

Spatialisation As A Service (SaaS)

Interim Project Report

Callum John Spiller

Programme of study:
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Supervisor:
Johann Pauwels

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Contents

Glossary	2
Acronyms	2
1 Introduction	4
1.1 Project Background	4
1.2 Problem Statement	4
1.3 Project Aims	4
1.4 Project Objectives	5
1.5 Research Questions	5
2 Literature Review	7
2.1 Cloud Computing	7
2.2 Audio Spatialisation	7
2.2.1 Origins	7
2.2.2 From two to three	8
2.2.3 Getting the head in the game	8
2.3 Web Audio	9
3 Risk Assessment	10
3.1 Project Risks	10
3.2 Product Risks	11
3.3 Business Risks	13
4 Project Plan	15
4.1 Plan Preparation and Communication	15
4.2 Timeline	15
4.3 Resources	15
4.4 Methodology	16
5 Requirement Capture and Analysis	18
6 Infrastructure Design	19
6.1 Best Laid Plans	19
6.2 Refinement	20
A Appendix: Code Snippets	21
A.1 Lambda Function Dockerfiles	21
References	23

Glossary

AWS API Gateway An AWS service that allows developers to create and deploy their own custom APIs that allow access to data and application logic. [19](#)

AWS Elastic Container Registry An AWS function that allows the user to host and deploy container images. [20](#), [22](#), [23](#)

AWS Eventbridge A cloud service that allows the communication between disparate AWS serverless components through the use of events. [19](#)

AWS Lambda Part of Amazon's serverless computing services, these Lambda functions allow a software developer to host and run individual fragments of code that are triggered in response to events. The feature manages the resources required for these pieces of code to run. [19](#), [20](#)

AWS Step Function A service that allows a software developer to orchestrate and schedule serverless workflow pipelines through the use of state machines and tasks. Through this service, a developer is able to easily control the use and order of other AWS services. [19](#)

container image A standalone package of software that contains everything needed in order to run an application. This allows for the identical deployment and running of applications independent of the underlying infrastructure. [20](#)

DevNet A private web resource accessible only to licensed PlayStation developer, publisher and middleware companies. On this site you are able to access PlayStation API documents and order PlayStation development kits. [4](#)

Docker A set of products that allows developers to virtually deploy operating systems and software packages in reusable containers. Docker is one of the most widely used products for this purpose. [20](#)

Node.js A free and open-source server environment that allows the execution of JavaScript code outside of a web browser. In this project it was used to build the front-end web interface. [19](#)

PlayStation Partner The name given to any video game developer or retailer who engages with the PlayStation ecosystem in order to sell or develop their products. [4](#), [6](#)

React.js A free and open-source Javascript library, maintained by Meta, that is used primarily for developing front-end user interfaces by rendering components to the DOM in web browsers. [19](#)

spatial audio Is the manipulation of sound produced by stereo speakers to mimic the human localization of sound sources in three-dimensional space. [4](#), [19](#)

Tempest 3D Audio Engine The proprietary audio engine used by the PlayStation 5 in order to render ambisonic audio files to headphones. [4](#)

Acronyms

API application programming interface 4, 5, 9

AWS Amazon Web Services 5, 11–13, 15, 19, 20

CI Continuous Integration 12

CI/CD Continuous Integration/Continuous Deployment 16

DSP digital signal processing 4

GDPR General Data Protection Regulation 14

HRTF head-related transfer function 5, 8, 9

IDE Integrated Development Environment 16

MVP minimum viable product 13

PaaS Platform as a Service 7

POC proof of concept 5

PS5 PlayStation 5 4, 9

SDK Software Development Kit 19

SIE Sony Interactive Entertainment 4–6, 13, 14, 16

SLA service-level agreement 4

1 Introduction

1.1 Project Background

This project has been undertaken as a part of a degree apprenticeship with **Sony Interactive Entertainment (SIE)**. As such, the final year engineering project for this author will consider the business domain of the sponsoring company.

With the release of the **PlayStation 5 (PS5)** in November 2020, **spatial audio** technology has come into focus for **SIE** as game developers seek to leverage the **Tempest 3D Audio Engine** espoused by the video game console. In addition, **SIE** is undergoing a shift to cloud-based infrastructure¹ across the wider business in order to leverage the cost, flexibility, and reliability benefits that cloud technology affords [Qian et al., 2009].

With respect to these developments in the business, this project seeks to engage both of these emergent technologies in order to address one of **SIE**'s major **service-level agreements (SLAs)** with a software solution.

1.2 Problem Statement

The onboarding of **Partners** to the developer and publisher platforms managed by **SIE** is an area in the company that has been targeted for improvement. One of the primary targets for improvement has been the reduction of friction in the process of getting **Partners** engaged with the PlayStation ecosystem.

While the **Partner** onboarding process has been automated and refined over time, this author argues that the ability for potential **Partners** to engage with and trial PlayStation's spatial audio technology is too restricted.

This project was founded upon the hypothesis that, for a user who wishes to experiment with or experience **spatial audio**, the barrier for entry is too high. Engaging with a working demonstration of customisable **spatial audio** requires a user to perform a significant amount of preparation and setup on a local machine; it demands a time commitment and pre-requisite technical knowledge that is far greater than is reasonable for an interested party to quickly evaluate what is possible.

Currently, **Partners** who want to experiment with **Tempest 3D Audio Engine** must apply for and order a **PS5** development kit, wait for it to arrive, perform the setup of the development kit, then figure out how to engage with the **application programming interfaces (APIs)** provided by **SIE's DevNet**. This process is time-consuming and sub-optimal for a **Partner** who wishes to get a quick insight into what is possible.

This project proposes an alternative solution where a **Partner** who wishes to engage with the **spatial audio** paradigm is able to experiment with the technology by using a familiar audio file of their choosing. The fact that the system will be accessible through a browser will mean that the **Partner** will have much easier access, increasing the overall positive impression of the **Partner** platform.

1.3 Project Aims

The aim of this project is to research, design, and engineer a web service that allows a user to easily experience **spatial audio** in a way that reacts to their input. Despite the fact that this project will make use of **digital signal processing (DSP)** and requires a front-end for the user to interact with, the primary complexity of this project concerns the cloud infrastructure design

¹like many other companies relying on web technology [Qian et al., 2009]

and implementation that forms the backbone of the “*Spatialisation-as-a-Service*” concept, that is, moving compute-heavy tasks from the local machine to a cloud environment. Taking this into account, the project should be classified as an infrastructure project, and will focus upon the challenges relating to this area.

The proposed workflow would allow a user to use a standard web browser² to upload an audio file to a webpage and then receive back a new audio file that has rendered the stems from the original file into a 'spatialised' format informed by **head-related transfer functions (HRTFs)**. All the audio processing would execute in **Amazon Web Services (AWS)** cloud environments to circumvent real-world hardware requirements and challenges.

For information security reasons, the prototype produced as a part of this project will *not* feature any proprietary **SIE** software and instead use only libraries and code that exist in the public domain. Because of this, the prototype can be considered a **proof of concept (POC)** where, if successful, **SIE** software might be transplanted into the serverless pipeline.

