost wall is not within the source's field of vision. The vertical walls are partially within the field of vision and the horizontal walls, except for the bottom wall, are completely visible. The left vertical wall is obstructed by a horizontal wall however, so this wall does not lie within line of sight of the source. In this figure, the horizontal field angle is drawn, the angle between the source and the right and the left side of the wall. The angle between the source and the top and bottom part of the wall is also a part of the field of vision. Our game so far only uses walls with four corners [1], so calculating the field of vision for walls with more than four corners is not considered.

To check if a point, hereafter called a target, is seen by the mirror source, the intersection point between the line between the target and the source and the plane described by three of the corners of the wall is calculated. This point is projected on two lines, from the middle of one side of the wall to the middle of the opposite side of the wall, see Figure 4.4.

A line with its projection is shown in Figure 4.5. If the left angle and right angle depicted in the figure are both smaller than the field angle on both lines, the target lies within the field of vision of the target. This method works for every orientation of the wall, but not completely for walls which are not rectangular. If the intersection point lies in the upper left or upper right corner of the wall depicted in Figure 4.4, the point will be determined to not be within the field of vision. Since the game so far only has rectangular walls, this design was deemed sufficient.

If the mirror source is mirrored in another wall, this wall too needs to lie within the source's field angle. Only the part of the wall on which it reflects needs to be visible, however. Which parts these are is calculated when the line of sight to the player is calculated and when the new mirror image is reflected in other walls. This means that a number equal to the number of walls of mirror sources and lines of sight need to be calculated to judge whether this new mirror source is not, partially or completely valid. To reduce the number of calculations, a mirror source is mirrored in another wall if the center of that wall is within its field angle [13, p. 884-885].

If the line between target and source is obstructed, it intersects a wall other than the wall in which the source was mirrored. The wall in which a mirror source was mirrored is hereafter called a source wall. Fur-

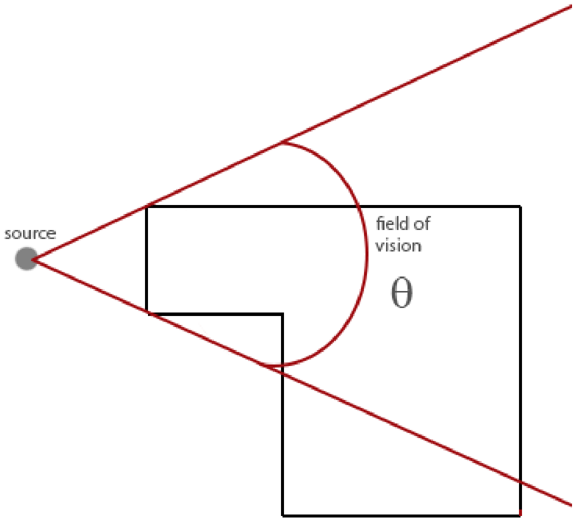


Figure 4.3: Field of vision θ for a source mirrored in the leftmost wall

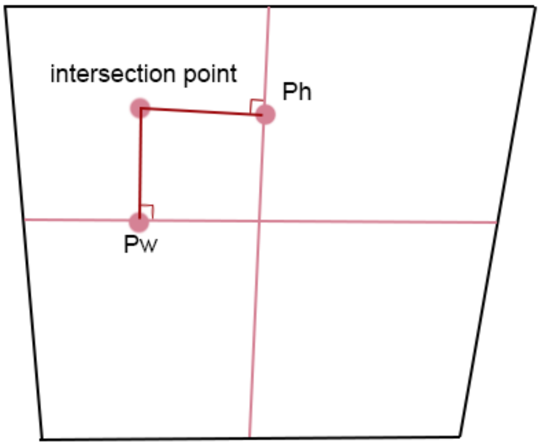


Figure 4.4: Projection of intersection point on the average height and average width axes of a wall

thermore, this intersection has to occur between the source wall and the target. If the target is within the field of vision defined by a possibly obstructing wall and the source, the line of sight is possibly obstructed. If the distance between the intersection point of the blocking wall and the intersection point of the source wall and the distance between the intersection point of the blocking and the target are both smaller than the distance between the intersection point of the source wall and target, the wall lies between the target and the source wall. This means direct line is blocked and there is no line of sight.

4.2.5. COLLISION

To calculate the collision, the distance from the player to the wall is needed. If this distance is smaller than a set distance, the player has collided with a wall. A set distance is used to allow for the width of the player, which is represented as a point. By calculating the mirror sources, the point on the wall closest to the player, or the footpoint, is calculated. The distance between the footpoint and the player can easily be calculated and compared. Whether there is a collision is stored in a single bit, which is passed on to the gameplay block Basics [1].

