

The Development of a Web-based Multidimensional Data Plotter

AC40001 Honours Project

Sameer Al Harbi

ID: 190007048/1

BSc (Hons) Computing Science

Supervisor: Dr. Iain Martin

University of Dundee

Dundee, UK

ABSTRACT

Visualization is a fundamental part of any data analysis project. Yet, market solutions are falling further and further behind in the wake of Big Data pushing the limits of what traditional graphing software can computationally process and effectively communicate to users- Who often need extensive programming experience to use these solutions in the first place. This paper highlights the design and development of a new software application using GPU rendering to address these growing problems of inaccessibility on both fronts- creating an accessible solution that is usable with minimal programming expertise- while still providing the foundations necessary to support further development that can tackle the challenges posed by Big Data.

1 INTRODUCTION

Data visualization is an important step in the data analysis process. Whether used on its own as a tool for analysis, or as a final stop to clearly articulate and display results. It is in spirit a tool for communication, allowing abstract and complex ideas to be easily communicated to a wide audience, usually requiring minimal expertise to understand (Based on the visualization design done). Its ubiquity across all industries is then no surprise [41]. Yet limitations and shortcomings exist, the accessibility of tools to create visualizations are often complex and at odds with the accessibility of the created artifacts. This limits creators by requiring them to have considerable knowledge of programming fundamentals, or be limited by what they are able to create. This is further compounded with 3D+ Multidimensional data visualization, Which has an even smaller selection of accessible tools.

Another challenge, when considering all tools regardless of user accessibility, has been the effect of Big Data on the user requirements of these applications. The ever increasing size and complexity of datasets doesn't invalidate the value provided by visualization to smaller datasets. In fact, Its importance as a communication aid is greater than ever before. Yet, current visualization tools and techniques cannot keep up with this requirement [7]. In a way, this is just another accessibility problem- an inaccessibility of certain data types.

The aim of this project then was try to address the roots of these inaccessibility problems by creating a new market contender application focused with this problem in mind. This consisted of an academic long software development project undertaken by the student- with a resultant Multidimensional Scatterplot application created. This paper aims to highlight the decisions made in design

and development while also recording the entire process followed by a look back on if the project was successful.

2 BACKGROUND

The result of background research done for this project can be subdivided into two distinct sections being 'Related Work' and 'Tools and Technologies'. This was one of the earliest phases of the project whose results motivated the specific goals of this project- beyond just creating a Multidimensional plotting application as is required by the honours assessment that this project falls under, and explore what opportunities (in terms of tooling) exist to develop them.

2.1 Related Work

This section highlights the wider context that affected the structure and what the application was planned to do. The research identified here acted to directly influence what kind of application was developed, for what exact purpose and for what users.

2.1.1 Project Context. One of the first steps for this project was to place and understand the needs of this project through the lens of some wider context. By what metric should potential requirements be prioritised? and what those requirements should even be? Those are some of the questions whose answers will depend on the context that they are looked at. After some consideration, it was decided by the student to focus on the current business industry, and its needs as this context.

This context (the business market) sets the aim of this project to then be an application that would be considered a valuable market entry compared to its competitors. It should also preferably, address some specific pain points of the market that are not fully covered by some other solution on the market.

The alternative would also have been to look at this project from a more academic, literature driven view- where a project's success would depend on more research oriented exploratory work. This alternative though, had some drawbacks that ultimately resulted in the selection of a Business Context. Mainly, a focus on existing market solutions allowed a more logical selection of features to develop for a practical development project. Although it should be stressed that this doesn't mean that the academic background for this project was disregarded (See 2.1.3)- It's just that the focus was on the business-based requirements first and foremost.

2.1.2 Market Research. With the context set- It was then considered that an analysis of the current options on the market would be a prudent next step to start understanding what a successful project should incorporate. This analysis was open-ended and focused on identifying key points that differentiated each product apart.

Detailed notes on each competitor can be found in the Appendix 9.0.1, which are although not exhaustive, nevertheless highlight some important aspect of the overall market- But the main important trends and highlights identified are the following:

Firstly, it was found that most solutions are highly technical and need at least some degree of programming knowledge to use. A rough relationship would be that the complexity of using the solution and its capability is inversely proportional. Feature rich solutions need programming experience while the ones that don't, have more limited features, and are more likely to be not free to use. Obviously, there were outliers such as MATLAB which have both a UI interface and a programming interface, but this relationship still stands.

Another interesting point identified is that The Stack Overflow 2021 Developer Survey [43] shows that a large majority of the most used libraries and frameworks were for data analysis or data-based projects, using specifically Python. Which is also the third most used language identified by the Survey [43]. Although these statistics don't directly relate to visualization solutions, they help form an important background to the context in which visualization may be needed in. Which is that Python and its libraries are a highly prevalent option for undertaking data analysis projects, meaning that any visualization solution is likely to be part of a workflow that contains these tools.

But Solutions focusing on Visualization first and foremost seemed to be much fewer when compared to analysis solutions with visualization features. Those that were, were also much more likely to be highly technical. This point was found particularly important because data analysis and by extension visualization has been found to be needed in a wide field of industries, where programming expertise is not as widely common. And this need is expected to rise in the future with the advent of Industry 4.0- Which is a widely believed idea of increasing business productivity fueled by disruptive emergent technology in the near future [17].

Taking all this into consideration, several key points were identified on how to structure a new development project to create a valuable solution from the market's point of view:

- Focus on accessibility first and foremost, including an easy-to-use interface that does not need programming experience.
- Focus on the visualization aspect, but either ensure that adequate analysis tools are available or importing or exporting data is easy and straight forward. Visualization is often only one step of a multi-step analysis project.

On the other hand, some thing's to avoid are:

- Focusing on the features but not accessibility. It is unreasonable to try to beat the current market players on features alone. You can't get more feature-rich than a programming language such as Python, which is arguably one of the most used solutions on the market, See Appendix 9.0.1 for more

information. It is important instead to create an alternative that is powerful enough but makes the process of data visualization much easier.

2.1.3 Academic Background. A General study of research in the field was conducted with a focus on identifying any other similar projects such as this one undertaken by the student, and more importantly the wider context from an academic point of view. Which was followed by a comparison to previous market research in 2.1.2. This was done to give the student a better understanding of how visualization works in different settings and if there are any trends and patterns that can help prioritize functionality or uncover new opportunities.

This study was done by analyzing a small subset of important, state of the art research papers talking about data analytics and visualization. Some of these papers focus on market research which were particularly important to expand upon the market research done by the student themselves. The most important points identified are mentioned below (Consider this a continuation of the market research / section 2.1.2 points above):

- Current visualization techniques are not capable of handling big data [7]. New solutions are being created and investigated by both industry and academia. Strategies for creating new visualization systems that handle each of the troubling aspects of big data have been put forward in [28]. This is a big point that this project could contribute to fixing.
- No matter how good a visualization is- if it cannot be understood its value is nullified. There currently exists a gap between what computation is capable of creating and what can be easily grasped by a user. Naturally, there exists opportunity in creating solutions to close this gap by taking into consideration human cognitive psychology. [41] [7] [29]
- Solving the problems to visualization poised by big data would require the combination of current visualization solutions merged with new technologies. [41]

2.1.4 Other Research. Another important aspect of research that was done included a more technical look into general design points that could help drive the design of the application itself and how features are developed.

One specific aspect researched has been software planning methodologies. The student was aware of agile and waterfall techniques from their study but those techniques were usually applied in and made for multi-person teams, which naturally conflicted with the single-person structure of this project. Through this research, a technique called PSP [23] (Personal Software Process) was discovered. This is a methodology that allows a singular developer to apply a structured, continuously improving process to how they develop software. A further inspired process was also identified called PXP [6], which was a fusion of Agile XP principles adapted to a single person team inspired by PSP.

Another notable finding in this phase, was an analysis of graphing and visualization techniques. In the 2.1.2 Market Research phase a lot of different solutions with a large variety of graphing types were seen. An analysis of the most common ones seen, which also

had some overlap with The seven basic tools of quality (A collection of seven charts that need minimal training to use [24] for analysis) was undertaken with the hopes of identifying the most suitable graphs in terms of flexibility at higher dimensions (3+). The full analysis document can be seen in Appendix A2 but in summary- It was found that Scatterplot's fit these needs the most while also being part of the Seven tools meaning increased accessibility in who could use the application. The other main options included the Radar chart which was suitable but not part of the Seven tools.

2.2 Tools and Technologies

Research was also done to highlight what technologies and design paradigms would be available for the development of this project. This also included a comparison between them. Though it should be noted that no decisions were made during this research stage of the project- The research and analysis recorded here act to justify and shortlist the final design in section 4.1

It should also be noted that obviously not all combinations of technologies mentioned below are viable. Usually deciding on one aspect would limit what can be selected for another. But nevertheless, each section below was looked at separately to fully understand the opportunity cost for each decision when going one route as opposed to another.

2.2.1 Application Infrastructure. This section specifically focuses on the structural decisions in the design of an application that directly affect how it is created, run and in some cases what features are possible to implement. In general, the design options for this application in particular could be split into two groups.

Client-Side Run Application. This is the simplest design. All code that makes up the application is run on the user's device locally. No need for any server resources (Other than for serving the initial code which even then may not need a server, can distribute software on USB, Disc etc..) thus can be ran offline. But computing resources are limited to only what the user has and no inherit way to synchronize data among multiple users and devices- such as for user accounts, etc.

Server-Side or Full Stack Application. This is a solution to some of the limitations mentioned for Client-side. Either have the client application be able to connect to a central (or server-less functions based) server and offload some tasks to it, or have the application be fully computed on-server with only static content responses being sent to the user. This design is naturally more complicated and often results in a split codebase among backend and frontend components. There is a need to provision computing resources, and more security considerations need to be made.

2.2.2 Run Environment. This can be defined as the software environment the application will run on and be thus designed for. The main options identified were the following:

.NET Environment. .NET, which is an open-source developer platform for building Software supported by Microsoft [33]. It is cross platform among Windows, MacOS and Linux (With support for iOS and Android using frameworks such .NET Multi-platform App UI / MAUI [13]). It provides a great rich set of libraries and tools for any kind of projects including both frontend and backend webapp

needs and client ran applications (As long as .NET is installed on that device). .NET supports only 3 languages those being C#, F# and Visual Basic.

Node.js. Node.js is aptly described on its website as an "an open-source, cross-platform JavaScript runtime environment." [40] It is the most popular web technology among the Stack Overflow 2022 Survey respondents [43]. Although most commonly used for Server-side processing as a webserver, it can also be used for running local applications as long as it is installed on the client's device (although it usually makes more sense to serve the app over a network with node.js acting as a server side environment). For package managers, npm is tightly linked with node.js and provides a huge repository of packages. With the addition of Web Assembly, which is a new standard assembly like language that acts as a compilation target from a wide range of other languages, it is technically possible to use almost any language with node.js that has a compiler to web assembly made. [4]

Browser Engine. Browser Engine's- Modern browsers all have some JavaScript runtime engine, with V8 being the most widely used engine [1] [3] Although all browsers are supposed to be cross-compatible, in practice this can vary, and some incompatibilities can arise. Browsers naturally only run client-side code but communicating with backend solutions is a common practice. Only JavaScript is natively supported and Web Assembly in "4 major browser engines". [4]

JRE (Java Runtime Environment). JRE, is a runtime environment that allows an application to be cross compatible between Operating systems by acting as a compatibility layer. It runs Java bytecode which can be compiled from a large variety of languages. A standard library is also available with the runtime environment. Commonly used for backend development but also capable of Frontend. [8] [42]

Compiled Program (OS only environment). Compiled Program, One of the most flexible options on the list. Languages such as C++ and C compile to machine code which are run directly on a user's device. No inherit cross platform support and a need to recompile for each OS. Usually, higher performance due to lower abstraction. But a lower abstraction means more functionality needs to be managed by the programmer.

2.2.3 Rendering Solution. Being a project with visual requirements naturally meant that some rendering technology would be needed. Like with all other technologies mentioned thus far- there is a wide range of options that each have their own distinct design and ability. This section then aims to segment the available options by two factors at the minimum- One, the rendering solution must support 3D graphics in some capacity, and two, the solution must run and integrate with an application targeting one of the above-mentioned run environments. With those key requirements in mind, these were the identified options:

OpenGL. OpenGL is a low-level cross-platform rendering API which can be traced back to a release date in 1992 [56]. Although no longer in active development as of 2017, OpenGL still remains highly supported across both newly releasing GPUs and older. This also includes mobile devices. In terms of language bindings, OpenGL

is cross-language and can be called from almost any language and environment that has had bindings made for it. [45]

Vulkan. Vulkan is a cross-platform low level open standard rendering API that has superseded OpenGL in active development by the Khronos Group, but does not replace it. It's main driving improvement over OpenGL is lower overhead and more control over how code is run on the GPU. This greater control though does mean that development is more time consuming over OpenGL [54]. Being much newer, with the initial release date being 2016 [20], it can be assumed to be much less supported among older devices than OpenGL.

