**Music-Synced Smart Lighting System**

A dissertation submitted in

partial fulfilment of  
The requirement for the degree of  
**MASTER OF SCIENCE**

in

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By

**Ryan Urquhart**

**40099112  
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* aiXander – On GitHub, created a repo that I adapted, it provided fast Fourier transformations that I built the beat detection algorithm on top of.

Abstract:

This report covers the development of a Music-Synced Smart Light System. The development of this system was successful, however, due to time constraints the system is missing many aspects that would be desirable should the project be continued on. This is aided by the style of development of the system, the system has been developed in such a manner as to allow easy continued development. The system takes advantage of FFT of audio data from PyAudio to allow the system to detect the beat of music and change bulb brightness in time with that beat.

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## Introduction:

This report is focusing on the development of a Music-Synced Light Control System (hereafter referred to as, Bulb Bop). The report will consist of six chapters, Chapter One, Understanding the Problem, Chapter Two, User interface-design, Chapter Three, Architecture design and algorithm explanation, Chapter Four, Experimentation, Chapter Five, Testing, Chapter Six, Evaluation and Conclusion. The content of these chapters will be explained in the rest of the introduction.

Chapter One will contain my exploration of the problem and the basis on which I started undertaking the development of the software system. This will include my initial understanding of the project, based on the title and the preliminary meetings with my supervisor. It will then progress into my initial investigations about the potential solutions to the problem at hand. Finally, this chapter will end with the decided upon plan of action for development.

Chapter Two will contain the plan and the development of the user-interface. This will include the early iterations of the user-interface, and how these early iterations influenced the final design. It should be noted however, that the bulk of the work in this project was the beat detection algorithm and therefore, there was less thought put into the user-interface than there was into the back end of the system.

Chapter Three will contain the plan and the development of the architecture and algorithm design. This section will explain the architecture upon which the system can be ran, and the algorithms that allow it to run. This is the chapter in which the bulk of the work of this project will be explained.

Chapter Four will contain the experimentation that I have conducted due to this project. This will include looking at different languages that I attempted to utilise, as well as the research and experimentation that went into the development of the beat detection algorithm. Various iterations and experiments will be present in this chapter.

Chapter Five will contain the testing carried out on the project, during its development, and before the submission of the project. This will include risk assessments of the project, and a discussion of the rationale of the tests that were designed, as well as an examination of the areas of the project that were not thoroughly tested and an explanation as to why.

Chapter Six will be the final evaluation and conclusion of the project. Discussing the success or failure of the development of the system. It will evaluate different technologies utilised and how they have impacted the final system shape. There will be a reflection on my own development of the project, highlighting areas that were handled well, and areas where there could have been further development.

# Understanding the Problem

The initial description of the project is as follows,

“Develop a system that integrates music with dynamic lighting displays to create an "instant smart disco light" function or a “smart lighting solution for improved well-being.” The system should control a Wi-Fi-enabled smart light bulb, adjusting its brightness and colour in sync with music rhythms, enhancing the atmosphere in any setting.”

As well as this, there were four main functional criteria for the development of the system.

1. The system should connect to and control a Wi-Fi enabled smart light bulb
2. The system should detect music rhythm and tempo from an audio source and synchronise the light settings accordingly
3. The system should provide a primary control interface
4. The system should offer multiple lighting modes

There was no restriction placed on the technologies to be utilised in this project. No specific bulbs, programming languages, or web frameworks. However, due to having to use third-party hardware (The smart bulbs) there may be a specific API dictated by the manufacturer that would have to be used.

The initial prompt has no definition of the user the application is supposed to be designed for. However, during meetings with my supervisor the intended user was defined in a varied way. From families, to DJ’s, to people hosting a party. The decided goal was that the user would be someone hosting a party in their house, this user would be either using a microphone attached to the computer running the system, or the computer running the system would be playing the music from its speakers.

From the initial description of the project, research was carried out, this research covered two main areas. The first was the bulb, which brand would be appropriate for the project. The second was the programming language, this programming language had to fulfil two criteria, it needed access to the audio from the operating system I was developing on (Windows and Linux), it also needed to be able to host a web server which would provide the user interface.

The research into the bulbs brought up many different options for use, Wiz, TP-Link Kasa, TP-Link Tapo, YeeLight, Shelly, Philips Hue, Athom.tech, and switchbot. From all of these bulbs I decided to use Wiz bulbs. The reasons for this were the cost, the open API (*bulbs like TP-Link Tapo have closed API’s so users must use their app*), the app does not require a hub to operate (*Philips Hue does*), and from my reading of various forums wiz was highly recommended as a bulb brand. Based on this research I purchased a WizBulb A60.E27 bulb.