1.4 Project Objectives

In order to achieve the aims set out in 1.3 the project must produce a number of deliverables:

1. A project plan which outlines the timeline of both the research and development of the project
2. A review of pertinent literature relating primarily to:
 - Public Cloud infrastructure and services (especially those available from **AWS**)
 - Audio spatialisation
 - Web front-end technology and audio **APIs**
3. A review of existing stereo-to-spatial services and technologies.
4. A functioning stereo-to-spatial serverless pipeline.
5. A frontend that enables a user to interact with the conversion pipeline by uploading and downloading audio files, as well as setting parameters for conversion through a web **API**.
6. A testing framework that supports iterative development.
7. A report on user testing.
8. A review and analysis of how the produced system has met or missed the targets.

1.5 Research Questions

In order to guide the research and development process of the proposed system, this report will seek to answer the following research questions:

1. What are the characteristics of audio-processing pipelines that are executed within cloud infrastructure?
2. What is the impact of cloud technology in addressing physical hardware limitations?

²The project will most likely be designed for interaction through Chromium-based browsers and Firefox

3. How effective is cloud infrastructure in facilitating the execution of compute-heavy audio pipelines?
4. How can the leveraging of cloud technology improve the experience of the users of **SIEs Partner** platform?

2 Literature Review

As outlined in 1.3, this project attempts to engage with cloud infrastructure, spatial audio processing, and web development frameworks. To approach these topics thoroughly, this report performs a review of pertinent literature. In doing so, this report considers and incorporates existing ideas in these fields while providing a foundation from which to answer the research questions listed in 1.5.

2.1 Cloud Computing

Ever since internet service providers began the commercialization of cloud computing, it has become one of the major trends in the technology space [Qian et al., 2009]. According to Qian et al. [2009], ‘cloud computing’ is one of the most vague terms when it comes to the description of the technology on account of the breadth of its application

s2[Dillon et al., 2010]

Cloud computing technology is dominated by three major players, each with their own style of cloud services:

1. Amazon’s Web Services which began as a means of server virtualization [Amazon, 2022]
2. Google’s Cloud Platform, described by Qian et al. [2009] as a technique-specific sandbox that calls itself a Platform as a Service (PaaS) [Alphabet Inc, 2022]
3. Microsoft’s Azure Network [Microsoft, 2022]

2.2 Audio Spatialisation

2.2.1 Origins

Blauert [1996] notes in their seminal text, *Spatial Hearing: The Psychophysics of Human Sound Localization*, that: “human beings are primarily visually-orientated”, and that the other senses are less developed in comparison. This difference has been mirrored in the history of scientific research. Wade and Ono [2005] note that research in binaural hearing was developed later than binocular vision partially due to the difficulty in controlling the audio stimuli in experiments. It was only later on that the concept of distinction between the *sound event* and the *auditory event* as influenced by binaural hearing became prevalent. Blauert [1996] explains that this distinction informs the practice of audio replication analogous to its originating sound event:

The telecommunications engineer, of course, is especially interested in just those cases in which the positions of the sound source, and the auditory event do not coincide. The telecommunications engineer seeks to reproduce the auditory events that occur at the point where a recording or transmission originates, using the smallest possible number of sound sources (e.g., loudspeakers) [Blauert, 1996].

The patent filed in 1958 by Alan Dower Blumlein³ details an early stereophonic system, which exploits the human sound localization ability for the enhancement of entertainment

³[Blumlein, 1958]

experiences^{4 5}. Blumlein observed that in film theatres there was a certain level of cognitive dissonance whereby the actor’s voices sounded like they were coming from a different location than where they appeared on the screen [Alexander, 1999]. This patent, in response, specifically outlines methods for introducing stereophonic audio to sound film as a means of increasing the perceived “quality” of the entertainment experience. Blumlein acknowledges that human binaural hearing is responsible for the ability to localize sound, and his patent is an example of how one might induce an auditory event that exhibits spatialisation on the horizontal plane through the control of inter-aural time differences [Blumlein, 1958].

The patent marked an improvement in the way that auditory events might be replicated by introducing this form of spatialisation, and the vestiges of Blumlein’s ideas can be observed in modern spatial audio techniques [Politis et al., 2017, Beyer and Raichel, 1999]. What is perhaps the most salient aspect of the document, however, is that it recognizes the physiological factors that are involved in human sound localization. These physiological factors explored and expounded upon by Blauert [1996], and, as noted in the 1996 revision of his book, become more important as audio spatialisation and entertainment technology attempts to induce auditory events that imply three-dimensional audio spaces.

2.2.2 From two to three

The external ears superimpose linear distortions on the incoming signals, which, in each case, are specific for the direction of incidence of the sound wave and the source distance. In this way, spatial information is encoded into the signals that are received by the eardrums [Blauert, 1996].

Roginska and Geluso [2017] note that: “the word ‘binaural’ refers, at the most basic level, to hearing with two ears, but it later came to include all the spatial cues from the ears, head, and body of a listener”. Binaural recordings can therefore refer to the practice of capturing sounds that incorporate human physiology. This is executed with dummy mannikin heads with microphones placed inside the ears so that sound entering them are affected by the ‘blocking’ nature of the head; developments in this technology rapidly sped up throughout the 20th century [Paul, 2009]. While other forms of spatial representation were developed in this period [Gerzon, 1973, Noisternig et al., 2012, Berkhout et al., 1993], technology that considers the physical and physiological factors in human listening when attempting to induce auditory events that feature sound localization.

Roginska and Geluso [2017] identify that while capturing binaural audio is relatively easy, realizing the same effect through post-recording production is considerably harder and poses the challenge of modelling the human spatialization facility.

2.2.3 Getting the head in the game

The head-related transfer function (HRTF) can be described as a representation of the perceptual cues that facilitate human sound localization as a sound propagates from its source to the human ear [Suzuki et al., 2011]. This modelling of the human sound localization facility allows for this HRTF to be applied to a sound before reaching the human eardrum [Roginska

⁴This author acknowledges that this is not the first example of this kind of system; the control of inter-aural time differences was pioneered by Clément Ader as early as 4 years after Bell’s invention of the telephone. This was for the purpose of rendering a spatial transmission of the Paris Opera. This further solidifies a history of the desire for spatial immersion in entertainment.

⁵There is a rich history of considering space in the composition of music in Western Classical tradition, with Italian renaissance composers writing for *cori spezzati*, or multiple choirs that are spatially separated [Morucci, 2013]. This author mourns that the topic of spatialisation in historic acoustic performance goes beyond the scope of this report.

and Geluso, 2017]. It is with this technology that more and more modern entertainment systems begin to localize sounds [Blauert, 1996, Honda et al., 2007, Roginska and Geluso, 2017, Suzuki et al., 2011, Xie et al., 2013, Cerny, 2020, Hong et al., 2017] during audio playback.