Direct3D. Direct3D is a subset API of the proprietary DirectX family of multimedia APIs developed by Microsoft [18]. It is a low-level API similar to OpenGL but created exclusively for Microsoft Windows, Xbox, and some Embedded Windows versions. In terms of languages, only C++ is supported targeting an executable on one of the above-mentioned systems [49].

WebGL. A web integrated, JavaScript only low-level API version of OpenGL. It's developed as an open web standard and is implemented in most widely used browsers, without the need to install it in any way for the client or developer. It's a low-level API just like OpenGL and comes in two main versions based on OpenGL, WebGL 1.0 is based on the OpenGL ES 2.0 standard (OpenGL ES is an embedded subset version of OpenGL) while WebGL 2.0 is based on OpenGL ES 3.0 which is less supported among older devices. At the time of writing, WebGL remains the lowest level of abstraction for running GPU code on the web. [36] [19]

Metal. Metal is a low-level rendering API designed by Apple for their devices. It has a very limited set of supported hardware and is further limited to only iOS and MacOS for the Operating System. In terms of language bindings; Objective-C, Swift and C++ are the only supported options. [10] It was created by apple to replace OpenGL on their hardware which was depreciated in 2018. [9]

2.2.4 Optional Abstractions for Rendering Solutions. The underlying rendering technologies mentioned in the last section, although usable on their own, can be offloaded to be managed by a higher-level framework or engine. Although it must be stressed that the inherit properties of the underlying rendering solution still has an effect on the application being developed. The main reason to bring in an abstraction would usually be to lower development complexity, and in turn time. But the drawback often results in less flexibility regarding what can be made and lower performance.

Three.js. Three.js is a JavaScript library that abstracts WebGL to simplify the creation of 3D graphics [37]. It is highly extensive and offers a wide array of useful functions and constructs to that end. It is available as a npm package [52] and can be easily integrated into a web-based project. If comparing to WebGL though, which is already a part of the browser, three.js contributes to a much bigger application download footprint. It also suffers from the same general relationship mentioned at the start of this section, development is greatly simplified but a lot of the flexibility and performance is lost.

Unity. Unity, although first and foremost a game engine, can be applied to any development project where high performance

graphics are needed. Unity supports DirectX, OpenGL, Vulkan and Metal- with only a few settings changes. A wide range of target devices can also then be built for. It is also possible to target WebGL as a platform in a similar fashion for web applications. Beyond this great cross-device and API support- Unity has an extensive collection of tools and APIs to streamline development. Although it should be mentioned that web applications are not as well supported, especially on mobile devices. The engine also only supports C# as the only option. [39] [51]

2.2.5 Languages. There are a large variety of potential languages that could be used for writing this program. The following were selected based on how extensively the languages are supported in previously mentioned Rendering solutions and Run Environment Sections. And some key exceptions that were considered to be important for consideration by the student.

C++. A well know general-purpose compiled programming language most often used in performance critical applications. It is Object-Oriented but can be used to also write functional code. It is arguably the de-facto standard for systems programming. [50]

Rust. Rust is a relatively new general-purpose compiled programming language often used in systems programming. It is a modern alternative to C++ that combines its high performance with a multitude of modern features such as a default package manager, and numerous safety features especially for memory (While still keeping a low performance impact). [27]

Java. Java is a general-purpose, object-oriented focused programming language that compiles to Java Bytecode that can be run on any device running a JVM (Java Virtual Machine). [8] [42]

C#. C# is a general-purpose, multi-paradigm language developed by Microsoft. Although it is technically possible to compile to machine code, it is most often compiled to run on a .NET environment. [11]

JavaScript. JavaScript is the natively supported programming language on the web. It is multi-paradigm and is just-in-time compiled. It requires a runtime which is often a browser or dedicated runtime environments such as Node.js. [12]

TypeScript. Typescript is a superset version of JavaScript developed by Microsoft with a number of features such as stricter syntax with the ability to have types. It transpiles to JavaScript which is then run in the same way. [32]

2.2.6 Automated Testing. Automated testing is used in software development to run a set of pre-configured tests repeatedly, usually every time before code is committed to a repository or as needed. Once tests are setup and written, it is an easy way to quickly test all cases including edge cases that would otherwise be tedious or take too long to do manually. Automated testing is not always possible for all aspects of an application but nevertheless a number of options were looked at in case an opportunity to integrate automated testing arises.

Test Complete. Test complete is a GUI automation tool for testing a wide range of platforms and application types across Desktop,

Web and Mobile platforms. [47] But it's in-accessible price and no free tier limits its adoptability for this project. [48]

Robot Framework. Described on its website as a "Robot Framework is a generic open source automation framework. It can be used for test automation and robotic process automation (RPA)." [16] Being open-source it is free to use and has a wide range of libraries made for testing different device types and environments. [16]

Selenium. Selenium is a set of browser automation tools and libraries that can be applied to automate almost any part of browser interaction. It is open source and free to use- It functions by providing a "WebDriver" interface for writing testing instructions that can be run on different browsers. Tests can be written in a variety of languages but can only automate applications running in a browser. [46]

2.3 Summary

The background research mentioned in this section acted to ground the other-wise open-ended project to a set of goals, both mandatory and optional, to create an impactful and original project. The following paragraph then summarizes the goals previously brought up into a short, guiding statement.

The purpose of this project is to create a new market entry application for the creation of visualizations. This application would focus on user accessibility first and foremost, to be an application that is usable without programming knowledge. It will allow Multidimensional data to be plotted through a Scatterplot plot and possibly more chart options. In its creation it will not ignore the current problems poised by Big Data and will attempt to support it thorough the application of state of the art techniques to support its visualisations or be designed in such a way as to support their future integration into the application.

Otherwise the research mentioned thus far also sets an origin from which all further decisions are justified by. For the final selection and analysis of the tech stack chosen by the student to develop the application, see section 4.1. To see how market research affected the application design, see section 4.5. These are just two of the bigger sections building upon the research set here- thus, other references linking here are to be expected as different parts of the project are focused on.

3 SPECIFICATION

This section considers the formal project plan that was created for the development of this project, and the decisions on how it was structured. This phase of the project came after the specific project goals were identified during research (See 2.3) and act's to create a development plan based on achieving these goals.

Each of the subsections then focus on one particular aspect of that planning.

3.1 Development Methodology

PXP as introduced in the research phase 2.1.4 was selected for its well defined (extensively documented) agile based methodology that was well suited to a single-person development team. Agile in general though, was selected over a waterfall technique to allow user feedback to drive design and development which was planned to be often collected. As is a fundamental principle of agile this methodology was adapted to the project at hand (And the students work style) with some main changes and additions being:

- Allow refactoring to be raised at any point, also allow grouping of similar user stories to be refactored together. Allow fixing problems before they became too big and interlinked.
- MoSCoW and Cost factors agile ceremonies were applied to the project's user stories. Allowed better planning and time management.
- Instead of tasks created from user stories, user stories themselves were treated like tasks with any non-user story work labelled as tasks instead and treated the same as stories. Done to lower duplication of information and to fit better into GitHub Issues (See 3.3)
- No automated testing. This was a decision that was retroactively added here after prototyping during the design phase (See 4.4). The justification for this change is covered there but in summary, It was found that Graphics development is fairly tricky to automate the testing of as the large majority of testing is completely visual and subject to changes.
- Reworked development process in general to better fit the students workflow. See 3.4 and 3.5 for specific details

Feature sets were also adopted into the project. Where they played an important role in organizing tasks and user stories into logical sets based on source (User tester's suggestions, etc.) that could be prioritized and scheduled as part of a big picture overview. This big picture overview based on feature sets allowed the student to better manage their time by planning further ahead while still remaining flexible with development.

To see the resultant development flow with these changes in action see Section 5.

3.2 Requirements Gathering

With the goals that the developed application needs to achieve set as per the research phase (See 2.3)- It was considered important to then take these goals and create a concrete plan on what exact requirements would contribute towards achieving those goals. To do that, two main ideas were identified by the student.

The first idea was to conduct interviews with individuals who commonly use visualization tools or do general data science work. This would provide key insight into what real users of visualization technology think is key for a successful application to have. These requirements would constitute the first phase of the project and set a strong start to either a waterfall type methodology or an agile project. But there were a couple of downsides that cancelled out this idea at that time:

- With no initial product to focus insight into actionable requirements- the interview process is more likely to return conflicting or infeasible requirements.

- It might be difficult to offer insight that is not generic for the same reasons. "Application should plot data" vs "Application should do it like this instead of like that". With the latter insight being much more valued.
- Time and access to experts is very valuable and needs extensive preparation. It is important to make the most of it, which the student didn't feel like they could do at that time as per the points mentioned so far.

The next idea to identify requirements was one which was inspired by the development methodology chosen to be followed by the student in section 3.1, PXP, the methodology in question, describes the process for a developer to stand in for the client if the client is unavailable for planning. So, The student took on the role of the client to create a client brief using the insight gained during the research phase. This had a number of key advantages listed as follows:

- Minimal Preparation and much faster compared to planning and hosting an interview.
- Can take advantage of previous research into market competitors to inspire requirements.
- With the "Client" also being the developer it is possible to keep stories focused and ensure they are not conflicting.

With this technique, a planning stage was ran and a requirements brief was created. This brief can be read in full in Appendix 9.0.3 but in short, creates a written source document describing the minimum simplest application that would need to be created. It was considered that only a minimal version of the application should be planned at the beginning with further requirements created in a more agile way through user testing and analysis by the student based on how the project was progressing.

But the main reason to have created this brief instead of just skipping to creating user stories directly was to have a consistent main source from where user stories were pulled from initially that was focused on meeting the goals set during the research phase (See 2.3).

The stories (formal requirements) extracted from the brief formed the MVP (minimum viable product) feature set which was scheduled as further covered in section 3.4 to be completed on the 16th of January. The specific extracted user stories and their analysis follow as per Table. 1

3.3 Project Management Tools

A number of tools and services were employed in the development process to allow the organization and techniques mentioned to be applied. Those consisted of the following:

3.3.1 Git, Version Control. A version control tool is an important tool for controlling and recording changes to a codebase. Git specifically though was chosen due to the student having previous experience, and to allow GitHub to be used within the project for it's supporting tools (See 3.3.2 and 3.3.3).

3.3.2 GitHub, Cloud Code Repository. Github is a cloud host for git repositories with additional extensive tooling to support all aspects of a software development project. The student has had extensive experience with this platform thus it was chosen for this project to minimize learning downtime. Alternatives such as Bitbucket and



Figure 1: Development Timeline of a Single Story

GitLab also existed but did not offer any further advantages that the student considered worth the learning downtime.

3.3.3 GitHub Issues and Projects, Organizing Backlog and managing stories. GitHub also has integrated issues and project views for organizing and tracking stories. An alternative would not have been as tightly integrated with the code repository.

3.4 Scheduling

When a backlog of user stories is ready the next step is to combine similar stories into feature sets with a set deadline for their completion (As mentioned in 3.2). Then each user story and task within is analyzed using two main techniques:

- Estimate - Based on how long a story would likely take to implement relatively to other stories in the feature set
- MoSCoW - A prioritization technique based on how critical the story is to the application. Where a story is given one of four categories of importance being Must, Should, Could and Won't in order of priority. [26]

With this, a prioritized backlog is created that is split among the maximum iterations/sprints that fit into the feature set's time frame with a consideration for the students iteration velocity, with stories themselves being prioritized to an earlier sprint based on their MoSCoW value. This combination of analysis allowed the student to prioritize which sprint the story should go in (Using MoSCoW) and then ensure that not too much work was assigned in the sprint (Using estimate rating). On the off chance that there wasn't enough time to complete all stories and tasks, the student would have re-analyzed what stories and tasks could be dropped due to time constraints, taking into consideration both the Estimate and MoSCoW values.