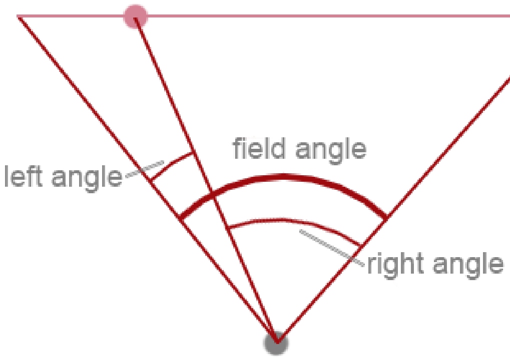


Figure 4.5: The angles between a line, the source and the projected intersection point

4.3. WALL ABSORPTION

The wall absorption has to be implemented to model different kinds of walls. Ideally, the wall absorption would be modelled by the complex reflection factor, found in Equation (3.5). This factor is however hard to measure and is mostly measured for materials with special acoustic properties [21], [22]. To keep our design flexible, the absorption coefficient is used, which can be found for many different materials. These absorption coefficients are valid for an angle of incidence of 0°. For other angles, the absorption coefficient is slightly different, see Equation (3.5). This difference is not computable with just the absorption coefficient and the angle of incidence. The reflection factor is needed. Therefore the effect of the angle of incidence was not implemented. Measurements of this absorption coefficient have a range of 125 Hz to 4 kHz or 250 Hz to 8 kHz for perpendicular sound incidence due to the geometry of the measuring set-up and the model for sound waves. Large walls are needed to accurately measure low frequencies [23]. The assumption that sound waves are plane waves places a limit on high frequencies. Wall irregularities also limit the maximum measurable frequency [22]. Hard surfaces, such as brick walls, concrete and hard floors have very low absorption coefficients for all frequencies, as can be seen in Table 4.3. Strongly vibrating surfaces absorb low frequencies, while soft surfaces, such as fabric, absorb mostly high frequencies.

Table 4.3: Typical absorption coefficients of various types of wall materials [5, p. 307]

Material	Centre frequency of octave band (Hz)					
	125	250	500	1000	2000	4000
Hard surfaces (brick walls, plaster, hard floors, ect.)	0.02	0.02	0.03	0.03	0.04	0.05
Slightly vibrating walls (suspended ceilings, ect.)	0.10	0.07	0.05	0.04	0.04	0.05
Strongly vibrating surfaces (wooden panelling over air space, ect.)	0.40	0.20	0.12	0.07	0.05	0.05
Carpet, 5 mm thick, on hard floor	0.02	0.03	0.05	0.10	0.30	0.50
Plush curtain, flow resistance 450 Ns/m^3, deeply folded, in front of a solid wall	0.15	0.45	0.90	0.92	0.95	0.95
Polyurethane foam, 27 kg/m^3, 15 mm thick on solid wall	0.08	0.22	0.55	0.70	0.85	0.75
Acoustic plaster, 10 mm thick, sprayed on solid wall	0.08	0.15	0.30	0.50	0.60	0.70

An approximation of the reflected energy from hard surfaces, or $1 - a$ can be made with Equation (4.3).

$$1 - \alpha = 0.985 - 0.04(1 - e^{-f/2000}) \tag{4.3}$$

This equation and those modelling a wooden door and a wall covered by curtains can be seen in Figure 4.6. By multiplying the Fourier transform of a sound wave by this approximation, the change in amplitude of sound reflecting off of a wall is modeled. The change in phase of the reflected signal is ignored here. in Equation (3.6) and Equation (3.7), the pressure of the incident wave and the reflected wave are described. Since the digital sound wave is a representation of pressure, and not of intensity, this wave needs to be multiplied by R, which is the square root of Equation (4.3), see Equation (4.4).

$$\sqrt{1-\alpha} = R \tag{4.4}$$

Because phase change is ignored, the standing wave pattern will change. Only the low frequency part of this pattern is noticeable and this part is modelled badly by the mirror source method anyway. Adding the change in phase is complex and this change would hardly be audible. Therefore it was chosen not to implement this phase dependency.