There are many software systems, toolkits, and frameworks that have been developed to allow engineers to build software that can utilise **HRTFs** and apply them to monophonic recordings [Cuevas-Rodríguez et al., 2019, Gorzel et al., 2019]. It is through these technologies that many video game systems such as the **PS5** are able to provide immersive 3D audio experiences. In commercial systems such as these, consideration must also be applied to the selection of the **HRTF** that are used. While each person’s experience of sound is as individual as they are, capturing the **HRTF** of each individual who engages with the product is not yet feasible due to the highly involved and costly process of capturing them. Considerable research has been done in order to develop and produce **HRTF** databases that appeal to a wide variety of subjects, taking into account individual and non-individual **HRTFs** [Armstrong et al., 2018]. It is common practice to have entertainment systems contain multiple **HRTF** options to choose from when setting up that system’s spatial audio capabilities [Shukla et al., 2018].

2.3 Web Audio

Audio-visual media on the internet is extremely widespread and its delivery takes a myriad of forms [Brügger and Milligan, 2018]. The means by which audio is delivered to users on the internet is most frequently through a web audio **API**, the most common of which is the one developed by Mozilla [W3C, 2021, Mozilla, 2019]. One of the major benefits of utilising web technology in combination with audio technology is that it allows developers and those who wish to present audio to an audience to do so with a rich toolset of graphical libraries that are easily accessed through a web browser [Pauwels, 2018]; this is most frequently seen in commercial usage through web audio players such as Spotify and SoundCloud as a natural evolution of the radio broadcasting format [Bottomley, 2020]. Web frameworks such as React.js⁶, Flask⁷, and Django⁸ are all capable of handling and displaying audio from a web page.

Audio delivery is primarily executed through the downloading and playing of a static file or as a packet stream from a server-based audio file source; however, more recently web audio can be delivered peer-to-peer in real-time through such technologies like WebRTC [Ünver et al., 2020, García et al., 2019].

⁶[Minnick, 2022]

⁷[Zhai et al., 2022]

⁸[Pauwels, 2018]

3 Risk Assessment

A risk is defined by the [Project Management Institute \[2021\]](#) as “an uncertain event or condition that, if it occurs, can have a positive or negative effect on one or more objectives”⁹. The effective management of project risk across a number of risk-management frameworks involves the prior identification of said risks [[Goman, 2021](#)]. This report seeks to perform a risk assessment across three major categories as a means of improving the likelihood of the project meeting its objectives as laid out in [1.4](#).

This assessment will take the form of three tabular risk registers with columns evaluating each risk’s impact and likelihood, as well as preventative actions being taken as a result of this identification. It is important to note that these risks will be subject to ongoing monitoring, therefore they may change as the project develops.

3.1 Project Risks

These risks would affect the project’s schedule and affect the project’s ability to be finished within a given timeframe.

Table 1: Project Risks

Risk	Impact	Likelihood rating	Impact rating	Preventative actions
Failure to access required information	Lack full understanding of the background material	Low	Medium	Be diligent in identifying alternative sources, as well as making use of the Queen Mary Library’s resource-purchasing facility
Scope creep	During development the scope of the project may increase and what is attempted goes beyond what is realistically capable over the duration of the project	Medium	Low	Clearly define the scope at the outset of the project, have a roadmap in place and be accountable for sticking to it
Low productivity	When work on projects slow, any delays can cascade and cause the project to miss its objectives by the end of the project duration	Medium	Medium	Be diligent in creating and sticking to a project plan - additionally communicate frequently with the project supervisor in order to be accountable and to resolve any issues promptly

⁹[[Project Management Institute, 2021](#)]

Lose access to AWS	Given that the project is hosted in the cloud, losing access to administrate the service would result in a severe delay in development	Low	High	Make sure that all credentials are up to date before starting development - check company policy surrounding credential expiry
Loss of work	If the codebase is lost during development then this means having to re-write all of the code, slowing down the project dramatically	Low	Medium to High	Ensure that codebase management systems are used - this means using a version-control system such as GitHub to store all code and documentation for the project - also ensure that any AWS deployments have backups
Inefficient working	When time is spent on menial, small, or administrative tasks that do not directly contribute to the project's completion, this can cause progress on the overall project to slow	High	Medium	Ensure that tasks are prioritised effectively, deploying agile scrum effort ratings when needed
Lacking requisite skills	When a challenge in the project requires skills that this author does not possess then they must spend time learning the skills required to overcome the challenge - this can slow progress on the project	Medium	Medium	When planning the project timeline, ensure that enough leeway has been granted to tasks to allow for extra time spent on learning and development
Unexpected levels of complexity	Only when projects are begun do certain challenges arise - the project may become far more complex and disorganised than originally planned	Medium	Low	As well as planning effectively, this author can ensure that they are diligent when it comes to researching the technologies they use - this means that they are able to develop the project effectively

3.2 Product Risks

These risks pose threats to the quality, or performance of the prototype.

Table 2: Product Risks

Risk	Impact	Likelihood rating	Impact rating	Preventative actions
Insufficient prototype testing	The product does not meet functional and non-functional requirements	Medium	High	Specify a framework for testing as soon as possible in the development process, automate testing where possible using a CI pipeline
AWS instability	In the event of the cloud hosting and processing services going down, the product's service will be unavailable	Low	High	Make use of different availability zones within AWS so that in the event of failure in a single area, the project can be spun up again elsewhere
Code issues	If the project contains code that lacks quality, then bugs and unstable performance may cause the product to fail	Medium	High	Conform to best-practice coding standards, frequently test code in regression and unit tests, ensure any bugs are promptly patched
Insufficient research	When a product is made without properly researching the best methods to do so, that product can be insufficient in comparison to competition in a business environment	Low	Medium	Ensure that enough time is scheduled to experimenting with different technology and researching pertinent literature before proceeding with development
Poor design	If the product has been badly designed then it will not meet the desired level of quality and user requirements - the product may even fail to work at all	Medium	Medium	Ensure that sufficient time has been given to the planning stage - in the event that unforeseen problems come to light ensure that help is sought to resolve the design issue and rebuild if necessary.