It should be though noted that the MVP feature set was treated a little bit different. MoSCoW analysis was not applied as each story was a "Must" by virtue of the feature set. It was also not initially split among sprints as other future feature sets were (See section 6.2) due to little information on what the students velocity is at the time (start of development).

The specifics of when each feature sets deadline was set and how it changed can be seen on a sprint by sprint basis in the implementation section (See 5), in the Evaluation section (See 6.2) and in the Requirements Gathering section (See 3.2) based on the exact feature set.

ID	Title	Estimate (Relative)
1	As a User, I want to be able to import a dataset into the application to graph it in a 3 dimension scatterplot	3
2	As a User, I want to be able to navigate around the generated graph in 3D space while having the axis stay accurate	6
3	As a User, I want to be able to view a scatterplot of data set against an axis with accurate scales	5
5	As a User, I want to move the 3D view of the scatterplot in 3D using on screen controls	3
6	As a User, I want to be able to zoom in and out of the 3D Scatterplot	10
7	As a User, I want to be able to rotate the 3D Scatterplot around all 3D axis individually	5
8	As a User, I want the application to have easy to use on screen controls for interacting with the application	3
9	As a User, I want to be able to access the application on landscape screens of different sizes	2
10	As a User, I want to be able to view instructions within the application on how to use the application	2
11	As a User, I want all interactable parts of the Application to be visible at all times	1

Table 1: Requirements Gathering #1 User Stories, MVP Feature Set, To be completed by January 16th

3.5 Development Flow

Development followed a predefined process (See Figure 1) where a user story or task was picked to be developed from the prioritized backlog as per section 3.4. Once the student has finished developing the one or more tasks/stories, the student would then push the code to the refactor branch where it would be organized and possibly re-worked to follow better practices. This process allowed the student to move fast and encounter obstacles in implementation much more quickly, which minimized the risks of large roadblocks knocking the schedule out of balance. But once a feature/s was reworked to a sufficient standard with bugs fixed, it would then be fully tested and only then would be pushed to the final Production branch, which was build and publicly hosted. This process helped ensure that any code committed to production was vetted and would be unlikely to cause unexpected issues. It also allowed the student to always have a safe version of the application for demos and user testing without having to worry about what work was done before hand. The production version is then pushed to the development branch and the cycle repeats.

4 DESIGN

An initial design phase was undergone by the student before development started. Although it should be noted that the work done did not constitute the final design as a waterfall methodology would require but was more akin to setting the scene for the start of development. The majority of design on how something should be coded, look and such was done on a story by story basis during sprints (See 5) This phase itself though consisted of the following key sections.

4.1 Technology Stack

The student decided to settle on a technology stack during this phase. Which although would still be open to changes should they be needed if any problems arose during prototyping (See 4.3), nevertheless set what the stack should be otherwise. This decision was done by comparing valid options built up from those identified during the research phase (See 2.2) The selection and justification of every element of the stack follow below:

Client-Side run application. This project was not expected to require any server resources such as central database access. As



Figure 2: TypeScript [57] and WebGL logos [22]

such, client-side only was chosen to allow the student to focus on a single code base. This also would simplify testing as there would be less infrastructure moving parts that could break and simplified data security considerations (See 4.6).

Browser Run Enviroment. Chosen for its greater accessibility over downloaded options and extensive support among devices without the need for any extra environment download by the user. Only a browser is needed which is usually preinstalled on most internet capable Operating Systems.

Rendering Solution. WebGL, no other rendering API is as widely supported by major browsers that is capable of 3D graphics. WebGL1 is further picked as the target version to further increase compatibility.

Optional Abstractions for Rendering Solutions. None, The student wanted to gain experience in how underlying low-level APIs worked, and did not want to sacrifice performance and flexibility of what was possible to create.

Languages. With the browser set as the environment, the choice was limited to JavaScript, TypeScript or another language through Web Assembly. To ensure the best support among existent web tooling though, TypeScript was chosen which has the wide support of JavaScript while providing useful language features not available in JavaScript. One of those features, types, were found to be particularly important as OpenGL and by extension WebGL is very heavily dependant on correct types being used at all times, which would have been very hard to do with only JavaScript.

4.2 Tooling

After the Technology Stack was identified, the next step was to identify the development tools for that stack. The following were selected for the project:

IDE or Code Editor. Visual Studio Code (VScode) was selected for all writing tasks (Both for code and writing latex). This decision came down to what the student was comfortable with using through previous experience but also had a practical factor for it's selection. With that mainly being a great selection of packages to help with development and great integration with GitHub.

Development Server. Node.js was used as a development and build server due to it's straightforward ability to download and manage npm packages while also running development tools such as parcel, which in addition to it's usage below, also acted as a development server providing developer tools such as hot reloading on changes and helpful error screens.

Compiler and Build Tool. As a compiler, Parcel was used to compile and optimize TypeScript into runnable by the browser JavaScript. As a build tool, parcel build all npm packages (including the usage of some node.js only features) into a handful of static client-side only files that could be hosted. This was crucial and allowed some code designs to be implemented that otherwise would not have been possible (See Model loading in 4.3.2).

Hosting Provider. Digital Ocean's App Platform was used to host and build the application from the production branch of the code repository. It was chosen due to the student having previous experience hosting resources on the platform, simple setup with minimal networking on the students part, integration with Github, support for building on a node.js environment (The same as the development environment, allowing for continuous integration from the production branch) and the availability of free credits to do all this. The site hosted here allowed user testers to access the application from anywhere at their own time.

Testing Framework. With this project set to run in a browser as per the rest of the technology stack (See 4.1). It was decided that Robot Framework would be the ideal choice for handling testing- This was expected to be done using WatchUI, a library for Robot Testing that runs selenium under the hood. This was done to make testing more flexible and less time consuming thanks to the wide selection of other helping libraries available with Robot Framework. Unfortunately, during prototyping (See 4.3.2) a number of issues cropped up that ultimately left user testing to be set aside. For further details see 4.4.

4.2.1 Additional Libraries. The other mentioned npm packages used are recorded here and the reason for their use.

Pico.css. Simple CSS framework to do the heavy lifting for styling the application UI. This allowed the student to focus more on rendering work.

gl-matrix. Pre-made functions for the math very commonly used in graphics development. Allowed the student to bypass creating these basic functions from scratch in turn saving time.

jquery-csv. A jquery syntax compliant .csv parser. No particular reason to select this particularly from other alternatives. Covers a lot of edge cases in parsing .csv files that would have taken a while to implement and test from scratch.

4.3 Prototyping

An important part of the initial design stage was creating simple prototype applications using the technology stack to give the student experience with using the stack and to identify any critical issues that may need the stack to be redesigned or tools to be changed. These were in a sense mock sprint runs to smooth out the process and prepare for when development would officially start. The prototypes created also turned out general enough that they were able to be reused for the development of the actual application, in particular prototype 2.

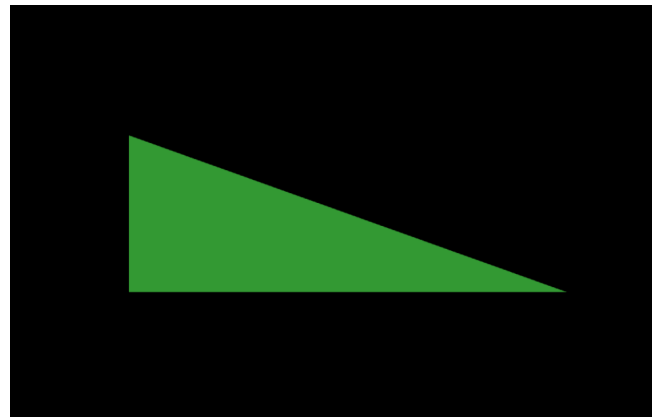


Figure 3: Prototype 1 - A simple 2D triangle drawn using the defined Technology Stack

4.3.1 Prototype 1. This was an important milestone in proving the validity of the development process identified. All of the tools and technologies mentioned thus far were setup and used to create a valid WebGL context and render a triangle (See Figure 3). It was found that this process was well defined and no changes were done.

4.3.2 Prototype 2.

WebGL is a low level API and considerable work needs to be done just to render a 3D model. With this prototype, the aim was both to further test the tech stacks suitability by doing more involved work, but also to see if a general purpose rendering engine could be created that implemented all of the critical functions for the application to be developed. It was considered important to create this as quickly as possible to identify any shortcomings as soon as possible that may bottleneck the project when development starts. Creating this prototype took approximately a month and yielded in the creation of a successful rendering engine with a charting focused design.

To be more specific, the features implemented by this engine were the following:

- 3D Mathematics with View, Projection and model system for rendering

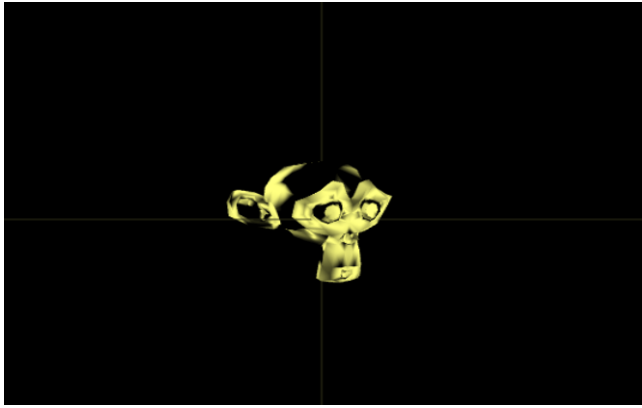


Figure 4: Prototype 2 - A 3D rendering engine

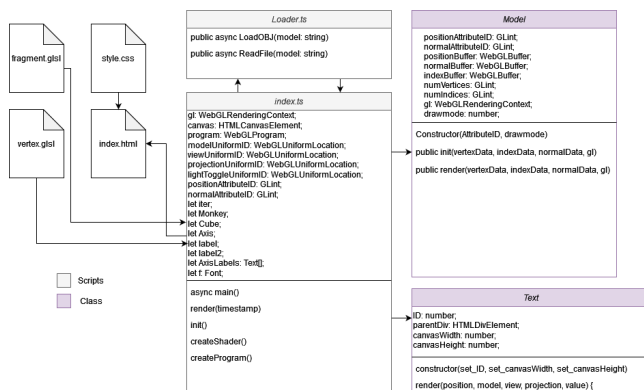


Figure 5: Prototype 2, Application Class Diagram

- Multiple Models Rendered at the same time
- Model Object Abstraction for storing and rendering a 3D model. Implements a prototype pattern where one object can be rendered multiple times. This is particularly useful as a memory saving measure for rendering lot's of models. Something that was considered a very likely scenario for a plotting application with likely many data points.
- Simple Flat Shading based on a preset light direction.
- Loader Object for loading and organizing data that is passed to Model. Allows .OBJ models to be loaded into the renderer to be displayed. This used the node emulation feature provided by parcel to translate the written file system code to run in a browser, this meant files like .OBJ models and .glsl shader files could be kept separate from the renderer code and only combined when the application was built.
- Rendering labels with HTML and positioning them approximately at some relative to WebGL scene coordinates.

One bottleneck though was identified during this development, which was to do with Automated testing. See 4.4 for the details.

4.4 Testing Methodology

Test Driven development is an important aspect of the PXP process when developing software. This is most often done with automated

testing for the best time efficiency and accuracy. But, during the creation of prototype 2 (See 4.3.2) the student encountered a number of critical issues that contributed to the decision to not implement automated testing, subject to possible further consideration later on. Those issues were:

- Graphics Development was found to be difficult to write tests for due to it's visual nature. This on it's own was not a problem as a solution using WatchUI was identified (See 4.2). What ended up being complex though was how rapidly the visuals changed during development, this made making tests useless as they could not be reused since they depended on comparing what the application rendered to reference images.
- Minimal UI to test, Automated testing on the web is particularly well suited to testing UI. Unfortunately, there wasn't any UI to test at the starting stages of development.

This points were expected to become less true as the application developed. Nevertheless, the student considered it unwise to setup tests for the start of development. Another process had to be identified in the meantime to allow the student to focus on bringing value to the project (completing user stories). This was the application of manual, visual inspection testing during the refactoring branch as per the specified development flow (See 3.5).

4.5 UX Design

As mentioned in the research phase- Ease of use and accessibility for non-programmers was a priority for this project. One that had to also dictate design decisions around how a user would interact with the application and how that application would communicate with the user. Those key decisions are mentioned here.