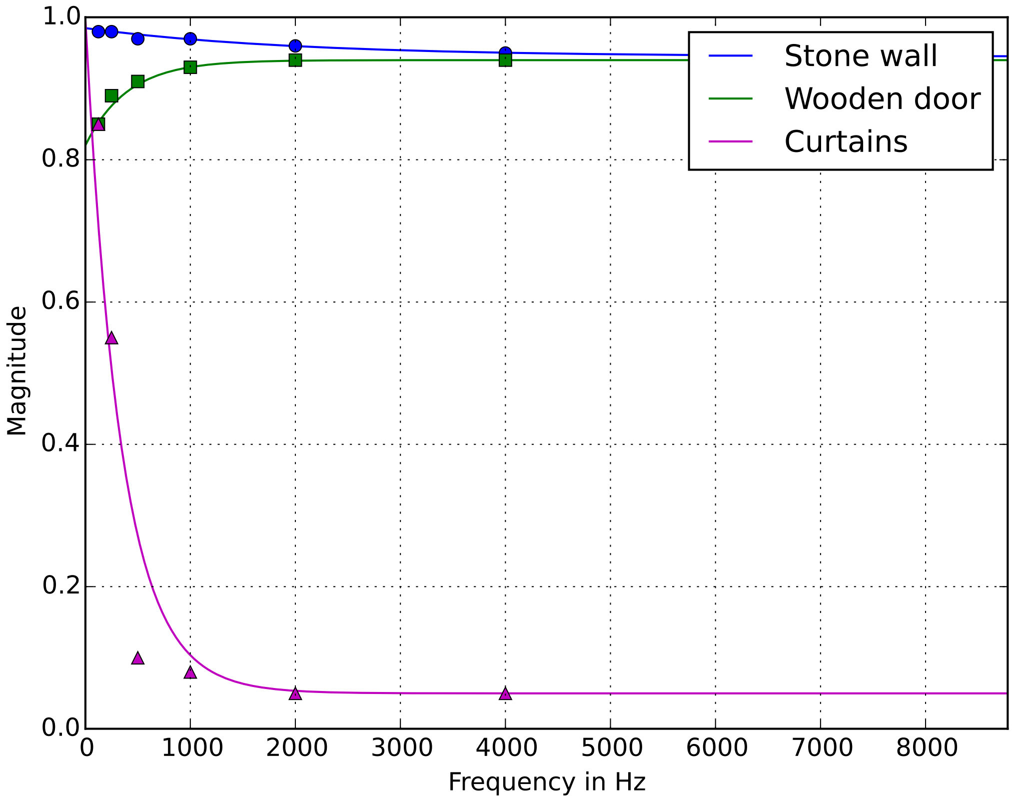


Figure 4.6: Damping lines (1-a) for different wall types, the points are taken from the absorption table

In Figure 4.6, the percentage of reflected sound pressure from a wall can be seen.For the wooden door, the absorption coefficient of a wooden door was used [24], instead of the absorption coefficient of wooden panelling.

4.4. PROGRAMMING DETAILS

Both Matlab and Python are usable programming tools. Calculations took about the same time. The other groups found that Python better suited their needs, therefore the whole game was programmed in Python.

A digital representation of sound consists of one or two arrays of numbers (depending on whether the representation is in mono or stereo) for the amplitude of sound pressure and a number signifying the sample rate. For this design, a single string of sound and the sample rate are needed to calculate the reflections. Localization changes the mono sound to a stereo sound. Sound is inserted into the Reflections block in parts to allow for real time modelling. The wall absorption is frequency dependent, therefore it is more efficient to calculate its effect on a signal in the Fourier domain. The discrete Fourier transform (DFT) algorithm is of order $O(N^2)$, with N the number of data points. If a block with $N = 2^r$, with r a natural number, the fast Fourier transform (FFT) can be used more efficiently. This transform algorithm is of order $O[Nlog_2(N)]$. For a signal with N = 1024, the FFT improves the speed of the DFT by a factor of 204.8. For a signal with $N \neq 2^r$, the FFT can still be used. In this case, the signal has to be padded with zeroes until $N + \text{zeros} = 2^r$. To optimize calculation speed, the number of data points in a block need to be an order of two [25, p. 195-203], [26, p. 376-378].

5

RESULTS

In this chapter, first the results of the design of the calculation of the position of reflection sources will be shown. After this there is a section about the collision that is implemented. The results of the wall absorption calculation are covered after that. This chapter ends with an section about the performance

5.1. POSITION OF REFLECTION SOURCES

In the design process first a 2D version of the model of the positions of reflection sources is built. This design is improved to a 3D version for concave rooms. In this section the results of this process will be explained.

5.1.1. 2D DESIGN

Figure 5.1 shows a room with first and second order mirror sources. In the room, the rectangle in the middle, outlined by thick red lines, are a receiver, depicted by the blue circle, and a sound source, depicted by the big blue star. The locations of the modelled first and second order image sources are depicted by smaller red stars and the smallest green stars and crosses, respectively. The thin blue lines makes it easier to see how they are mirrored from the original source. There are eight second reflection sources. Four of them, the small green crosses, are double sources. The 2D room is easily to understand.