Poor project management	If the project is managed poorly then the product may not be built to a satisfactory level - delays and lack of proper oversight can cause a drop in the quality of the delivered product	Low	Medium	Ensure that the project management software is correctly set up - use alerts for deadlines and make an effort to work on the project often
Unrealistic project goals	If the targeted MVP is not of appropriate scope then the product might not get finished in time for the project deadline in the event that there is too much work to do	Low	High	Work in an agile and iterative fashion - start small on tasks and gradually build up complexity
Insufficient resources	If the project does not get the compute power or cloud resources it needs then the product's performance will be lacking or it may not function at all	Low	Medium	Have a clear outline as to what resources are needed and allow enough time to get the requisite permission from the company's AWS administrators

3.3 Business Risks

Since this project is being undertaken as a part of a degree apprenticeship, there will be associated business risks:

Table 3: Business Risks

Risk	Impact	Likelihood rating	Impact rating	Preventative actions
Unauthorised use of proprietary materials	Business-critical materials are leaked and cost SIE competitive advantage	Low	Critical	Never use any material developed by SIE as a part of business activity, use only open-source libraries
Large AWS fees	The project causes cloud fees charged to SIE to spiral out of control, costing the company far more than budgeted for	Medium	Medium	Make proper use of the AWS cost centre, define a budget, and set limits and alerts for budget usage in the AWS console

Cyber-security attack	In the event that the cloud app has a security vulnerability, the rest of the SIE tech stack may be at risk of being compromised	High	High	Utilise domain allow-listing, parameterization of user credentials, and routinely check the vulnerabilities of external dependencies - additionally, develop a breach response plan
Data mis-handling	In the event that the product stores user data that it does not have permission to, then the company may be liable for severe penalties under the GDPR ¹⁰	Low	High	Keep stored user data to a minimum - in the case that user data is required, ensure that it is handled and disposed correctly, obtaining permission to do so

¹⁰IT Governance Privacy Team [2019]

4 Project Plan

4.1 Plan Preparation and Communication

To develop an effective plan for the project, the key deliverables for the project¹¹ were analysed and roughly estimated based upon the perceived complexity of producing that deliverable. Each deliverable was given a broad estimate of the time this would take in proportion to that complexity, with more complex tasks, and tasks that were prone to delay, given more breathing room in the time allocated to them. These estimates were then mapped to the overall timescale of the project, and set dates were then applied to the completion of these deliverables in relation to the key milestones of the project, such as submission deadlines. Subsequently, the broader deliverables were then broken down into subtasks and milestones to provide a more granular view of the project plan. Text-based artefacts were given dates by which certain chapters needed to be completed, and development tasks were given dates by which certain parts of the application should be built and deployed by. These subtasks helped to keep track of the project's progress.

This project makes use of the ClickUp¹² software to perform project management functions and to organize this author's workflow. This software has been chosen over other pieces of software in the education¹³ and project management¹⁴ space on the basis of cost and ease-of-use, as well as its ability to synchronize across different platforms. In addition, the platform was also used to communicate the project's progress with the project supervisor who is able to see the project plan and its progress over time through the updating of subtask statuses.

Prioritizing communication with the supervisor was integral to the success of the project because of the accountability and oversight it provided to this author. Having a platform such as ClickUp drastically reduced the likelihood of error in communication and time management. Additionally, a meeting with the project supervisor was scheduled every two weeks in order to identify and remedy issues with the project's execution.

4.2 Timeline

The below series of figures (1, 2, 3) detail the tasks, subtasks, and the planned timeframes for completion. Timeframes were adjusted in accordance with the perceived complexity of each task following enlightenment from the literature review and market research. Dependencies for each task were also calculated and can be seen as arrow representation in the timeline figures.

4.3 Resources

This project intended to use minimal resources in its development. As outlined in 2, one of the many advantages of cloud computing is its flexibility and ease of resource management. Given that the application would be hosted entirely in cloud environments, there would be no hardware costs associated with the project. The costs that do apply will relate to the use of the AWS platform. These costs needed careful management, as explained in 3.3.

Other resources utilized included:

¹¹As outlined in 1.4

¹²[ATD Staff, 2022]

¹³[Badaru and Adu, 2022]

¹⁴[Phipps, 2022]

1. Queen Mary library resources
2. The project supervisor
3. Knowledge sharing from colleagues at [SIE](#)
4. JetBrains' [Integrated Development Environment \(IDE\)](#) Suite
5. Open-source audio-processing libraries.
6. Online articles and tutorials

4.4 Methodology

[Murray \[2016\]](#) notes that the “traditional” manner of software development follows a linear path from requirements, to design, to execution, to testing, and so on. This method often results in inflexibility when it comes to software project execution. This is because of its dependence on the full set of requirements being gathered before the development process begins. Any issues with the requirements (incompleteness, inaccuracy) using this method are typically only found at the end of the process, instead of along the way through a cycle of development and feedback¹⁵. This project is of relatively small scope, and the number of shareholders are small on account of its proof-of-concept status. As such, it serves to incorporate some, but not all, aspects of the ‘Agile’¹⁶ development methodology into the process:

An Agile project starts with only the most high-level requirements. Sometimes these are referred to as “user stories.” Such a requirement might sound like, “A user will be able to buy a subscription to our product on a new e-commerce website.” There are no designs, no specifications.¹⁷

While this project will not go so far as to remove the need for a design or specification altogether, the foundation for the project’s execution will rest on high-level user stories and identified functional requirements. In addition, the project will require frequent testing as development progresses. The intention, therefore, is to endeavour to implement a [Continuous Integration/Continuous Deployment \(CI/CD\)](#) pipeline to ensure any updates to the prototype can be tested and deployed in an online environment as it is being developed.

¹⁵[\[Murray, 2016\]](#)

¹⁶[\[Beck et al., 2001\]](#)

¹⁷[\[Murray, 2016\]](#)