4.5.1 Visualisation Design. One of the project's goals (See 2.3) was to use a Scatter plot. To achieve that, two suitable rendering techniques were identified by the Student. Those are the following:

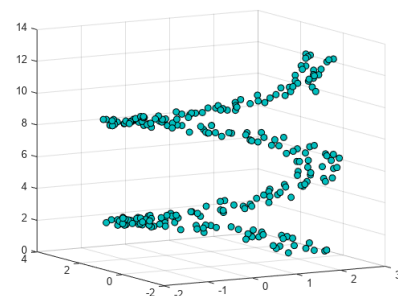


Figure 6: A 3D scatterplot generated through MATLAB, example of a classic cut-off figure [31]

- Unlimited Axis Values, World View. The scatterplot would be rendered into a 3D world by directly translating data values into world coordinates. The resultant graph could then be navigated by the user akin to 3D modelling software or a video game (first-person camera). Axis lines would be part of that world and would extend to infinity from origin.

Original	Modified
Write chart properties programmatically	Change properties through UI controls
Static chart image rendered once code written is run	Dynamically update rendered image as properties are changed
Difficult to explore	Exploration possible

Table 2: Comparison of design changes to how figures are created in the application developed compared to programmatic market alternatives

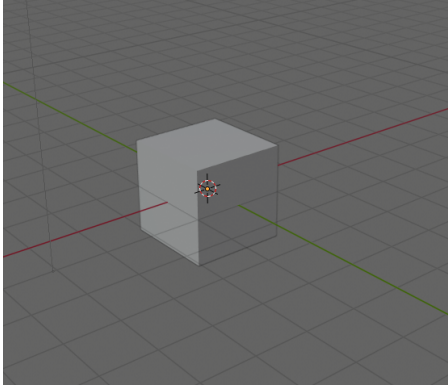


Figure 7: Screenshot from Blender [15], A 3D modelling application, similar to the Unlimited Axis World view presented

(See Figure 7 for a visual example) This is a very easy to implement design but might be difficult to navigate for an inexperienced user and to appropriately combine together with UI across different screen sizes.

- Classic cut-off figure. This is directly inspired by the way the majority of applications seen implement scatterplots. As a user of those systems, you would load in some data and set aspects such as the position, view angle and zoom programmatically which would generate an image as seen in Figure 6. This kind of view is not much harder to render but is much more concise as all data can be made to fit in a predefined visual space. This also allows greater control on how the graph is rendered allowing for a more consistent user experience to be tailored. But, this option has a severe disadvantage- where unlike the previous option, it is not commonly navigated but generated for specific parameters-making exploration not an obvious feature to implement.

In the end, the student decided to go with a modified option two. That modification was to replace the programmatic controls that have been seen to be used to compose / generate the chart in applications such as MATLAB (See Figure 6) with instead corresponding UI controls. In a sense, the design that the student came up with abstracts the programming to user controls instead, which are much easier to use (which is the guiding goal for this project) even if they may be more limited in their capability. On input, the chart can be regenerated allowing exploration to be done in a similar sense, instead of moving the camera the chart is modified to show subsections of the data (See Table 2)

This would mean, as an example, instead of changing the view values in the code below and running the code again to look at the

chart from a different angle: (Using code written in MATLAB [31] to generate figure 6)

```
z = linspace(0,4*pi,250);
x = 2*cos(z) + rand(1,250);
y = 2*sin(z) + rand(1,250);

scatter3(x,y,z,'filled')
view(-30,10)
```

The user would be able to just click a button or drag their mouse to move the camera.

4.5.2 User Controls. The design created by the student in the last section (4.5.1) requires a robust design of user controls. The design and implementation for UI then followed an agile approach, where UI was designed and implemented as the need arose and the rendering counterpart could support it.

4.6 Data Security

This being a project that will end up processing data, there were legal considerations that needed to be addressed. Under the UK Data Protection Act 2018 [53] there are strict rules and regulations that control how personal information is used. It was not expected that the application created would need to process any personal data specifically, though the ability to upload any file did mean that the application might be used with personal data. Thus, it would have been important to ensure that the Application did not violate data protection regulations regardless of what data was used. To that end, each principle was analyzed in the context of the application being developed.

- "Information is used fairly, lawfully and transparently" [53] The Application should be transparent in what is done with data. This is important in the context of the following points.
- "Information is used for specific, explicit purposes" [53] Any data uploaded should only be used for the purpose specified, in this case, plotting on a graph.
- "Information is used in a way that is adequate, relevant and limited to only what is necessary" [53] For this application, this would mean not using data beyond what the user has been told the data will be used for.
- "Information is accurate and, where necessary, kept up to date" [53] This is not fully relevant as the application is not expected to store data. Though there may be features added to the application that will require compliance in the future (See Databases in 8.2). Though even without those additions data should not be misrepresented by the application, it should be graphed with accuracy.

- "Information is kept for no longer than is necessary" [53] This is also expected to not be a problem unless some additions as above change this (See Databases in 8.2).
- "Information is handled in a way that ensures appropriate security, including protection against unlawful or unauthorized processing, access, loss, destruction or damage" [53] The Application should generally ensure that the data is safe.

Compliance with these points was relatively straight forward. Having decided on no server (to off-load processing) nor permanent storage component (Database, etc.) minimized most risks when working with data (See 4.1 for more details). Though these points will have to be kept in mind and revisited for future development (See 8.2 in particular).

4.7 Summary

This design stage was critical in finalizing the last big questions that needed to be answered before development. With the application of the prototype phase (See 4.3), the student gained experience and confidence in working with the tools selected, meaning development could proceed much more smoothly.

5 IMPLEMENTATION

This project was developed over 8 sprints between 7-10 days each. The first one started on the 26th of December, 2022 and the last one ended on March 19, 2023. What follows is a detailed summary of the work done during those sprints divided into three subsections per sprint:

- Plan - Highlights what user stories were chosen to be implemented during the sprint and how long that sprint was.
- Implementation - How the features were implemented, any design decisions and any issues
- Summary - Have all user stories been completed? What went wrong? Anything learned and moved to next sprint?

5.1 Sprint 1 - Start 26th December

5.1.1 Plan. This was the first sprint undertaken for the project and so the focus was to test everything out and ensure that the process was right for the student. The initial MVP feature set was chosen for development and two user stories were planned for (See stories on Table 3). Those being user stories 3 and 11 with a total workload estimate of 6 over a 7 day sprint. The main goal for this sprint was to create a labelled scatterplot graph with some pre-set test data.

5.1.2 Implementation. Prototype 2 (See 4.3.2) was chosen to be extended into the application being developed. It was copied into the development branch and work was started on implementing the user stories mentioned. A 3D Cube with axis lines was created as the chart and an origin position was set from which data points would be rendered. This was not as difficult as expected as the model matrix used could be copied and modified by each data point to ensure that they were always at a correct position relative to the cube and axis lines.

The next step was to label the axis lines (also relative to the chart using it's model matrix). This caused some difficulty as test labels would not align properly even if they were supposed to be based

on their coordinates. This was particularly troublesome with perspective lines that had a considerable z change in position. This was found to be a result of inaccurate placement by the browser (browsers tend to favor flexibility over screen sizes instead of rigid pixel-perfect placement) and not fully correct world to screen coordinate calculation. Instead, it was decided that text should be rendered within the WebGL scene to ensure accuracy- To that end, a bitmap font technique was adopted.



Figure 8: Arial font bitmap glyph image



Figure 9: Glyph Structure

This is where a texture atlas with pre-rendered glyphs is embedded into the application and used to apply individual glyphs to flat surfaces (usually two triangles of geometry, See 9). This technique was mainly adopted due to it's simpler implementation and higher performance over the main alternative of using a geometric approach for rendering text. Where geometry is used to shape each glyph, which uses many more triangles. This alternative is highly inefficient as geometry is computationally expensive to render. Although it should be noted that bitmap font's do also carry their own limitations, mainly it is difficult to support large character sets as each character set would need to be saved into an image and embedded into the application meaning the whole application takes longer to load- and if changing font sizes is required, then that means different sized copies of the character sets need to be further available to avoid blurriness and pixelation at large sizes. For this project though, those were considered to be tolerable limitations. Blurriness could be avoided by keeping glyphs the same size and the limited glyph set wouldn't matter as much with only one supported application language. With bitmap fonts decided upon, the student started work on adapting the application to support rendering text in this way. This required a couple of key changes and additions within the renderer part of the application:

- It should be possible to apply textures to models- This was done by adapting the Model class to take-in, store and apply texture data on render
- There had to be some way to abstract which letter was rendered, manually slicing the bitmap texture to get each glyph would quickly become too tedious and time consuming for anything beyond a few glyphs- A State-Machine based Font Class was created that generated font texture data for an input letter that could be fed into a Model Object. See Figure 11.

- A Glyph set image and accompanying .JSON file for glyph data was embedded into the application. It's this data that allows the Font Class to function. See Figure 11 for more details.
- A new set of vertex and fragment shaders were created for just text. This was to allow texture data to be applied in the fragment shader.

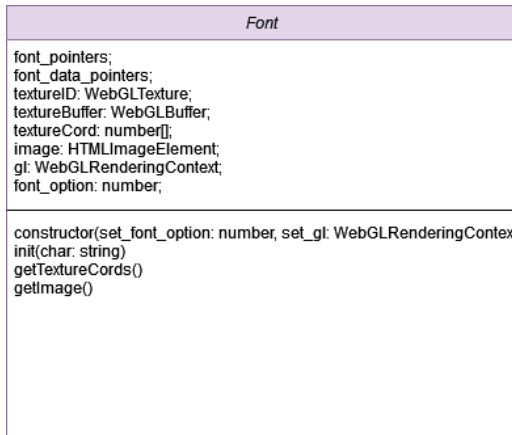


Figure 10: Font class created

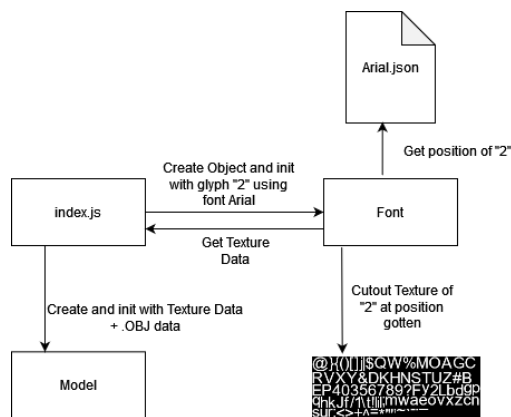


Figure 11: Process to prepare a single glyph model before rendering, Glyph "2" is taken as an example

The implementation of the Font Abstraction makes it very easy to have multiple different fonts (As in style) in the application. As long as font data is embedded in the application- It is trivial to change the font by simply changing a variable. With this, two fonts options were added- Arial and a bold variation of Arial.

5.1.3 Summary. The new technique for rendering text ended up fixing the accuracy issues caused by the previous label system, all user stories managed to be completed as expected and the application was pushed to production on January 1st, 2023. This was a slow start but the student expected that more user stories would be able to be tackled as the project progressed.

5.2 Sprint 2 - Start 4th January

5.2.1 Plan. This was the second sprint and the plan was to start adding user controls to allow a user to modify what was being rendered. This included not only the ability to upload custom data but also rotate the resultant graph. The MVP feature set was again the developed feature set from which 4 user stories were selected (See table 4), with a total work load estimate of 16 over a longer 11 day sprint. This was originally a 7 day sprint but an extension was deemed necessary to have an atomic conclusion to the sprint. In total, 16 Units of work were completed for an average of 8 per week.

5.2.2 Implementation. Loader was expanded to handle .csv loading which was done using jquery-csv, which sped up development considerably and covered a lot of edge cases in possible file uploads. For user controls, the use of modern UI frameworks was considered but at this moment in time- there wasn't much UI requirement for the application. Instead, as per PXP, the student focused on hitting user stories as fast as possible. Thus, an observer like structure was implemented using Event listeners connected to overlaid HTML Elements on the page (In a similar way to how the old label system worked, See label rendering in 4.3.2) which ran functions that modified the state of the application. With this design, 6 buttons were made to rotate each axis of the chart individually. Another button was added to upload a file that was handed to Loader. See below for an example Event Listener:

```
// Event Listener for a rotate x axis button
(<HTMLElement>document.getElementById("right"))
.addEventListner("click", function () {
    x_rotation += 0.1;
});
```

During this time, when implementing rotation- which consisted of applying a rotating model matrix component to the entire scene. An expected issue cropped up of having to rotate glyphs to always face the camera even when the scene rotates. This was solved by writing a custom shader, to be used when rendering text glyphs, implementing billboarding.