The research into the programming language to use initially started with Java, the reason for this simply being that much of the CSC7063 Computer Programming course has been taught in Java. Two libraries I looked at were TarsosDSP(Six, 2011/2025), and Jipes by Tagtraum(Schreiber, 2013/2024), both of which I was unable to gain access to audio data from the host machine using. Jipes was unsuited as it was not made for real-time processing of audio information. With regards to TarsosDSP, it used Gradle to build it, this was something that, given the time I needed to get the project started in, I was unable to figure out in time.

As such, I looked for another programming language that would allow me access to this host audio data. For this I turned to python, there is a python package names, PyAudio, and it reliably and easily allows developers access to the host machine audio data. The issue however, is that PyAudio does not allow access to the loopback api present on windows machines that allows the developer access to real-time speaker audio data. This was solved when I found a windows specific patch of the PyAudio library, called PyAudioWPatch. This allows PyAudio the ability to access the loopback api, this with the Django library that is able to serve web apps with a great deal of flexibility made python the perfect choice.

# User Interface Design

A black and white image of a person standing in front of a white sky

AI-generated content may be incorrect.A screenshot of a computer

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Figure 2 - Index Page (Mobile View)

Figure 1 - Index Page (PC View)

The user interface for this system is quite simple. There are a total of four different views that the user can access. Each of these views are dynamic to varying degrees, Django gives the option to develop html that will dynamically change based on a context provided by the developer. For instance, the bulbs on the index page render depending on if they are present in the database or not.

The first part of the user interface that we will discuss are the parts common to all views. The main part of this is the navbar, this contains the title, links to other views, buttons to activate functions of the system, and a light/dark mode toggle button. There is also a footer on the page, a line that contains the text, ‘2023-25 : Bulb Bop : Ryan Urquhart : 40099112’. Part of these aspects are dynamic, the audio sync option for instance, only shows when bulbs are recorded in the database.

The second view we are going to look at is the home page, the index page (figure 1 and 2), this is the main page that the user will be engaging with. This page displays icons for the bulbs that are recorded in the database, their names, as well as graphically displaying their state. There are tooltips that appear when the user hovers their mouse over the bulbs, this informs the user that should they click on the it will toggle the state of the bulb. Should the user not yet have connected the system with any bulbs then the index page will display a prompt to the user to use the discover function of the system (figure 3).

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Figure 3 - User prompt when bulbs aren't saved

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Figure 4 - FAQ Page (PC View)

The third aspect of the user interface we will discuss is the ‘FAQ’ (frequently asked questions) page (figure 4). This page covers some basic setup questions that a user may have, from connecting lights to troubleshooting, and a contact email for support (not a real email). This page is referenced in the tooltip to help new users get started with the application. It also links to the WizBulb app, to show users how to connect their bulbs to the local network (unfortunately using the system to connect the bulbs to the local network was impossible as it requires Bluetooth and is undocumented).

The fourth page of the system to discuss is the ‘About’ page. This is a simple page that just displays information about the project, it’s goals, and some information about the author if the project. Like every other page, this page has the navigation bar which allows the user, should they have bulbs saved in the database, to activate the audio sync. As this page is mostly static, apart from the navigation bar, there is nothing else to say about it.

The final page to discuss in this section is the ‘Edit’ page, for the bulbs. This page allows the user to edit or delete the bulbs that they have saved in the database. The user can edit the bulbs name and Ip address, but that is all. As when the system has a bulb saved with a name and an Ip address, then it will query the bulb and update its status in the database itself. When the user clicks on edit, it will show a modal that the user can interact with to edit the bulb. When the user clicks on save edit, or delete, the page will display a success or error message in the bottom right corner.



Figure 5 - Edit page (PC view)

A green screen with white text

AI-generated content may be incorrect. A red sign with white text

AI-generated content may be incorrect. Figure 6 - Delete Success Message Figure 7 - Edit Error Message

# Architecture Design and Algorithm Explanation

In this section of the report I will be going over the ‘backend’ of the system. This will include a description of the api endpoints, how the system was configured to interface with bulbs on the network, a description of how I gained access to the audio data of the host machine, and finally an explanation of the algorithm to detect beats in music. This section will encompass most of the work done on this project and therefore will be the longest section in this report.

## API Endpoints

This project has 14 different API endpoints, not including requests that get images and JavaScript code. Four of these endpoints are for different views or pages, of the user interface, one is reused for bulb form submission, therefore, these will not be discussed in this section, as the views were mentioned in chapter 2. There are three endpoints for bulb control, four (including the reused view endpoint) for database operations and, two for error and success handling.