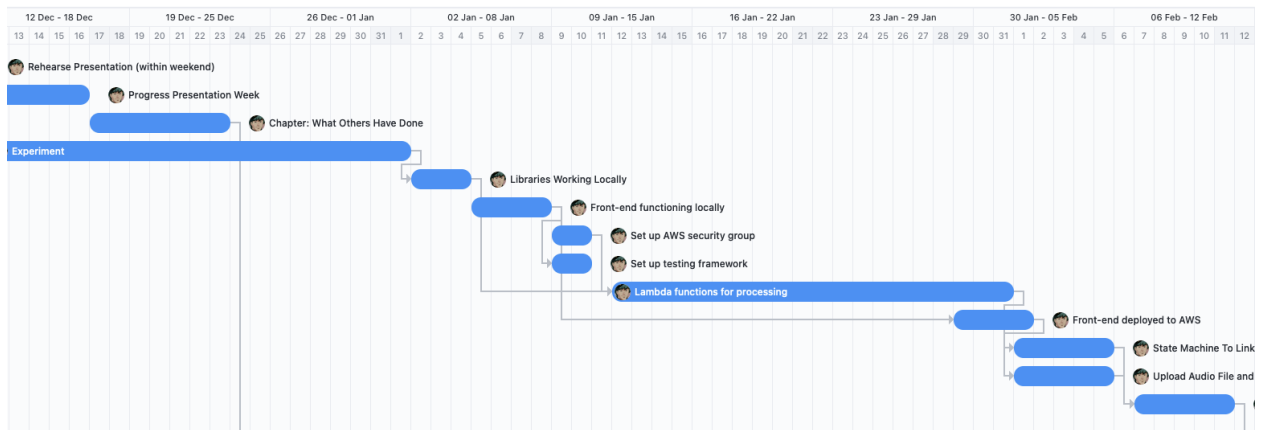


Figure 1: Timeline: *Dec 12th* \rightarrow *Feb 12th*

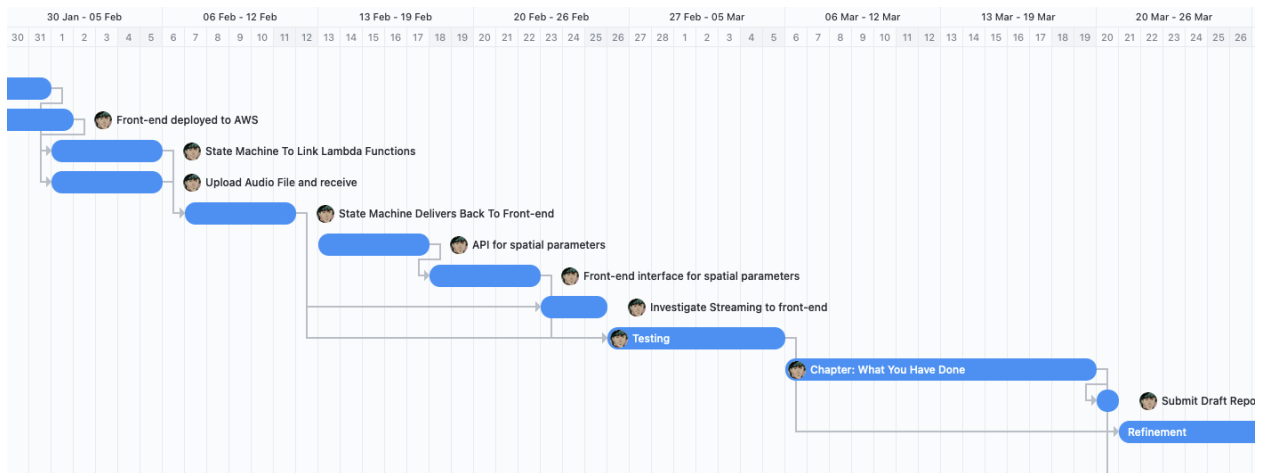


Figure 2: Timeline: *Jan 30th* \rightarrow *Mar 26th*

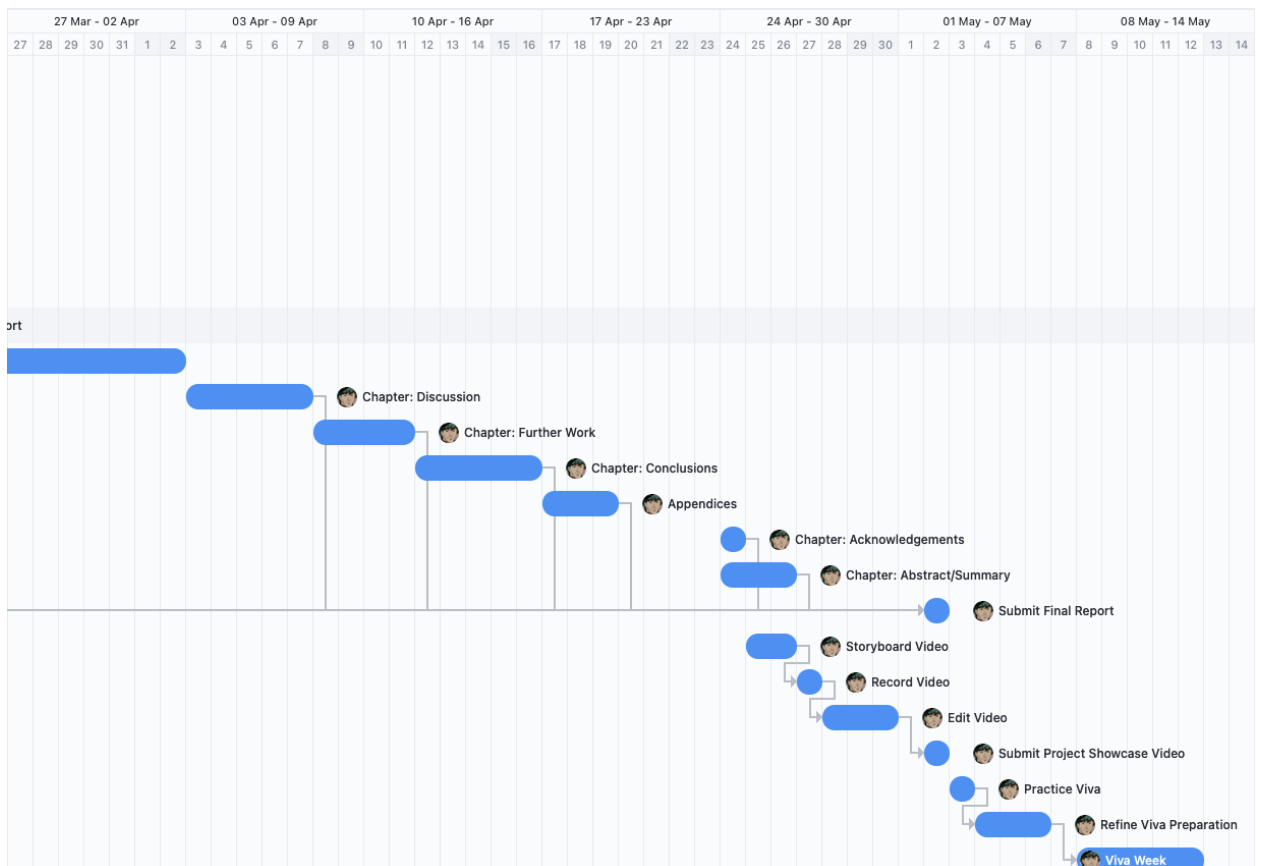


Figure 3: Timeline: *Mar 27th* \rightarrow *May 14th*

5 Requirement Capture and Analysis

As discussed in

6 Infrastructure Design

Observe that 4 details the initial design for the project’s cloud architecture. The diagram provides a high-level overview of the primary user journey, and the AWS products that were intended to meet the user requirements. However, this design was subject to change as development progressed, in accordance with the Agile methodology. This section aims to describe how the initial design changed to accommodate the changing requirements of the project.