5.2.3 Summary. This was almost a double sprint. This was mainly due to lower work hours done by the student during the winter vacation. Nevertheless, All user stories were completed and the application was pushed to production on January 29th. This delay was due to the previously mentioned lower hours and semester start travel. At this point, a technically functional plotter was created, though still very limited in functionality (See Figure 12). The MVP feature set's deadline was pushed to Feb 3 at this time, as the initial goal of January 16 was missed.

5.3 Sprint 3 - Start 29th January

5.4 Plan

This was the third sprint and first sprint undertaken during semester 2. The plan was to tackle some of the biggest requirements from the MVP feature set- in turn making the application more capable. A total of 5 User stories were selected (See table 5) with one of them, story 6 alone being ranked at a workload of 10. In total, the sprint consisted of 24 work load points over a period of 12 days. This was

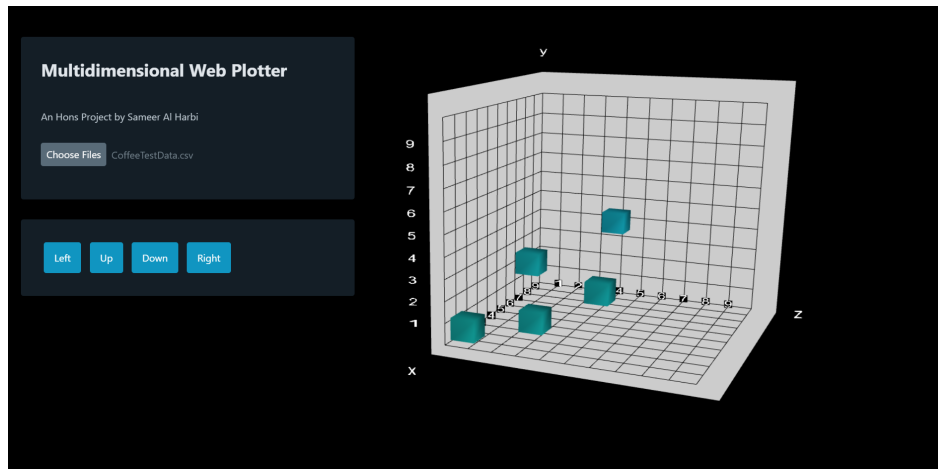


Figure 12: The application at the end of Sprint 2

the biggest sprint undertaken to date but the student was confident in rising up to the challenge.

5.4.1 Implementation. One of the user stories was to implement the ability to change what slice the graph showed / what the axis values are (See 4.5). This was the beginning of adding dynamic navigation to the data that was mentioned in the design. During this sprint, this idea of navigation was distilled down into 2 essential parts. With that being:

- Moving the chart "slice" in each axis. An example would be if a 1-10 on each axis chart is moved +1 in the y direction the chart x, z axis would still show 1-10 but the y axis will now show 2-11.
- Zooming. This can be considered as increasing the size of the slice shown by a chart. If a 1-10 on each axis slice chart is scaled to a factor of 2x it would now show 1-20 on each axis.

Before any of these could be implemented though, glyph rendering had to be reworked to allow values consisting of more than one digit to be shown at each labelled line of the chart. This was a relatively straight-forward addition where instead of a single glyph being rendered at each line, an array of glyphs was rendered instead. With each digit of a number being a single glyph in order stored in the array.

This did not take full advantage of the Model class prototype abstraction pattern. Technically it would have been possible to just store the unique texture data of each glyph making up a value and repeatedly apply it to a single model then rendering each glyph in turn, which would have meant less repeating of data through multiple Model objects- but this would have a greater performance impact as the one model would need to be re-initialized for every glyph every frame before rendering.

Moving the chart was next to be implemented. This was done by adding new movement buttons (2 for each axis that either moved the axis ahead by 1 or back by 1) then using event listeners getting the modification value and applying it calculate the range of axis values that needed to be rendered (This was at most 10 values). These

values were then applied in order for each labelled line on the chart. This was a relatively straight forward addition.

Zooming was one of the most challenging features of this project to implement. The implementation at this time attempted to create a visually pleasing effect (See Figure 14) where axis lines would move out to give the illusion that the camera was moving closer without actually changing the camera position nor size of the viewing graph cube. This was an easy enough effect to achieve and one that could correctly sync up with the position of data cubes too. The problem then, was correctly labelling axis lines at every possible state of zoom level. In other words, Even though positionally the cubes and axis lines were correctly placed at all zoom levels- figuring out what the exact values of each line were was very challenging, this was further exacerbated by the ability "move" the graphed slice to show different values. After extensive tinkering, labels were turned off when the application was in an uncertain state- As a temporary solution, a hardcoded zoom modifier was set for maximum and minimum zoom values (These were the only levels at which the zoom mod values could be confirmed as correct) allowing accurate labels to be shown at those two levels. With this, the application could now zoom up to a maximum of 5x showing values from 0 to 50 and a minimum of 1 to 10 at 1x. In between those two maximum and minimum levels (including those levels) there were 10 pre-set zoom values that could be scrolled through.

5.4.2 Summary. This was one of the most important sprints undertaken in terms of extending chart capabilities. All mentioned user stories were completed and the application was pushed to production on February 9th. At the end of this sprint the application was starting to become ready for user testing and could technically handle most data- Further information on user testing is mentioned in section 6.2. Since the extended deadline for the MVP feature set was missed, a new deadline was set to complete the feature set ASAP (As soon as possible).

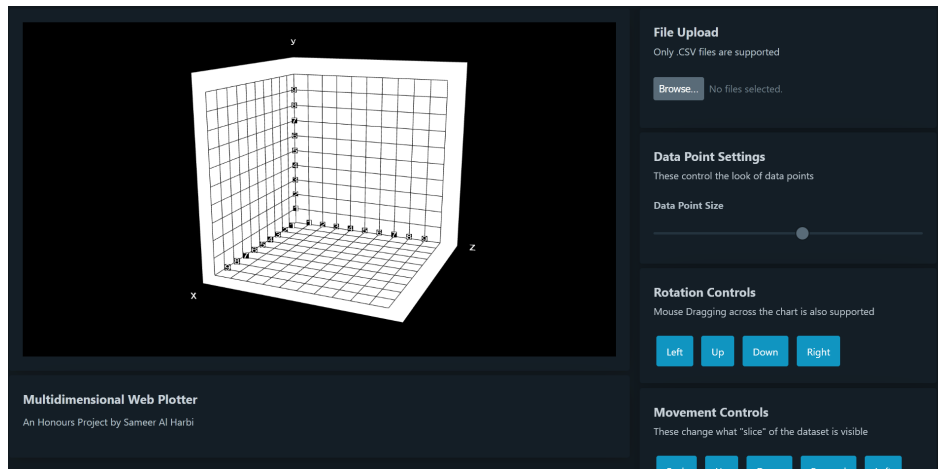


Figure 13: The Application at the end of sprint 4)

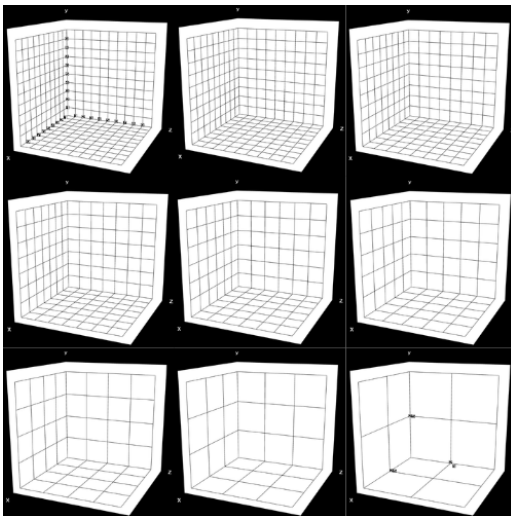


Figure 14: Zooming effect formed by Axis Lines (Zooming Out left to right, top to bottom)

5.5 Sprint 4 - Start February 10th

5.5.1 Plan. This was the fourth sprint. The main driving factor during this sprint was to prepare the application for user testers. To that end, the last 4 user stories were selected (See table 6) from the MVP feature set with a total workload of 10 points. These all focused on critical UI accessibility problems that would likely otherwise dominate user feedback. The sprint was planned to run for 6 days.

5.5.2 Implementation. This was a relatively straight forward sprint. No major systems or additions were added and most work used the UI Observer pattern using Event listeners as previously defined for UI needs. Although it was starting to become noticeable that adding more controls was starting to affect code quality and maintainability- There were also issues with how to organize controls as they could no longer easily fit on one page, a new design

was created using the FlexBox layout model. A refactoring task was added to the backlog to look at opportunities to restructure the app.

5.5.3 Summary. The sprint was completed in record time. All user stories were implemented and the app was pushed to production on Feb 12, two days after the sprint started. The remaining time was instead reallocated to plan for user testing. At this point, the application could not only render most data but had reasonable ability to display that data correctly and provide basic user controls to that end. It would now be important to get user feedback to drive the application forward beyond it's most basic state.

This sprint was also important in the sense that it completed all User stories from the MVP feature set. This was about a month later than the originally planned end date of January 16 (See 1), which was not unexpected as there was little knowledge initially of what the students velocity would be like.

5.6 Sprint 5 - Start February 19th

5.6.1 Plan. This was the fifth sprint. User testing 1 has already started at this point in time and the student was waiting for results to finish coming in before analysis could start. In this relative downtime. A 7 day sprint was planned with 2 user stories (See Table 7) for a workload of 9 points. These were task based stories that arose during development in previous sprints, and the student thought they would be important additions to have.

5.6.2 Implementation. The first story was to display names for each axis taken from the first row of the dataset. This was pretty straight forward thanks to the Font + Model Abstraction and was promptly implemented.

The next user story though was to look at new ways to structure the app to increase maintainability. The main areas of opportunity thus found were as follow:

- Restructure application to be fully Object-Oriented - At the moment the application is a script that extensively uses Objects (From classes such as Model and Loader) to implement the chart in a high level as a result of the abstractions provided by those objects. This is fine and probably the best

design for a single chart to be rendered but there may be potential for further abstraction to allow multiple charts per page that can interact with each other.

- Find a way to better manage UI state. This is currently not a problem with the relatively simple user controls but may become cumbersome when more controls are added and if some controls might start being dependant on other controls.
- Find an overarching architecture to manage UI and Rendering code. At the moment user controls are highly coupled to rendering which is not ideal. It would be best to decouple them in some way to make adding more UI components easier.

Each of these points were researched in turn and prototyped with in turn. Although time was a very limited factor as the student considered it important to provide value to the user first and foremost. Which meant refactoring would likely not be able to continue beyond this 7 day sprint as requirements extracted from user testing would then be higher prioritized. With that in mind, first, some attempts were made to restructure the render loop into an object but it was more work than expected to port everything correctly so it was abandoned.

As for state management, there were a number of techniques and pre-made solutions for managing state. React + React Context though, has been found to be a great fit for the project. React is a UI library for creating user interfaces through components and now has support for state management by sharing states between these components. Parcel also has great support for react so integration would not have been too problematic. Unfortunately, the unique circumstances of this project made the student reject integrating react into the tool stack at the current time for the following key reasons:

- Performance cost. Although most likely negligible, there is still none the less a performance cost in using an abstraction such as react. This is particularly important as the application already was performance heavy due to 3D rendering.
- Lack of time and experience. In a perfect world the library could be easily implemented with no downtime and no future issues. Unfortunately, the reality is that adding react would have heavily changed the tech stack that could cause unknown problems. This is further exemplified by the student not having any considerable experience in using react meaning any issues that did pop-up would be much more difficult to solve. There was also no time to have a prototyping phase to mitigate these concerns as there was with the current stack at the start of this project.
- Minimal Value added. As previously mentioned the current system worked as needed and did not need any changes to provide further functionality to the user. As such, it would have been hard to justify work done of porting the application to react over only future concerns. PXP prioritizes doing the simplest design and not worrying about future requirements as those tend to change constantly.

The final point, to find an overarching architecture, the student found that the application fit very well into the MVC pattern (See

Figure 15 for completed Application architecture). As such, the student starting working on implementing the pattern- which went smoothly as the application had already been unknowingly made to partially fit the pattern by the student. The application was structured as follows:

- View - Static Written HTML index.html
- Model - The application render loop rendering chart. The chart rendered is a result of multiple control variables which make up the model (Model as in MVC not Class Model)
- Controller - This was the new class created. All event listeners and control functions were moved to be managed by this class.