5.1.2. 3D DESIGN

With the designed reflections algorithm the mirror source positions can be calculated in all sort of concave rooms (all corners less than π). 3D pictures on a 2D piece of paper are not very clear, so first an easier intermediate result is shown. In the calculation of the positions of the mirror sources the assumption has been made that all sources have equal sign.

ADDING FLOOR AND CEILING

In Figure 5.2 a rectangle room with floor and ceiling, made flat, is shown, as are the positions of the source and mirror sources, stretched flat on the x,y-plane. Compared with the 2D function (Figure 5.1) the 3D script generates the same locations in the x,y-plane. The plot has only calculated the first three orders of reflections, because in practice calculating more orders is too time consuming.

The plot of the 3D positions (Figure 5.2) is not easy to understand. Most of the sources are printed double. Only on the edges, there are third order single sources. Depth is not easy to make clear, especially when plotting dots, so it is printed as a 2D figure. Because floor and ceiling are planes with a fixed z-coordinate, the sources too are located on layers with a fixed z-coordinate. On each layer above or below the of the original source is one source less on the edges.

CONCAVE ROOMS

Rooms with more complex shapes than the rectangular one can produce invalid sources due to lack of a line of sight. The line of sight script checks whether the receiver or the center of a wall lies within the field of vision of a source. This means concave rooms can be modelled. Work has been done on checking whether a wall other than the one the mirror source was reflected in crosses the line of sight. Up to a few orders it is checked that the positions are correct. In Figure 5.3 the result of this is shown. This obstruction script is not completely finished.

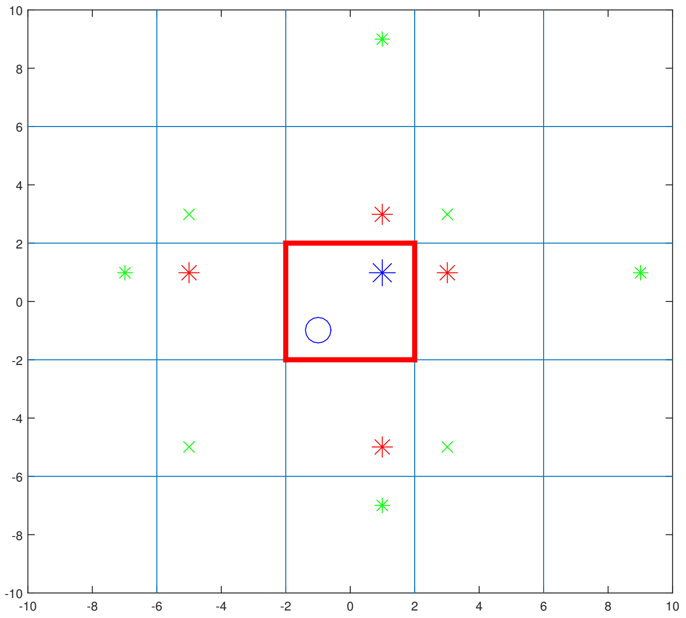


Figure 5.1: Model of the mirror source method with a rectangle 2d room.
Thick red lines: walls of room
Blue circle: sound receiver
Big blue star: sound source
Smaller red stars: 1st reflection
Smallest green stars and crosses: 2nd reflection

5.1.3. LINE OF SIGHT

Mostly due to lack of time, the line of sight algorithm was not fully implemented. The field of vision works, but the obstruction check, whether there are other objects between the target and the source, blocking the line of sight, is unfinished.

5.2. COLLISION

Because the distance to the wall is calculated in the reflection sources calculation it is easy to check whether an object collides with the wall. That is an extra function that is implemented within the reflection block.

5.3. WALL ABSORPTION

In Figure 5.4 an audio signal in the frequency domain and its damped versions can be seen. A discrete signal in the frequency domain is an infinite series of repetitions of itself. The second part is symmetric to the first, therefore only the first half of the graph needs to be considered.

Figure 5.5 shows a zoomed in version of Figure 5.4. There is hardly any damping caused by the stone wall and wooden door. The curtains however damp the higher frequency signals pretty well. The difference between reflections in a room with wooden door walls and stone walls are nearly indistinguishable, which is not that surprising, seeing as how both of these wall types hardly absorb any energy. The difference between those two and the room with curtain walls is clearly audible. Figure 5.6 shows the signals in the time domain. Here, it can be seen that the amplitude of the signals reflected by the stone wall and the wooden door is a tiny bit smaller than that of the original signal. Only the signal reflected by the curtains shows a clearly visible change.