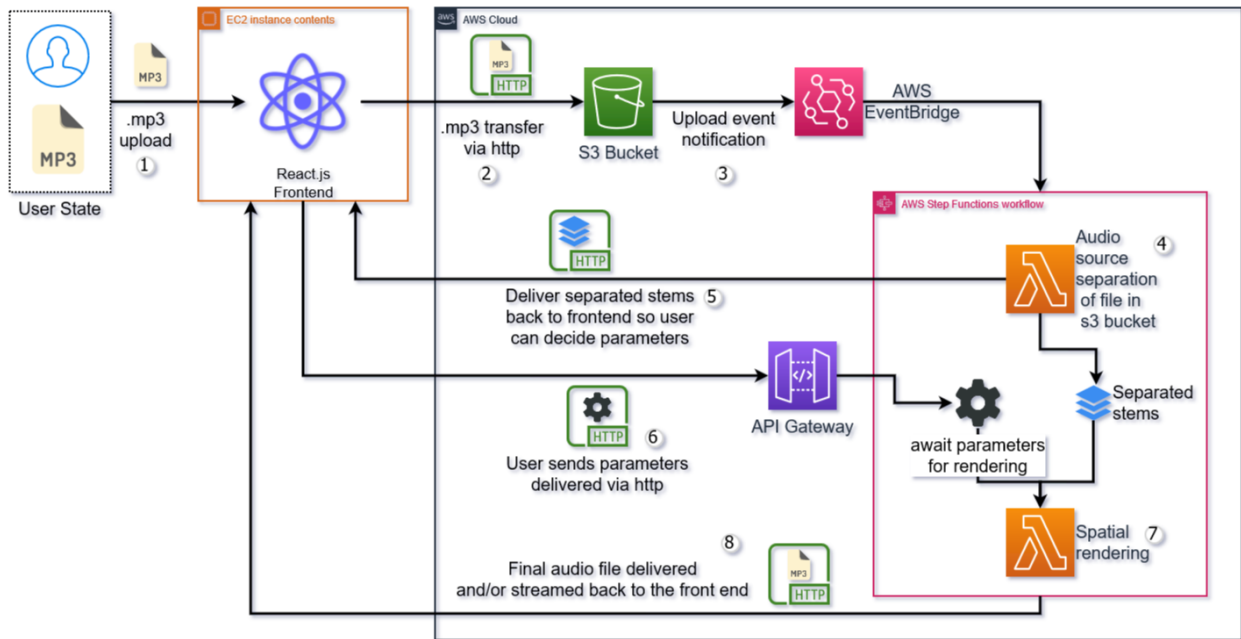


Figure 4: Preliminary Design for Cloud Architecture

6.1 Best Laid Plans

Given that the product is designed for use by users without an extensive knowledge of **spatial audio**, a web-hosted user interface was essential to the product. The user’s primary mode of interaction with the service would be through a website built using the **React.js** front-end library. This library was chosen because of its ubiquity in modern web engineering; the depth of documentation available, and this author’s existing familiarity with the framework.

The front-end was designed to make use of the **AWS Software Development Kit (SDK)** for **Node.js**. This would allow the interface to initiate and interact with the audio processing pipeline hosted in **AWS**.

It is also possible to see that figure 4 displays the two **AWS Lambda** functions that would comprise the backbone of the audio processing pipeline. Furthermore, these **AWS Lambda** functions would be coordinated and executed using the **AWS Step Function** service. This service was highly desired for this purpose since the processing pipeline would follow a series of discrete steps that require input from the user. **AWS Step Functions** would be able to accommodate this easily.

The entire service was also initially intended to be coordinated solely through the use of the internal messaging service: **AWS Eventbridge**. This service, in conjunction with **AWS API Gateway**, was intended to form the most of the communication between the back and front ends of the application.

6.2 Refinement

As development progressed; it quickly became apparent that there were a number of issues with the initial design.

The first problems arose with the development of the [AWS Lambda](#) functions that would be used to process the audio. [AWS Lambda](#) functions require a deployment package to be created and then uploaded to [AWS](#) in order for the function to have the resources it needs to run. Unbeknownst to this author, there is a limit of 50 MB on the size of the deployment packages that could be uploaded directly to [AWS Lambda](#). Given that the 3D Tune-In Toolkit and the Spleeter source separation libraries have significant dependencies that are more than 50 MB when zipped, a re-design needed to occur.

The issue was solved by making use of the [AWS Elastic Container Registry](#) service. This service allows a developer to host and deploy [container images](#), crucially, with a size limit of 75 GB allowed for each image uploaded to the registry. Through the use of [Docker](#) container images, the code for the Lambda functions were bundled into deployment packages that could be uploaded to a [AWS Elastic Container Registry](#) and then linked to a Lambda function while staying well under the limit offered by the container registry. The dockerfiles for the source separation and spatialisation lambda functions can be found in [A.1](#). Note the installation of the AWS Lambda runtime environment for both Python in [Listing 1](#) and C++ in [Listing 2](#).

A Appendix: Code Snippets

A.1 Lambda Function Dockerfiles

```
1  # Define global args
2  ARG FUNCTION_DIR="/function"
3  ARG BASE=python:3.9
4
5  # Pull base python image
6  FROM ${BASE} as build-image
7
8  # Install dependencies needed for lambda runtime API
9  RUN apt-get update && \
10     apt-get install -y \
11     g++ \
12     make \
13     cmake \
14     unzip \
15     libcurl4-openssl-dev
16
17  # Declare args for build
18
19  ARG SPLEETER_VERSION=2.3.2
20  ENV MODEL_PATH app/pretrained_models
21  ARG FUNCTION_DIR
22  RUN mkdir -p ${FUNCTION_DIR}
23
24  # Install pip dependencies from requirements file
25  COPY requirements.txt .
26  RUN pip install \
27     --target ${FUNCTION_DIR} \
28     -r requirements.txt
29
30  # Copy app files
31  COPY app/ ${FUNCTION_DIR}
32
33  # Pull clean image for second stage
34  FROM ${BASE}
35
36  # Install dependencies needed for Spleeter
37  RUN apt-get update && \
38     apt-get install -y \
39     ffmpeg \
40     libsndfile1
41
42  # Copy output from 1st build image into working directory
43  ARG FUNCTION_DIR
44  WORKDIR ${FUNCTION_DIR}
45  COPY --from=build-image ${FUNCTION_DIR} ${FUNCTION_DIR}
```

```

46
47 #Declare entry points for the function and the lambda handler command
48 ENTRYPOINT [ "/usr/local/bin/python", "-m", "awslambdarc" ]
49 CMD [ "app.handler" ]

```

Listing 1: Dockerfile for source separation Lambda function that is hosted in the [AWS Elastic Container Registry](#)

```

1  # Pull latest amazon linux image
2  FROM amazonlinux:latest
3  RUN yum update -y
4  RUN yum install -y yum-utils
5
6  # Install required tools
7  RUN yum -y groupinstall "Development tools"
8  RUN yum install -y gcc-c++ zlib-devel cmake3
9
10 # Specify compilers
11 ENV CC=gcc CXX=g++
12
13 # Install required tools
14 RUN yum clean -y metadata
15 RUN yum install -y libcurl-devel
16 RUN yum install -y openssl-devel
17 RUN yum install -y pulseaudio-libs-devel
18 RUN pip3 install awscli
19
20 # Fetch and install AWS Lambda Runtime for C++
21 RUN git clone https://github.com/aws-labs/aws-lambda-cpp-runtime.git && \
22     cd aws-lambda-cpp-runtime && mkdir build && cd build && \
23     cmake3 .. -DCMAKE_BUILD_TYPE=Release \
24     -DBUILD_SHARED_LIBS=OFF \
25     -DCMAKE_INSTALL_PREFIX=/usr \
26     && make -j8 && make install
27
28 # Fetch and install AWS C++ SDK (S3 and transfer libraries only)
29 RUN git clone https://github.com/aws/aws-sdk-cpp.git --recursive aws-sdk-cpp && \
30     cd aws-sdk-cpp && mkdir build && cd build && \
31     cmake3 .. -DBUILD_ONLY="s3;transfer" \
32     -DBUILD_SHARED_LIBS=OFF \
33     -DENABLE_UNITY_BUILD=ON \
34     -DCMAKE_BUILD_TYPE=Release \
35     -DCMAKE_INSTALL_PREFIX=/usr/local \
36     && make -j8 && make install
37
38 # Fetch 3DTI toolkit and dependencies
39 RUN git clone https://github.com/3DTune-In/3dti_AudioToolkit.git 3dti_AudioToolkit && \
40     cd 3dti_AudioToolkit/3dti_ResourceManager/third_party_libraries/ && \