Figure 8 - API Endpoints

The endpoints for bulb control are as follows, “/discover/”, “/toggleBulb/”, “/queryBulb/”, and “/colorBulb/”. Of these four, only three are currently utilised in the system, “/colorBulb/” was developed for use, but when testing with a colour changing bulb, and a non-colour changing bulb this endpoint caused issues, so was left for future development, which ultimately ended up being scoped out of the project. “/discover/” is used to discover new bulbs on the network, it sends a broadcast UDP packet, to which bulbs connected to the network respond with their current state. This response is shown to the user, who can give the bulb a name, which is then sent to another endpoint, which will be mentioned later. “/toggleBulb/” is the main endpoint the user will trigger from the user interface, when they click on the icon of a bulb it will trigger this endpoint, which sends a packet to the specific bulb and instructs it to turn off, or on, depending on the state of the bulb recorded in the system. “/queryBulb/’ is similar to “/discover/”, except rather than sending a broadcast packet to all Ip addresses, it send packets to specific addresses to query the state of specific bulbs.

The endpoints that control database operations are, “/”, “/delete/<str:ip>/”, and “/edit/<str:ip>”. The “/” endpoint is the index endpoint, when this endpoint is triggered with a GET request, then it renders the home page, when it’s triggered with a POST request, then it submits a Django model form. This Django model form is how the system saves new bulbs in the database. When the form is submitted, it is checked to ensure that it contains no errors. The criteria for this check is that the Ip address is valid, and that the name of the bulb is not null. The other information for the bulb is filled in from the return from the broadcast packet that was sent during discovery. The next two endpoints are accessible to the user through the edit bulbs page, “/delete/<str:ip>/” and “/edit/<str:ip>/” both of these endpoints require the Ip address of the bulb in which they are editing, as a unique identifier. “/delete/<str:ip>/” will delete the bulb with the specified Ip address, and “/edit/<str:ip>/” will submit a form, that is verified, of a new Ip address or name for the bulb, this then updates the model in the database for that bulb.

There are two endpoints that control error and success handling, these clear the error and success messages, both are to prevent error, and success messages being displayed multiple times. These endpoints are never interacted with by the user manually, they are triggered through JavaScript that runs when every page loads. While this does not interfere with a message that is being displayed in the page that has just been loaded, it will prevent a message from being displayed in another page that the user navigates to.

There are two endpoints for controlling the audio synchronisation, “/activateSync/”, and “/stopsync/”. These are self-explanatory, “/activateSync/”, this endpoint accepts a POST request that contains the index number of the audio device selected by the user. This then activates the audio sync in the system for that audio device, the system waits thirty seconds to ensure that the sync program has activated, then it sends a status message to the user interface.

This concludes the endpoints of the API that are activated by the user, or the JavaScript the pages contain. The next step of this chapter is to discuss how communication with the bulbs was achieved by the system, documentation that was followed, and the technologies that were involved in its process.

## Bulb communication

One of the reasons that the Wiz brand of bulbs was chosen for this project was the level of documentation about the bulb (*WiZ Pro API Reference*, n.d.), to augment this, there is also a python package called, ‘pywizlight’ which utilises this documentation to provide communication to wiz devices (Traub, 2020/2025). I did not use this package, and instead primarily relied on the wiz documentation to enable communication to the bulbs.

Utilising the API reference, I have implemented five UDP packets which are used by the system, I have also included two other UDP packets, which are not currently used, but can be implemented in further development. The seven total packets have the following functions, bulb discovery, turn on bulb, turn off bulb, turn to half brightness, turn to full brightness, bulb registration, and turn bulb to colour. Bulb registration and turn bulb to colour are unused by the system, while both were used in the development of the system, it was unfeasible to implement them properly in the time given for the project.

## Host Audio Parsing

The reason that I used Python over Java was that Python had access to the audio of the host machine. Initially I had only used PyAudio and was able to access microphones attached to the host machine, however, I then discovered PyAudioWPatch. PyAudioWPatch takes advantage of Windows Audio Session API (WASAPI) (drewbatgit, 2021), this allows the audio of output devices to be intercepted and parsed by the library. With the discovery of PyAudioWPatch I was then able to allow the system to parse music played from the system and control the lights accordingly, this is a considerable improvement over having to use the system with a microphone which would have picked up all stray noises, making the beat detection a much harder task (using a microphone is still as possible as using a speaker is). On Linux PyAudioWPatch does not work, as WASAPI is a windows only API, however, using PulseAudio on a Linux machine, it is easy to create a loopback of a speaker so that it registers as an input device.