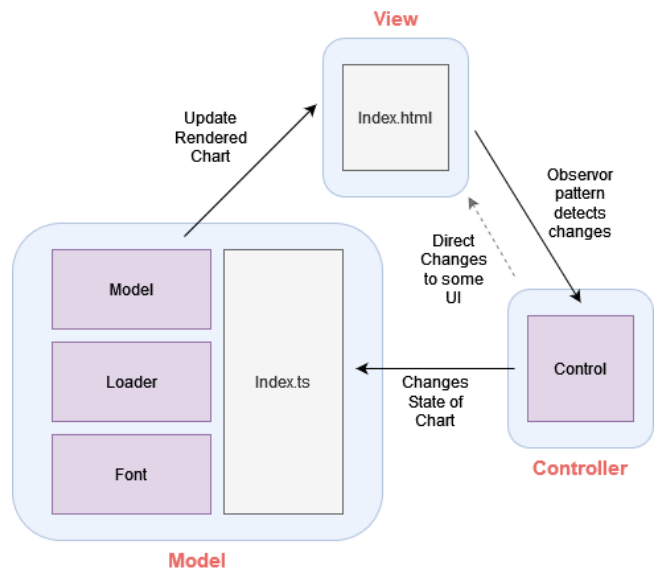


Figure 15: Model-View-Controller Architecture Created (Scripts are grey, Classes are purple)

5.6.3 Summary. This was an important sprint that worked to refactor the application to be easier to work with, especially when adding new UI elements. The 2 user stories were thus completed and the application pushed to production as Version 2 on March 4th. It was completed just in time as user testing had come to a close and analysis begun.

5.7 Sprint 6 - Start March 05

5.7.1 Plan. This was the 6th Sprint, and the first sprint starting work on the second version of the project. Two new FeatureSets were now available for user stories to be selected from. One composed from user testing analysis as further described in section 6.2 and A further improvements feature set created in a similar fashion as the first MVP feature set (By the student through the research phase). For this Sprint, 5 Stories were selected (See Table 8 and 9) from both feature sets with a priority for Must. In terms of workload, a wide range were selected for a total workload of 23 points over a 5 day sprint period.

5.7.2 Implementation. The first important story done was reworking how zooming worked. User testers asked for a zoom that showed labels for each level which was found to be difficult to calibrate with the zooming visual effect as mentioned in Sprint 3. So instead, the zoom was reworked to always show 10 axis lines and only change position of data points and labels on zoom- This was generally straight forward and created a robust zoom that hit the criteria, even if it didn't look as visually impressive.

The next addition was to modify the renderer to allow picking / highlighting data points. To achieve this, two main techniques were identified by the student.

- Raycasting - This works by taking the screen coordinates clicked on by the user and projecting them into the 3D scene. From this scene position a ray is then shot and a check done to get any intersections with objects.
- Colour Picking - This is a technique where Object ID is encoded into the colour of an object. When a user then clicks on an object, it is possible to get what object was clicked on by picking the colour at the click position (pixel clicked on) and matching it to an object in the scene.

After analysis of the two, Colour picking was chosen over ray tracing for the following key points:

- More Complex implementation with raycasting.
- Raycasting is highly CPU dependant, which is not ideal for a single threaded application with UI requirements, it would be preferable to offload as much computation as possible to a GPU and leave the CPU free for a responsive UI experience.
- More flexible, it is possible to have hover over effects without having to constantly raycast which would have made the application unusable performance wise.

To implement colour picking then, the student extended the renderer to render data points twice- The first render would render to a texture in a different buffer, this first render would also encode an ID for every Model rendered into 3 rgb Channels giving a unique colour for every model drawn (up to around 16 million). After that, render is called again but to the screen buffer instead. This means that the user only see's the the second render (Which can freely use colour) instead of the first one. `glGetPixel` would then poll what colour pixel the user's mouse is hovering over from the texture. During the next frame as each model is rendered, it's id is checked to see if it matches the selected id extracted from the colour of the hovered over pixel. If it does, the model is highlighted and it's data saved to be displayed. See Figure 16 and fig 17 for a visual representation of what is rendered off-screen vs on screen for colour picking to work

5.7.3 Summary. All User stories were completed as expected and the application pushed to production on March 11. With this sprint almost all Must stories from both Feature sets were completed making this a very productive sprint and one that set the project on good track to be completed by the end of the month.

5.8 Sprint 7 - Start March 12

5.8.1 Plan. This was the 7th Sprint. The highest priority user stories were once again selected from both feature sets. This included

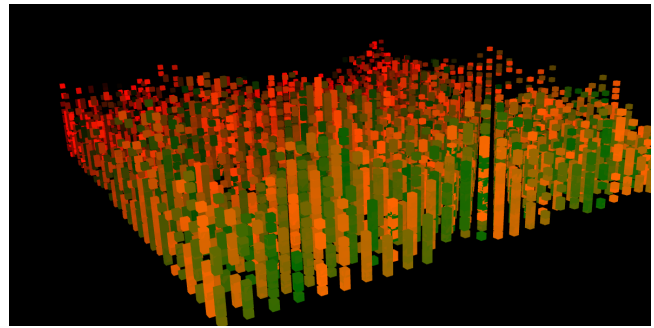


Figure 16: What is rendered to off-screen texture buffer for colour picking, used to identify what model is selected at mouse position based on colour

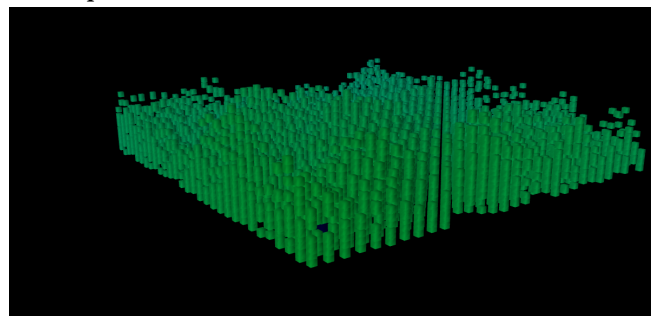


Figure 17: What the user see's on screen (Only points are being rendered here for clarity, usually the chart will also be rendered)

the last 2 Must stories and 2 Should stories (See table 10 and 11). In total, the workload was 21 points over a 5 day period. The main focus of this sprint was to expand the application to support one more dimension and create a new suite of user controls to view and assign data to chart axes.

5.8.2 Implementation. To add a new dimension, the student had to start looking at different ways to represent dimensions. The main options identified were Alpha/Transparency, Single Channel / Saturation component, Full Colour component and Shape component. Of those, Shape was dropped due to limited range (Have to have a different model to represent each possible values). Alpha was also dropped due to limitations in how the browser handles transparency. Finally, Saturation was chosen over colour as having all 3 channels might be confusing for users to extract values.

During the following implementation- the first problem encountered was how to plot an infinite range of values between the minimum and maximum Saturation values on a single colour channel. For this problem the student identified the use of a squashing function that formed an asymptote at the limits. By then also allowing the user to change those limits, any data can be effectively plotted with saturation. See Figure 19 for a plot using saturation.

Once the mathematical basis was solved, the implementation was relatively straight forward. The next main addition worked on was to create a new section of user controls. To that end, a tabular

$$\frac{1}{1 + e^{-mod*value}}$$

Figure 18: Squashing Function, where mod affects the range of values to divide the limited saturation range over while value is the value of the data point plotted

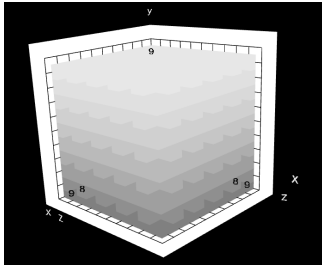


Figure 19: DataCube Dataset (More on dataset in 6.1), where y is set as both the y component and saturation c component. Making points with lower y value darker

design was adopted for aspects of the application that demanded large screen real estate and focus from the user. This consisted of three total tab sections as follows:

- Graph View - This is what has been shown so far, the rendered graph.
- Data Management - This will be a new tab. Here, the data uploaded is displayed in a tabular fashion with data point IDs for cross reference with the graph. Additionally, a set of selectors were created on the page that allowed the user to select which column from the table would apply to which axis to be graphed (or to saturation).
- Help tab - This is a FAQ based help section, Answers to common (or expected to be) questions.

This was also relatively straight forward to implement, although with the data management tab- the UI system was pushed to it's limit in terms of state management and component composition. The student had to design the UI in such a way as to minimize UI elements depending on each other for state. Although there still are nevertheless some less than ideal control implementations.

One example would be how column name labels in the graph view had to depend on a variable that told it when to update the text- this variable had to be manually set each time anything changed in the UI that prompted the column names to update such as a file upload. This is fine for a single variable but with more similar controls it would become very difficult to cover all edge cases and keep everything up to date. A state machine abstraction as discussed in 5.6 to manage states would be ideal.

Any considerable future UI work will preferably need to bring on some helping tool to minimize development time and complexity.

5.8.3 Summary. All user stories were completed as expected and the application was pushed to production on March 18th. The usability of the application took a considerable upgrade this sprint-

with the application itself almost fully completing both feature sets User Testing 1 and Further Improvements.

5.9 Sprint 8 - Start March 19

5.9.1 Plan. This was the 8th sprint and expected to be the last sprint before user testing 2 could start. 3 user stories were initially selected (See Table 12 and Story 49 in Table 13) for development with a total workload of 13 points over a 5 days span. Most of the time this sprint was dedicated to preparing for user testing over development. Nevertheless this was still an important sprint that covered some of the last few to be implemented Should stories.

5.9.2 Implementation. Implementation went as expected except for story 49- It was decided mid-development to skip this story to focus more on writing the report and finishing user stories. The story also was expected to have a heavy performance penalty unless extensive work was done to add dedicated database support for it (See Story 49 further discussed in 6.2 and 8.2) Otherwise the stories that were developed mainly consisted of some minor UI additions to improve usability.

5.9.3 Summary. All stories except for 49 were completed and the application was pushed to production on March 29th. With this sprint, the application was ready to be user tested again, and development was considered finished for this project.

5.10 Implementation Summary

Development of the application started on the 26th of December and ended on the 29th of March with 8 Sprints done. In that time, the following feature sets were completed (See each sprint for details of stories done):

- The MVP feature set (Created from the initial brief as per section 3.2) was fully completed (All stories in set were implemented).
- User testing 1 feature set (Created from user feedback as per 6.2) was completed except for the stories mentioned on table 13.
- All Further Improvements 1 feature set stories (Inspired from user feedback as per 6.3) were completed.

Each sprint was assigned stories from these sets and the subsequent design and implementation followed to implement those stories. The resultant application developed is described as per section 7. Design wise, the UML Class Diagram shown by figure 23 represents the final design of the application created. Which developed over each sprint in an agile way- with the initial UML Class diagram design being as shown in Section 4.3, Figure 5.