```

```

41     git clone https://github.com/USCIBLab/cereal.git cereal && \
42     rm -rf sofacoustics && \
43     git clone https://github.com/sofacoustics/API_Cpp.git sofacoustics && \
44     rm sofacoustics/libsofa/lib/libsofa.a
45
46     # Build 3DTI toolkit
47     RUN cd
48     ↪ 3dti_AudioToolkit/3dti_ResourceManager/third_party_libraries/sofacoustics/libsofa/build/linux
49     ↪ && \
50     make CONFIG=Release
51
52     # Fetch and install C++ logger
53     RUN git clone https://github.com/gabime/spdlog.git && \
54     cd spdlog && mkdir build && cd build && \
55     cmake3 .. && make -j && make install
56
57     # Copy program source files
58     RUN mkdir -p src
59     ADD src ./src/
60     ADD utils ./src/
61     COPY CMakeLists.txt ./src/
62     COPY config .aws/
63
64     # Build source files
65     RUN mkdir build && cd build && \
66     cmake3 ../src -DCMAKE_BUILD_TYPE=Release \
67     -DBUILD_SHARED_LIBS=OFF \
68     -DCMAKE_INSTALL_PREFIX=/usr
69
70     #Build AWS deployment package
71     RUN cd build && make && make aws-lambda-package-spatialisation
72
73     # Unzip deployment package
74     RUN cd build && unzip spatialisation.zip -d unpacked
75
76     # Point to compiled function
77     ENTRYPOINT ["/build/unpacked/bin/spatialisation"]
78
79     # Uncomment line below for Docker Image Debugging
80     #CMD ["/usr/sbin/init"]

```

Listing 2: Dockerfile for spatialisation Lambda function that is hosted in the [AWS Elastic Container Registry](#)

References

Robert Alexander. *The Inventor of Stereo: The life and works of Alan Dower Blumlein*. Routledge, 1 edition, 1999. 8

- Alphabet Inc. Google cloud overview, 11 2022. URL <https://cloud.google.com/docs/overview>. 7
- Amazon. Aws cloud essentials, 2022. URL <https://aws.amazon.com/getting-started/cloud-essentials/?pg=gs>. 7
- Cal Armstrong, Lewis Thresh, Damian Murphy, and Gavin Kearney. A perceptual evaluation of individual and non-individual hrtfs: A case study of the sadie ii database. *Applied Sciences*, 8(11), 2018. ISSN 2076-3417. doi: 10.3390/app8112029. URL <https://www.mdpi.com/2076-3417/8/11/2029>. 9
- ATD Staff. Clickup. *TD: Talent Development*, 76(6):9, 2022. ISSN 23740663. URL <http://ezproxy.library.qmul.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edo&AN=157202341&site=eds-live>. 15
- Kazeem Ajasa Badaru and Emmanuel O. Adu. Platformisation of education: An analysis of south african universities’ learning management systems. *Research in Social Sciences & Technology (RESSAT)*, 7(2):66 – 86, 2022. ISSN 24686891. URL <http://ezproxy.library.qmul.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=159642901&site=eds-live>. 15
- Kent Beck, Mike Beedle, Arie van Bennekum, Alistair Cockburn, Ward Cunningham, Martin Fowler, James Grenning, Jim Highsmith, Andrew Hunt, Ron Jeffries, Jon Kern, Brian Marick, Robert C. Martin, Steve Mellor, Ken Schwaber, Jeff Sutherland, and Dave Thomas. Manifesto for agile software development, 2001. URL <http://www.agilemanifesto.org/>. 16
- A. Berkhout, Diemer Vries, and P VOGEL. Acoustic control by wave field synthesis. *J.Acoust.Soc.Am.*, 93:2764–2778, May 1993. doi: 10.1121/1.405852. 8
- Robert T. Beyer and Daniel R. Raichel. Sounds of our times, two hundred years of acoustics. *The Journal of the Acoustical Society of America*, 106(1):15 – 16, 1999. ISSN 00014966. URL <http://ezproxy.library.qmul.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edo&AN=ejs48802680&site=eds-live>. 8
- Jens Blauert. *Spatial Hearing: The Psychophysics of Human Sound Localization*. The MIT Press, 10 1996. ISBN 9780262268684. doi: 10.7551/mitpress/6391.001.0001. URL <https://doi.org/10.7551/mitpress/6391.001.0001>. 7, 8, 9
- A.D. Blumlein. British patent specification 394325. *Journal of the Audio Engineering Society*, 6(2):91, April 1958. 7, 8
- A.J. Bottomley. *Sound Streams: A Cultural History of Radio-Internet Convergence*. University of Michigan Press, 2020. ISBN 9780472054497. URL <https://books.google.co.uk/books?id=f9fkDwAAQBAJ>. 9
- N. Brügger and I. Milligan. *The SAGE Handbook of Web History*. SAGE Publications, 2018. ISBN 9781526455444. URL <https://books.google.co.uk/books?id=kwJ6DwAAQBAJ>. 9
- Mark Cerny. The road to ps5, March 2020. URL <https://www.youtube.com/watch?v=ph8LyNIT9sg&t=2304s>. 9