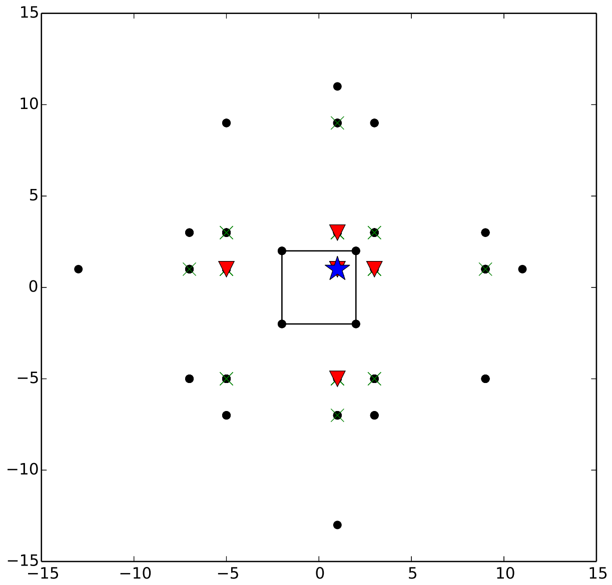


Figure 5.2: Flattened plot of the calculated positions in 3D with maximum order 3 in a concave room With:
Blue star: original source
Red triangle: first order
Green crosses: second order
Black circles: third order

5.4. PERFORMANCE

5.4.1. TIME

In Table 5.1 the calculation time used for the reflections calculation is shown. It was calculated with the CPU as specified in the requirements. It is tested for both rooms: the rectangle room (from Figure 5.2) and the other shaped room Figure 5.3.

Table 5.1: Time needed to calculate in ms

Order	Rectangle room	Other shape
1	50	50
2	70	70
3	350	190
4	820	430

In combination with wall absorption with FFTs the calculation took at least 1 ms per source. With a second order calculation there are already 30 second order and 6 first order sources. The total execution time will be a least 36 ms. With a simplified model of the wall absorption this time could be lowered, because FFTs would not be needed anymore.

With the different shaped room, shown in Figure 5.3, the calculation time is shorter. The line of sight is very useful here because many sources are invalid and do not have to be calculated.

The reflection script is also tested on the fastest computer in the group. This computer calculates the the first two orders of reflections in a rectangle room in approximately 35 ms.

5.4.2. MEMORY

Calculating the first two orders of reflection in a rectangular room took 45 MB. Adding an order the memory usage increased to 97 MB. With four orders, the reflections (750 fourth, 150 third, 30 second and 6 first order sources) took up 142 MB.

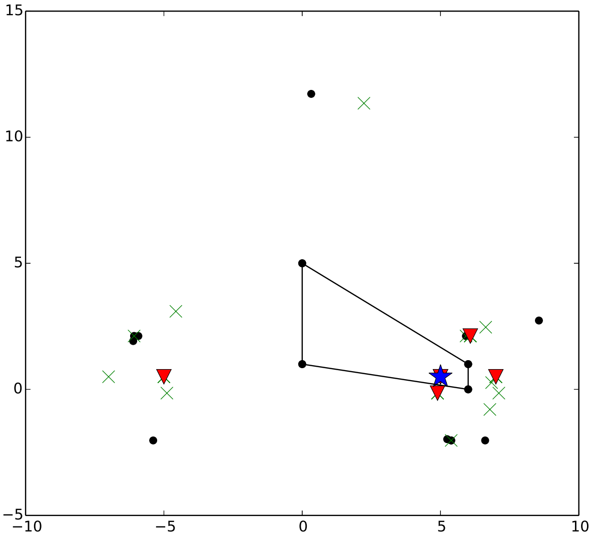


Figure 5.3: Flattened plot of the calculated positions in 3D with maximum order 3 in a concave room. With:
Blue star: original source
Red triangle: first order
Green crosses: second order
Black circles: third order