So due to this I had access to the raw audio output of a selected microphone or speaker of the host machine. This however, was unhelpful when it comes to detecting beats, as from PyAudio (or PyAudioWPatch) I am just getting a stream of un-processed data. This un-processed data needed to be sorted into frequencies and amplitudes, necessitating the use of Fast Fourier Transformations. This however, is a complicated process, so to handle this for me, I found a repository on GitHub that would handle this calculation for me, Realtime\_PyAudio\_FFT (*aiXander/Realtime\_PyAudio\_FFT: Realtime Audio Analysis in Python, Using PyAudio and Numpy to Extract and Visualize FFT Features from Streaming Audio.*, n.d.). The repository itself was helpful; however, it was not designed for my needs, this meant that I had to modify it. This meant making it work with PyAudioWPatch, but it had to still work with PyAudio (to allow it to work on Windows and on Linux).

A screenshot of a computer

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Figure 9 - Screenshot of changes made to Realtime\_PyAudio\_FFT (McClean, 2024/2025)

To manage this edit, I changed it so that rather than visualising the audio output the repository would instead just return the stream of frequencies and amplitudes that are being produced by the audio device. I also changed the repository so that it would use the ‘PyAudioWPatch’ library, if possible, but would fallback to ‘PyAudio’ if ‘PyAudioWPatch’ is not available (i.e. on Linux rather than windows). Another change that I made, was the editing of channels and audio rate, this was necessary to allow the use of speakers with the system. This final change was necessary, as speakers often use two channels, for left and right, they also tend to use a higher rate for the audio than microphones do.

With the libraries and changes made above once the user selects an audio device and clicks to start the synchronisation of music, then the system will start a stream of amplitudes and frequencies. This stream is then parsed by the system and using the beat detection algorithm will send UDP packets to the bulb(s) to turn them up, or down, in brightness in time with each other and the music. This beat detection algorithm is what will be discussed in the final section in this chapter.

## Beat Detection Algorithm

Now the system is getting a stream of computed frequencies and amplitudes from the audio device, as the final goal of the project is to have the beat of the music be what influences the control of the bulbs, the audio data will need to be manipulated to detect the beat. From my research this is an extremely difficult task, a lot of beat detection does not happen in real-time, rather it observes an audio file in it’s entirety and detects the beat that way (‘Beat Detection’, 2021). Therefore, I looked at an example of beat detection that is used in real-time (*Beat Detection Algorithm – Parallelcube*, 2018), this example comes with formulas that I was able to adapt to serve the purposes of the system.

When it comes to the system parsing the audio, the start was to figure out the frequencies that needed attention, and which ones could be ignored. I ultimately decided that all frequencies over one hundred and fifty hertz were to be ignored. The higher frequencies contain vocals and other instruments that are not indicative of a beat in the melody. The lower frequencies, however, are where most of the drum set is contained, this is where the beat will be most noticeable, and therefore these are the frequencies that the system will be using in the beat detection. The rest of this section will cover the input of frequencies and amplitudes and how it is manipulated to define a threshold for beat detection.

The above equation is how the system gets the sum of the amplitudes (E) for a particular set of frequencies (i to k+n). This is achieved by calculating the sum of the FFT amplitudes (FFT[i]) where ‘i’ is the frequency. This is done for the range i=k, i.e. the starting frequency of the sum, and k+n, where k+n is the max frequency of the sum. In the system this is done for three ranges of frequencies, where n always equals 50, but i is equal to, 0, 50, and 100. This leaves the system with a sum of amplitudes, from 0hz to 49hz, 50hz to 99hz, 100hz, to 149hz. Every frequency about 150hz is ignored.

This sum of amplitudes is then added to an array, one amplitude for each unit time. The unit of time in this case is dependant on how fast the host machine can compute the amplitudes of the audio data which it is manipulating. This means that an average can be calculated for each array of amplitudes, this is done as below.

This average can then be used to determine the fraction of the average compared to the sum of the amplitudes for that frequency range, this fraction can be considered the variance. The sum of these variances for the length of ‘buffersize’ can then be considered to be ‘F’.

This sum can then be used to calculate the average variance (V), however, to ensure that the average variance is greater than the one (this is needed so that the beat limit is greater than the average frequency range amplitude), when calculating the average variance, if the variance is less than one, then the inverse of the variance is taken.

Now that the average variance (V) has been calculated, this can be used to calculate a threshold value, this is the threshold which if the sum of amplitudes for a frequency is greater than, then it will be considered a beat. The equation to calculate the threshold is as follows.

Upon the detection of a beat by the explained algorithm, the system will then send a UDP packet to all bulbs connected to the system and it will change the brightness of the bulbs appropriately.

# Testing

In this chapter the testing that has been carried out on the system will be discussed. This will cover two main sections, automated testing, and manual testing. Test cases for both will be discussed, their results, future testing that could take place, and weaknesses of the testing procedure will also be discussed.

## Automated Testing

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