- María Cuevas-Rodríguez, Lorenzo Picinali, Daniel González-Toledo, Carlos Garre, Ernesto de la Rubia-Cuestas, Luis Molina-Tanco, and Arcadio Reyes-Lecuona. 3d tune-in toolkit: An open-source library for real-time binaural spatialisation. *PLoS ONE*, 14(3), March 2019. doi: [doi:10.1371/journal.pone.0211899](https://doi.org/10.1371/journal.pone.0211899). URL <https://doi.org/10.1371/journal.pone.0211899>. 9
- Tharam Dillon, Chen Wu, and Elizabeth Chang. Cloud computing: Issues and challenges. In *2010 24th IEEE International Conference on Advanced Information Networking and Applications*, pages 27–33, 2010. doi: 10.1109/AINA.2010.187. 7
- Boni García, Micael Gallego, Francisco Gortázar, and Antonia Bertolino. Understanding and estimating quality of experience in webRTC applications. *Computing*, 101(11):1585–1607, 2019. ISSN 1436-5057. doi: 10.1007/s00607-018-0669-7. URL <https://doi.org/10.1007/s00607-018-0669-7>. 9
- Michael A Gerzon. Periphony: With-height sound reproduction. *Journal of the audio engineering society*, 21(1):2–10, 1973. URL <http://www.aes.org/e-lib/browse.cfm?elib=2012>. 8
- Maksim Goman. How to improve risk management in it frameworks. In *2021 62nd International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS)*, pages 1–6, 2021. doi: 10.1109/ITMS52826.2021.9615327. 10
- Marcin Gorzel, Andrew Allen, Ian Kelly, Julius Kammerl, Alper Gungormusler, Hengchin Yeh, and Francis Boland. Efficient encoding and decoding of binaural sound with resonance audio. In *Audio Engineering Society Conference: 2019 AES International Conference on Immersive and Interactive Audio*, Mar 2019. URL <http://www.aes.org/e-lib/browse.cfm?elib=20446>. 9
- Akio Honda, Hiroshi Shibata, Jiro Gyoba, Kouji Saitou, Yukio Iwaya, and Yôiti Suzuki. Transfer effects on sound localization performances from playing a virtual three-dimensional auditory game. *Applied Acoustics*, 68(8):885–896, 2007. ISSN 0003-682X. doi: <https://doi.org/10.1016/j.apacoust.2006.08.007>. URL <https://www.sciencedirect.com/science/article/pii/S0003682X06001824>. Head- Related Transfer Function and its Applications. 9
- Jooyoung Hong, Jianjun He, Bhan Lam, Rishabh Gupta, and Woon-Seng Gan. Spatial audio for soundscape design: Recording and reproduction. *Applied Sciences*, 7:627, 06 2017. doi: 10.3390/app7060627. 9
- IT Governance Privacy Team. *Powers of Supervisory Authorities*. IT Governance Publishing, 2019. ISBN 9781787781924. URL <https://app.knovel.com/hotlink/khtml/id:kt012G0L03/eu-general-data-protection/powers-supervisory-authorities>. 14
- Microsoft. Azure application architecture fundamentals, 08 2022. URL <https://learn.microsoft.com/en-us/azure/architecture/guide/>. 7
- C. Minnick. *Beginning ReactJS Foundations Building User Interfaces with ReactJS: An Approachable Guide*. Wiley, 2022. ISBN 9781119685586. URL <https://books.google.co.uk/books?id=J89cEAAAQBAJ>. 9
- Valerio Morucci. Reconsidering "cori spezzati": A new source from central italy. *Acta Musicologica*, 85(1):21–41, 2013. ISSN 00016241. URL <http://www.jstor.org/stable/24595484>. 8

- Mozilla. Web audio api, 05 2019. URL https://developer.mozilla.org/en-US/docs/Web/API/Web_Audio_API. 9
- Anna P. Murray. *The Complete Software Project Manager: Maturing Technology from Planning to Launch and Beyond*. John Wiley & Sons, Incorporated, 2016. URL <https://ebookcentral.proquest.com/lib/qmul-ebooks/detail.action?docID=4383484>. 16
- Markus Noisternig, Alois Sontacchi, Thomas Musil, and Robert Höldrich. A 3d ambisonic based binaural sound reproduction system. *Advances in Engineering Software*, January 2012. 8
- Stephan Paul. Binaural recording technology: A historical review and possible future developments. *Acta Acustica united with Acustica*, 95:767–788, 09 2009. doi: 10.3813/AAA.918208. 8
- Johan Pauwels. pywebaudioplayer: Bridging the gap between audio processing code in python and attractive visualisations based on web technology. In *4th Web Audio Conference (WAC)*, October 2018. URL <https://qmro.qmul.ac.uk/xmlui/handle/123456789/60834>. 9
- Jenna Phipps. Asana vs clickup: Compare project management software. *CIO Insight*, page N.PAG, 2022. ISSN 15350096. URL <http://ezproxy.library.qmul.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=157666126&site=eds-live>. 15
- Archontis Politis, Symeon Delikaris-Manias, and Ville Pulkki. *Overview of Time–Frequency Domain Parametric Spatial Audio Techniques*. John Wiley & Sons, Ltd, 2017. ISBN 9781119252634. doi: <https://doi.org/10.1002/9781119252634.ch4>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119252634.ch4>. 8
- Project Management Institute. *A guide to the Project Management Body of Knowledge (PMBOK guide) and the standard for Project Management*. Project Management Institute, 2021. 10
- Ling Qian, Zhiguo Luo, Yujian Du, and Leitao Guo. Cloud computing: An overview. In Martin Gilje Jaatun, Gansen Zhao, and Chunming Rong, editors, *Cloud Computing*, pages 626–631, Berlin, Heidelberg, 2009. Springer Berlin Heidelberg. ISBN 978-3-642-10665-1. 4, 7
- A. Roginska and P. Geluso. *Immersive Sound: The Art and Science of Binaural and Multi-Channel Audio*. Audio Engineering Society Presents. Taylor & Francis, 2017. ISBN 9781317480105. URL <https://books.google.co.uk/books?id=elk6DwAAQBAJ>. 8, 9
- Rishi Shukla, Rebecca Stewart, Agnieszka Roginska, and Mark Sandler. User selection of optimal hrtf sets via holistic comparative evaluation. In *Audio Engineering Society Conference: 2018 AES International Conference on Audio for Virtual and Augmented Reality*, Aug 2018. URL <http://www.aes.org/e-lib/browse.cfm?elib=19677>. 9
- Y. Suzuki, D. Brungart, K. Iida, D.A. Cabrera, Y. Iwaya, and H. Kato. *Principles And Applications Of Spatial Hearing*. World Scientific Publishing Company, 2011. ISBN 9789814465410. URL <https://books.google.co.uk/books?id=N7rFCgAAQBAJ>. 8, 9
- W3C. Web audio api, 06 2021. URL <https://www.w3.org/TR/webaudio/>. 9

- Nicholas J. Wade and Hiroshi Ono. From dichoptic to dichotic: Historical contrasts between binocular vision and binaural hearing. *Perception*, 34(6):645 – 668, 2005. ISSN 0301-0066. URL <http://ezproxy.library.qmul.ac.uk/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=psyh&AN=2005-09528-002&site=eds-live>. 7
- B. Xie, R.P.I. Dr. Ning Xiang, and J. Blauert. *Head-Related Transfer Function and Virtual Auditory Display: Second Edition*. A Title in J. Ross Publishing’s Acoustics: Information and Communication Series. J. Ross Publishing, 2013. ISBN 9781604270709. URL <https://books.google.co.uk/books?id=fvDLCgAAQBAJ>. 9
- G. Zhai, J. Zhou, H. Yang, P. An, and X. Yang. *Digital TV and Wireless Multimedia Communications: 18th International Forum, IFTC 2021, Shanghai, China, December 3–4, 2021, Revised Selected Papers*. Communications in Computer and Information Science. Springer Singapore, 2022. ISBN 9789811922664. URL <https://books.google.co.uk/books?id=fm1rEAAAQBAJ>. 9
- Alp Ünver, Bitu Kheibari, and Müge Sayit. A webRTC architecture assisted by software defined networks. In *2020 28th Signal Processing and Communications Applications Conference (SIU)*, pages 1–4, 2020. doi: 10.1109/SIU49456.2020.9302042. 9