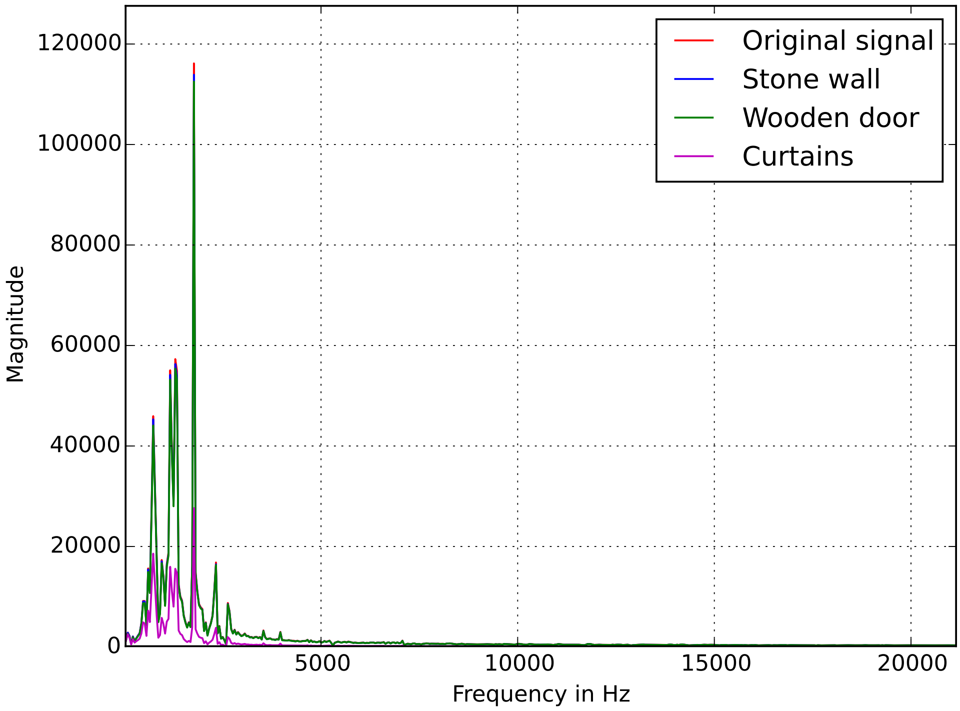


Figure 5.4: Damping in frequency domain

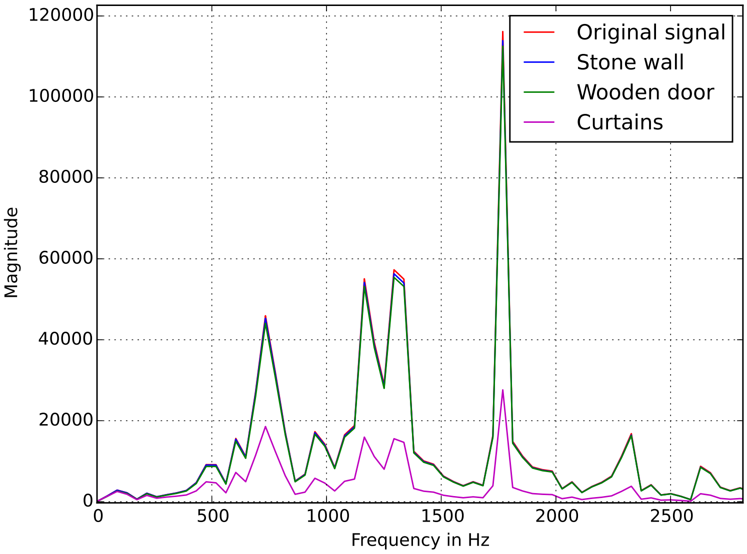


Figure 5.5: Zoomed in damping in frequency domain

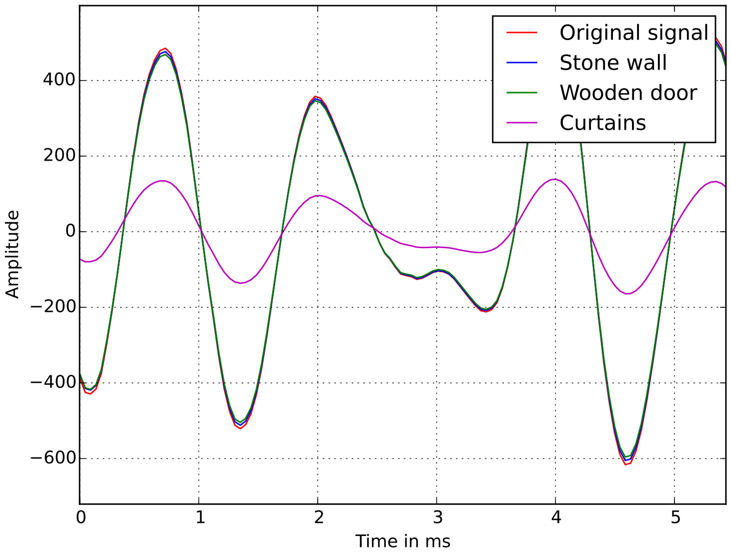


Figure 5.6: Damping of a sound signal

6

DISCUSSION

In this chapter the results will be discussed. As already was seen in the literature the mirror source method has some big shortcomings:

- Implementing a line of sight algorithm is hard
- Low frequencies are not accurately modelled
- Much calculation power is needed

These are things that could be improved. In the next section this will be explained. Some other issues, such as possible improvements, will be put forward.

6.1. LINE OF SIGHT

Calculating whether something lies within line of sight is doable. Obtaining conditions to determine whether a wall is possibly an obstacle or whether it cannot possibly block the line of sight is tough. Checking for every wall whether it blocks the line of sight is very inefficient and costs too much time. The script checking for obstacles is unfinished. It is only checked whether the receivers or other walls lie within the field of vision. This means concave rooms can be modelled, but more complex rooms cannot.