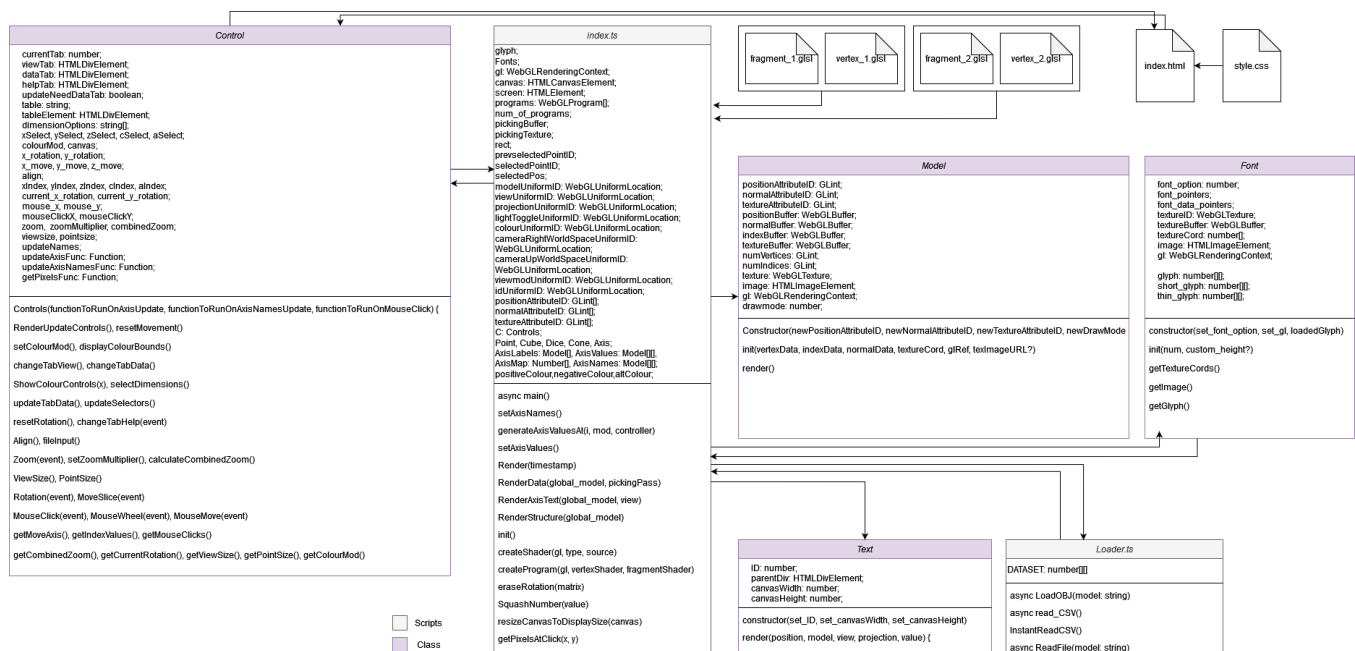


Figure 20: UML Diagram - Final App Version

ID	Title	Estimate (Relative)
3	As a User, I want to be able to view a scatter-plot of data set against an axis with accurate scales	5
11	As a User, I want all interactive parts of the Application to be visible at all times	1

Table 3: MVP Feature Set, Sprint 1

ID	Title	Estimate (Relative)
8	As a User, I want the application to have easy to use on screen controls for interacting with the application	3
1	As a User, I want to be able to import a dataset into the application to graph it in a 3 dimension scatterplot	3
18	The Axis should scale with the values shown	5
7	As a User, I want to be able to rotate the 3D Scatterplot around all 3D axis individually	5

Table 4: MVP Feature Set, Sprint 2

ID	Title	Estimate (Relative)
2	As a User, I want to be able to navigate around the generated graph in 3D space while having the axis stay accurate	6
5	As a User, I want to move the 3D view of the scatterplot in 3D using on screen controls	3
6	As a User, I want to be able to zoom in and out of the 3D Scatterplot	10
9	As a User, I want to be able to access the application on landscape screens of different sizes	2
24	UI doesn't scale very well and not all controls visible	3

Table 5: MVP Feature Set, Sprint 3

ID	Title	Estimate (Relative)
10	As a User, I want to be able to view instructions within the application on how to use the application	2
26	The User should be able to change the size of the data points	2
29	The User should have the ability to use Mouse Controls for transformation controls	3
30	There should be a visible way to identify negative axis values	3

Table 6: MVP Feature Set, Sprint 4

ID	Title	Estimate (Relative)
43	Refactor Needed (MVC Pattern potential)	5
41	Each Axis should be named / display a name based on the column names in the dataset	4

Table 7: Backlog Tasks, Sprint 5

ID	Title	Estimate (Relative)	MoSCoW
52	As a Tester, I want data labels to be always visible even when zooming	2	Must
54	Mentioned by Testers, If the slice viewed is not at origin, then using the data zoom should not result in data points moving out of the graph	5	Must
53	As a Tester, I want to be able to click on a data point and have the value of that point be displayed	8	Must

Table 8: User Testing 1 feature set, Sprint 6

ID	Title	Estimate (Relative)	MoSCoW
42	Create a more robust zoom not limited to only 2 levels	7	Must
70	Have a Favicon	1	Must

Table 9: Further Improvements feature set, Sprint 6

ID	Title	Estimate (Relative)	MoSCoW
58	As a Tester, I want to be able to return the graph to it's starting point with a button click	1	Must

Table 10: User Testing 1 feature set, Sprint 7

ID	Title	Estimate (Relative)	MoSCoW
63	The application should be able to use saturation as an extra dimension	6	Must
64	The application should have an option to apply columns to different dimensions	9	Should
74	The application should have a view where the data table can be viewed	5	Should

Table 11: Further Improvements feature set, Sprint 7

ID	Title	Estimate (Relative)	MoSCoW	Feature Set
47	As a Tester, I want to be able to zoom in and out of the graph using the scroll wheel	1	Should	User Testing 1
48	As a Tester, I want to be able to focus on a single axis through the click of a button- i.e View the graph from one side	2	Should	User Testing 1

Table 12: User Testing 1 feature set, Sprint 8

ID	Title	Estimate (Relative)	MoSCoW
50	As a Tester, I want to be able to view trend lines generated from the data	10	Should
51	As a Tester, I want there to be lines that can help identify the data points location	3	Should
56	As a Tester, there should be no performance issues when using Opera	?	Should
57	As a Tester, Graph fully doesn't render in rare cases	?	Must
60	As a Tester, I want to be able to highlight multiple data points to more easily track patterns	4	Could
55	As a Tester, Nodes should not overlap	?	Could
49	As a Tester, I want to be able to search for a specific point- such as "Find a point above $x = 5$ if it exists"	10	Could

Table 13: User Testing 1 feature set, Stories not implemented

ID	Title	Estimate (Relative)	MoSCoW
81	As a Tester, The mouse zoom should be flipped to scroll up to zoom in and scroll down to zoom out	1	Must
82	There is a chance that axis titles get stuck and don't update when another file is input	3	Must
83	As a Tester, I would like better performance with large datasets to better concentrate	10	Should
84	As a Tester, I would like data points with saturation to be outlined to be easier to see	4	Should
85	Fix bugs with picking, not accurate and jumps back to a point when nothing is selected	2	Must
86	Files are still uploaded if they are not CSV, have it so name of failed to upload file is not shown	1	Must
87	Labels Flicker bug	8	Must
88	Labels are not clipped correctly, remaining dots	5	Must
89	Headers in Data Management do not match with table	2	Must
90	As a Tester, I would like to use full Colour as a dimension	5	Should
91	As a Tester, I would like scroll bars to rotate the camera	2	Could
93	As a tester, I would like a "Feature Finder" that zooms into where data is if it's beyond the current view position	7	Should

Table 14: User Testing 2 feature set, Stories not implemented

ID	Title	Estimate (Relative)	MoSCoW
94	Research and integrate a Modern UI framework or library to handle state and UI component management	10	Must
95	Optimize Model Class for higher performance	5	Must
96	Identify and fix any bugs causing inaccuracy in what point is selected	6	Must
97	Fix Fragment shader bugs causing unclear text	4	Must
98	Research SDF font's for clearer text	5	Could
99	Create Clearer Instructions for the 4th dimension controls	3	Must
100	Look into opportunities to rework how the 4th dimension controls work	5	Should

Table 15: Further Improvements feature set, Stories not implemented

6 EVALUATION

An important driving factor for this project and the application developed was a system of evaluation at all levels of development. To that end, the student employed a number of techniques and phases to convert feedback into actionable input that would then influence how the project progressed. Each of those techniques is covered in detail in the following subsections.

6.1 Development Testing Process

Under PXP, the refactor branch was adapted to also serve as a final testing stop before the student pushed code to production (See 3.5). Automated testing was considered as mentioned in the Design section (See 4.4) but was found to not be suitable for this project.

Instead, refactoring was done manually on the refactoring branch based on visual inspection for rendering artifacts. To help with this process, a python command line tool was written to generate a wide range of datasets for edge case testing. The datasets and python tool are all attached in appendix 9.0.4 but some notable datasets are as follows:

- DataCube - This is a data set that creates a 10x10x10 Cube of data points. If the application renders correctly, this dataset would fill every visible space (with a grid pattern) at the initial zoom and slice position. (See Figure 19)
- Terrain Data - This is a Stress test dataset consisting of perlin noise generated terrain coordinates in a 30x30x30 sized chunk of 27000 points. It is a test for not only performance but also ability to handle data points with decimal values. (See Figure 17)

Other testing datasets were also manually created using excel:

- Minimal Data - A single data point at 1, 1, 1. Minimal test to make sure uploading files works and renders correctly
- Hidden Data - 1 Point - A navigation and zoom test, single point at -25, 25, -25
- Negative Data - 100 Points all with one or more negative component. Made to test negative data
- CoffeeTestData - 10 Points - A simple dataset for testing during development
- StockTradeData - 5 Points - A simple dataset with larger values for testing during development

These datasets also served to provide a wide range of example data for user testers to use in addition to datasets created specifically for user testing:

- Coffee Shop Stats - 60 Points - For testing 4 dimension analysis
- Nutritional Information of Popular Cereals (Single Serving) - 100 Points - A dataset to test if users could notice patterns in 3D data using the application (See Figure 22)
- Secret Structure Data - 40,000 Points - Performance and navigation test, renders a Pyramid in negative y space, generated with Python (See Figure 21)
- Sine Wave - 200 Points - Tests specific point identification and general structure analysis

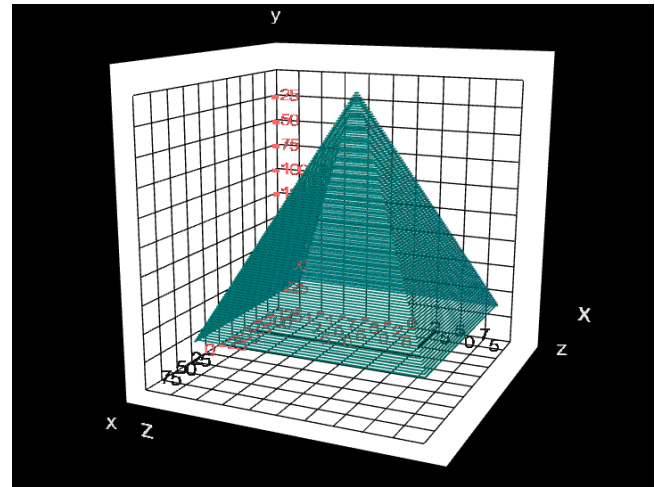


Figure 21: Secret Structure Data, Forms a Pyramid

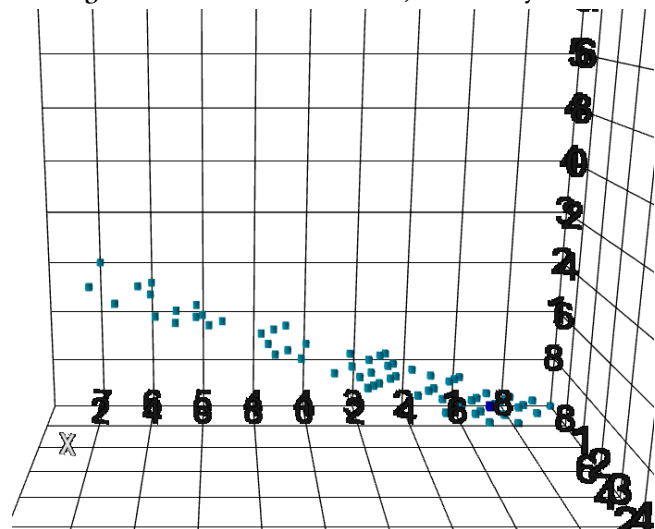


Figure 22: Nutritional Information of Popular Cereals (Single Serving)

6.2 User Testing

User testing was an important step in gathering requirements and paving the way for further development beyond the most basic, fundamental requirements. In total, 2 User testing phases were ran. The first one after the completion of the MVP feature set post Sprint 5 and the second one after the completion of the further additions feature set and user testing 1 feature set post sprint 8.

The process for these two phases revolved around an anonymous questionnaire with data collected as per the prepared ethics documentation for honours students (See all ethics documentation at Appendix 9.0.13). To support the testing process, the student created a simple static webpage to act as a central source for all links to the application, the questionnaire, testing data and ethics documentation that guided a tester through the entire process. Having

this page really simplified testing as the student would only need to share a single link which self-contained everything needed. The page itself and HTML source is available to view in the appendix 9.0.5.

The questionnaires themselves asked a tester to download a specific dataset and use the application to identify some factor or knowledge placed in the data by the student. The datasets were also designed in such a way that the questions could best be solved if the tester used some specific controls, or understood some aspect of the graph that the test focused on. This was then followed by the testers personal thoughts on a variety of questions concerning usability and how they went about solving the problems set out. An example task is as follows:

How large is the slice of terrain shown in terms of length in the x and z axis? Also alternatively, what is the highest point shown? Or the lowest. This is in the Terrain dataset. (User Testing Phase 1, Question 9)

The full list of questions from both testing phases can be viewed in appendix 9.0.6.