6.2. WAVE EQUATIONS

The mirror source model is pretty accurate for high frequencies. For low frequencies, however, using the wave equations is more accurate. Audio signals could be filtered into a high and a low frequency part. The high frequency sound can be modeled by the mirror source method and the low frequency sound can be modeled by the wave equations.

6.3. CALCULATION POWER

Requirement 6 is not satisfied. The time it takes to compute the reflections for one original source with four walls, floor and ceiling and maximal two order reflections is around 70 ms. The goal set was 10 ms. This is a problem. When the code was integrated this was done on the fastest PC in the group. There it took around 35 ms to run the script. With a refresh rate of 10 Hz (a larger blocksize then normal) the game works fluently. The code can be optimised for a faster result. But the calculation time necessary is a shortcoming of the mirror source method.

In combination with wall absorption with FFTs the calculation took at least 1 ms per source. With a second order calculation there are already 30 second order and 6 first order sources. So this sums up to an execution time of at least 36 ms. With a more simple version of wall absorption this time could be lowered, because then no FFTs are needed.

6.4. WALL ABSORPTION

Not much information could be found on the modelling of wall absorption. Therefore, only a basic implementation was made. Much more accuracy could be obtained if the acoustic impedance of different types of materials was added to the model. The change in phase angle is not modelled, as is the effect of the angle of incidence on a wall. Furthermore, for uneven walls, diffusion will occur strongly enough for it to become non-negligible. Finally, The influence of objects within the room on sound is non-existent. This could also be implemented.

6.5. CONCAVE ROOMS

All sort of concave rooms can be made but each wall (or floor or ceiling) must be made of a plane of four points. So with a room with some more corners and a sloping ceiling the amount of walls is much higher. It also is not easy to program. This could be solved with a more flexible definition of walls

More difficult rooms (like L-shaped) can not be implemented. The line of sight algorithm is not extensive enough to calculate this. More research has to be done and much testing would be required.

6.6. COMPARISON

The Mirror Source method that has been implemented could be compared with other ways of modelling reflections in rooms. For instance, it would be interesting to compare it with the results of Martinez [18]. It was not possible to investigate this within the time of this project.

6.7. SPATIAL COGNITION

Because the line of sight was not as far developed as we hoped to achieve we couldn't test enough how well the reflections help gaining spatial cognition. We know from testing the game that the reflections of the footsteps in the room are quite useful to visualize where the walls are. So reflections do aid with that. Furthermore, we experienced that the reflections make the sound more full. In larger rooms reflections were experienced as echoes.

Because of performance limitations, calculations up to large orders aren't possible. For very reverberant rooms like churches, or concrete rooms, the reflections cannot be calculated accurately. The assumption must be made that reflections have faded out at the third order reflection.

Reflections do create an impression of the materials of the walls of the room, though whether this impression is entirely accurate has to be tested further. When someone singing within a small room with stone walls was modelled, it sounded like someone singing in the shower, while the exact same configuration, only with curtains for walls, instead of stone, did not call forth that impression.

On a whole, reflections results in some spatial cognition. A difference is heard between walking close to walls and walking in the middle of the room.

7

CONCLUSION

Reflections were modelled using the mirror source method. This method is partially implemented in the game for visually impaired children. The line of sight algorithm, which calculates whether a source can be heard, was not fully implemented and thus only concave rooms could be successfully modelled. With a fully implemented line of sight algorithm, every shape of room can be modelled, as long as the walls in it have four corners. The limits on wall shape are caused by the definition of walls decided by the gameplay group [1]. The sign of the mirror source is not calculated, this results in a not entirely correct superposition of sound. Furthermore, not enough testing was done to conclude whether reflections create an impression of the size and shape of a room. There is an audible difference between walls made out of curtains and those made of stone or wood. Stone and wood however are hard to distinguish from each other. Not enough testing was done to determine if this difference is audible with training. Thus requirements 1 to 4 are not completely satisfied.

The reflections block works perfectly with the rest of the game so requirement 5 is met. The blocks were all integrated and tested together. It works fine.

The time to calculate reflections for higher order reflections is too high. In the game only up to second order reflections in simple rooms can be calculated. In the future, the optimisation of the calculation speed could be worked on. The wall absorption could be simplified. Instead of the mirror source method a different method of modeling could be chosen. Requirement 6 is not met. There is less memory used than the maximum set by the requirements. Requirement 7 is met.

The system has been developed within nine weeks from 20 April 2015. One week was spent on a literature study, six weeks were spent developing the game and writing this thesis cost two weeks. No development software with additional costs was used. First matlab was used, which is available for all students of the TU Delft. Later Python was used, due to limitations of matlab which hindered the gameplay and localization group, which is open source. Thus requirements 8 and 9 are met.

A

ETHICS

This chapter is about the ethical implications of our design. The influence of our product, a game for visually impaired people, and its production on the visually impaired and on society will be described. Furthermore, our responsibility as game developers is defined

Our game has two goals:

- Improve distance estimation
- Improve spatial awareness

Finally, in this chapter will be explained if these are goals are ethical, according to the four major ethical theories.

A.1. IMPACT ON THE LIFE OF VISUALLY IMPAIRED

People will be able to better localize sound and have an improved spatial awareness by playing our game. This is neat for non visually impaired people, but it will not make much of a difference. Visually impaired people however will benefit from being better able to localize by sound and by having an improved spatial awareness. They might be more confident when moving in new environments. It might make them more independent.

A.2. IMPACT ON SOCIETY

Visually impaired people with improved confidence when moving in new environments might partake in traffic more often. This might compromise the traffic safety. People still have to take into account that visually impaired people do not have as much sensory input as an average person. There are already sufficient traffic rules for dealing with blind people however, so this should not be much of a problem. Our product will be downloadable online, so no physical components are needed. No factories or employees are necessary creating our product, except for the game developers.

A.3. RESPONSIBILITY GAME-DEVELOPERS

Promising more confidence and less fear for visually impaired people is a large promise. Before the product can enter the market, tests must be prove an improvement on localization and spatial awareness after having played the game. Furthermore, the game-developers, the other staff and the investors need to get paid. Therefore, the game cannot be too cheap. Making it too expensive means tricking visually impaired people out of their money. This would be unethical and therefore the game cannot be too expensive.

A.4. OTHER RESPONSIBILITIES

The power consumption of a computer when playing the game is the only aspect of the game that will have an influence on the environment. We do not feel it is our task to minimize this consumption. Our game will be downloadable online, so no physical components need to be produced.

The audio played by the game cannot be over a sound pressure level (SPL) of 85 dB for prolonged periods of time when played by most standard headphones, to prevent hearing impairment [27]. Reflections can enhance a sound, making the original direct sound louder. This has to be accounted for. We cannot account for every type of headphones. If we account for one pair of headphones that can play audio very loudly, another pair of headphones which cannot might play sound too soft for people to be able to play the game. Proper warnings to prevent hearing impairment need to be added. Other safety risks of playing a game are negligible.

A.5. ETHICAL DIRECTIONS

CONSEQUENTIALISM

Consequentialism says that an action should result in more happiness than unhappiness. If visually impaired people become more confident when moving in new environments, it will improve their happiness. Other people however might not like having to allow for more visually impaired people in public areas. Assuming that the happiness of the visually impaired people outweighs the unhappiness of the non allowing people, our game is approved by consequentialism. Furthermore, we create our game to be enjoyable. Our reflections aid in this by making audio sound realistic and by creating a spatial impression of the virtual surroundings. We hope it provides short and long term happiness.

VIRTUE ETHICS

Virtue ethics describes that people should act on virtues and by acting with good intentions, improving themselves. Our goal is to create a training game for visually impaired people. By doing this we will be productive and will learn a lot about the creation of audio games. By working hard on this project we will improve ourselves. People will play our game for different reasons. Visually impaired people training to improve their audio localization and spatial awareness will play to improve themselves. This is what our game was meant for. Improving oneself is a virtue, therefore our game is approved by the virtue ethics

DEONTOLOGICAL ETHICS

Deontological ethics states that people have the obligation to act according to a set of (morally just) rules. Acting against these rules, such as 'do not lie' and 'do not kill,' is considered wrong. Creating a training program which will help people and which does not already exist is a very admirable course of action according to deontological ethics. Just creating a game for visually impaired people is already encouraged. Creating a game to help or entertain a minority which is mostly ignored by developers of games is a morally right thing to do. Therefore deontological ethics approves of the creation of our game

CARE ETHICS

Care ethics describes that when people see someone in need, they are obligated to help this person. Blind people currently do not have a training program for localization and spatial awareness other than walking around. The games created for blind people are few and most of them are badly made. Creating this game is therefore a ethical choice according to care ethics.

A.6. THE COMPANY

This section is about how we would structure our company if we were seriously interested in making a business out of creating a training game, instead of producing just a working concept for our bachelor graduation project Our company would value teamwork, discipline and honesty. The company would consist of a small number of people, each responsible for its own part of a whole.

Cultural diversity is not a focus for hiring requirements. We would like to have people capable of doing their job. Their skin colour, gender or culture is not deemed relevant.

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