This questions gave the testers a real task to do which helped focus responses and allowed the student to construct a critical understanding of how real users used the application to solve typical problems the application was designed in mind with. Were users able to get the correct answer? What controls did they use? Did they use the controls as the student expected? Though it should be mentioned that the results likely aren't fully representative of the demographic tested due to the limited number of testers. Of which, a majority were computing students. This likely shifted results for usability specifically. Though ideally, testing tried to represent college students who were likely to work with data and all Adults in general.

The responses collected were then analyzed and turned into user stories to be developed, with the two testing phases each forming the User Testing 1 feature set and User Testing 2 Feature set respectively. The following give specific detail of each phase and the analysis performed on user stories. But in general, analysis followed a process where a users answer to a question or suggestion such as:

"Highest point - 6 Had trouble finding the lowest point Z-10 X-12" (Anonymous Tester 3, User Testing Phase 1, Question 9)

Would then imply that there may be opportunities to make point identification easier, the student then would research ways to solve this problem- possibly taking inspiration from other user answers such as:

"If you add the ability to highlight a data point you could also have the values highlight with them aswell" (Anonymous Tester 4, User Testing Phase 1, Question 21)

To then create a user story:

As a Tester, I want to be able to click on a data point and have the value of that point be displayed (Story 53, See Table 8)

Once the story is made, the student would consider the story's priority values as per section 3.4 with MoSCoW being based on how critical the issue that this story would solve is and how many testers mentioned issues that could be solved by the implementation of this story.

The process as above was applied to every response to generate stories. The following sections then give a high level overview of the resultant stories that arose from this analysis done in each of the phases. All questionnaire questions and responses are also available to view at Appendix 9.0.6.

6.2.1 User Testing 1 - Starting February 17th. This was setup and ran right after sprint 5 was complete. The focus for this testing phase was to identify what controls were still missing to help users do real work using the application. The questionnaire was created to that end and user testing began. The user testing was then concluded a week later with 5 total responses. In general responses were positive, though there were some trending limitations and gripes across testers:

- Controls were good but a bit bare-bones. Most suggestions recorded were quality of life additions to the UI.
- Identifying specific node values was the least popular task across testers. With the overall NPS (Net Promoter Score) being at a -25, the lowest recorded value in the test.

These points were interesting because otherwise, most testers rated ease of control usability quite high- At a NPS score of +40. The overall feel was that the user controls that were there were good but not enough to fully explore the data as was asked.

The answers given formed user stories which were analyzed and prioritized using MoSCoW and the Workload Estimate system previously used for the MVP feature set. All of theses stories formed the User Testing 1 feature set which was given a 1 month total development time (to be completed on the 1st of April). The feature set was then divided among 4 sprints as follows:

- Sprint 5 - See Stories on Table 7
- Sprint 6 - See Stories on Table 8
- Sprint 7 - See Stories on Table 10
- Sprint 8 - See Stories on Table 12
- Some User Stories though, were chosen to not be developed, they are mentioned here (See Table 13)

Some notable analysis notes on user stories follows:

- Story 57 (See Table 13) was pinpointed to Apple Devices, which would not render the chart correctly. It is unknown what the issue exactly is but it is likely something to do with how Apple supports WebGL [21] (See 'Metal' in 2.2.3).
- Story 56 (See Table 13) was created after one tester mentioned poor performance using the Opera browser. Nothing specific towards this claim was found so this may have been a problem on the testers device.
- Story 50 (See Table 13) was created on popular demand to have automatically rendering trendlines. This would have required a math library to generate a best fit line for the data which would be rendered. This task was not assigned to a sprint due to limited time but could be a good future addition.

- Story 51 (See Table 13) was proposed to solve the same point identification as picking which was done in favor of this as it was more popular (and helpful in the Students opinion).
- Story 49 (See Table 13) was created after a tester asked if they could search thorough the data. This is an interesting use case that implies the suitability of having a database backend for running queries on data as a possibly useful feature. See Databases in Future work, 8.2
- Story 55 (See Table 13) was created when a tester asked for data points to not intersect. This was found to be too difficult to cover edge cases for as a balance between visibility and non-interaction had to be found for any possible values of points- This story was abandoned in favor of keeping the user themselves in control of sizing

In summary, this user test identified a number of UI problems and opportunities to expand how users can better interact and view the data.

6.2.2 User Testing 2 - Starting March 30th. This was setup and ran right after sprint 8 was complete. The focus for this testing phase was to see if the new controls made tasks easier to do and what users thought of the new 4th dimension representation. The questionnaire was once again created and the testing concluded on the 21st of April with 8 responses. In general, responses were positive and trended towards being more positive than during the last user test- previous testers (The questionnaire asked to answer some questions if they previously tested, See 9.0.6) rated the application as much better with an overall NPS score of +100. Further key points were as follows:

- Identifying specific node values rose from an overall NPS of -25 to +57, with multiple testers mentioning that they used the new hover system to identify points. This implies that the new picking system for selecting points successfully solved the arguably biggest issue identified during the last user test (See Identifying specific node values in 6.2.1).
- The new zoom was unanimously favored over the old one by repeating testers- and positively viewed by new testers.
- The Data Management had a positive impact on user experience. Most testers used it in their tasks and found it as a helpful addition to the overall graph view. Though many testers mentioned bugs in how the table was presented and with some selectors. This was found to be likely a result of state bugs specifically and a cause of uncovered edge cases.
- The Help tab was much less popular than the other tabs but still was rated as useful by the few testers that used it.
- Clarity of data points was the biggest issue mentioned by multiple people. Bad clarity was mentioned in general with specific descriptions being "grittiness", "flickering" and "dots on numbers".
- The 4th dimension had mixed results, most testers did not understand it's use and opted to use only the 3D graphing functionality. Those that did use it mentioned further difficulty with how to use it.

The overall consensus was that usability and design has improved dramatically over the first user testing phase and most

issues mentioned dealt with bugs rather than problems with using the application. As for the 4th dimension, it's addition to the application had not been done very well. Further design and modification will be required to better communicate it's use and simplify operation for users.

The answers given were once again analyzed and prioritized using MoSCoW and the Workload Estimate system previously used. All of these stories formed the User Testing 2 feature set which would make a good start for future development. The user stories are all compiled here (See Table 14)

Some notable analysis notes on user stories are as follows:

- Story 87 was been pinpointed to be a performance issue when labels are updated, such as when the graph slice is moved using the movement controls (See 5.3 for more details) This confirms that the decision done to prepare all labels before rendering was the right way to go as otherwise labels would flicker constantly every frame (See glyph rendering rework in 5.3). Though the performance is still not suitable, the model class would have to be looked at for opportunities to increase performance.
- Story 88 refers to user tester mentioning dotted dots on numbers. The student believes that this may be some issue with how the fragment shader for text clips the texture. Further optimization and research is needed.
- Story 85 mentions inaccuracy in picking. This could be caused by the off-screen buffer texture somehow becoming out of tune with the size of the actual screen (Resizing browser tab) but further research is needed to confirm this and identify any other edge cases.
- Story 83 may be a repeated issue with the Opera browser but is likely also the result of more demanding datasets given to be tested (See Secret Structure Data in 6.1)

In summary, this testing phase has made a number of important points very clear for the application. The functionality that is there is very successful and fixes almost all problems previously faced by by testers during the first test phase. Except for the 4th dimension functionality, the application implements all needed controls and functionality to be a successful analysis tools for the questions poised to testers. The main drawbacks though are a number of bugs within the UI and within the renderer. The bugs within the UI almost all stem from incorrect management of state edge cases and is the first time a precedent is set to justify bringing in outside tools for the direct sake of the user experience quality. Otherwise, when this problem was last visited this important precedent was missing (See the refactoring discussion during sprint 5, 5.6).

6.3 Further Improvements Feature Set

The further improvement feature sets were created to encompass all created tasks that did not directly link back to a suggestion or issue mentioned by testers. These tasks instead focused on what the student thought would be valuable additions based on their research (Similar to how the MVP feature set was created, see 3.2) and analysis of user testing trends. 2 of these feature sets were created in total with each being in tandem with the creation of the User testing feature sets (See 6.2). These feature sets were considered by the student as an important part of overall evaluation and acted as

a culmination of further gathered requirements in the context of user testing.

Further Improvements Feature Set 1 tasks were allocated across the 4 sprints after sprint 4, to be completed in 1 month (On the 1st of April). The set consisted of 6 total tasks and focused on general ideas that the student had to improve the application. Those can be seen per sprint as follows:

- Sprint 6 - See Stories on Table 9
- Sprint 7 - See Stories on Table 11

Further Improvements Feature Set 2 would make a great starting point for future development. This set consists of 7 total tasks and focuses on ways to fix the applications current problems. Those tasks can be seen on Table 15.

7 FINAL PRODUCT

The Application developed is a client-side, web-based plotting application rendering a 3D cube graph showing 10 values on each axis. CSV data can be uploaded and the user can select which columns to render on which axis's, 3 of which are positional and one modifying the saturation of the plotted point. Provided user controls include buttons to allow the user to move each axis separately to show a different slice of values, zooming controls to increase or decrease the difference between each axis line, rotation through mouse dragging or button clicking, changing data point sizes, modifying how saturation is applied to labels, selecting points on hover to view the values they represent. The application also allows the user to view the data uploaded in a tabular format. The application can be accessed on different devices with different screen sizes including mobile devices as long as WebGL and a reasonably modern browser is available. Although highly dependant on device specifications, the application can be reasonably expected to render data with 1,000+ Data points. With Modern laptops found to be capable of rendering at least 40,000 non-decimal Points with acceptable performance. This functionality is provided by a total of 3 tabs, The Graph Tab (See Figure 23), The Data Management Tab (See Figure 24), The Help Tab (See Figure 25).

8 CONCLUSIONS

The following look at the results achieved by the project and future opportunities.

8.1 Appraisal

The final application created is believed by the student to have successfully hit the initial goals set forth (See section 2.3). In terms of direct comparison to the market competitors looked at in Appendix 9.0.1- The application fit's in as follows:

- The application created has simple controls similar to Tableau that can be used by users without programming experience. The Application created can also be used to create both 3D and 2D (2D in a 3D view) scatterplots, which is not directly supported in Tableau (Only a 2D view is available). Though Tableau has a greater variety of charts that can be created, which although in a 2D view are much more flexible and can be used to display Multidimensional data through other features such as colour.

- The Application provides a number of user controls that can modify the chart created in realtime. These controls are a lot more limited than those offered through MATLAB or GNU Plot but they do not require code to be written and ran before the plot is rendered, which allows data to be more easily explored (See section 4.5).

In general, The application created is a viable market entry that simplifies the creation of scatterplots and offers a wide range of controls. It may not have as many features and controls as some other market options, but it's simple operation and support of up to 4 dimensions gives it a valuable place on the market according to the students initial research (See section 2.1.2).

The only major shortcoming according to the initial goals would be the lower focus on Big Data capability and support. The Student believes that this was nevertheless a correct decision, focusing on the basic visualization and accessibility has lead to the creation of a usable application that is in a good position to be further developed to fully support Big Data- Something that would have been much more complex to do from the start. Even at the current state of the application there is still some support for 2 properties [25] of Big Data:

- Size - The application is capable of rendering large datasets and the slice view design allows a smaller subset of data to be rendered at a time to avoid resource strain.
- Complexity - Up to 4 dimensions can be viewed and relationships compared, the student believes that this is helpful to addressing some complexity of data, but further design and research opportunities exist to address other complexity aspects. [25]

Another minor shortcoming would be that no other graph type was implemented- It would have been nice to allow the user to view the data through different graph types but it wouldn't have been possible to provide as many controls as for a single-focused charting application. Though with the abstractions in place created for scatter plots, future addition of new graphs would be much simpler and faster.

In terms of preparation, Prototyping was key for this project and allowed the student to practice using unfamiliar tools and debug the majority of setup issues before development started- which allowed the student to start development focusing on user stories instead of debugging issues. The creation of prototype 2 also greatly sped up development by getting basic rendering functionality done further allowing greater focus on user stories. (See 4.3 for more details)

PXP also set a good base agile methodology (See 3.1 for more details) that the student could restructure to fit the project. Those changes all helped the student to work more efficiently and greatly helped with tracking project progress. Though the inability to apply automated testing to rendering was a definite limitation. For a future project, it would be great to allocate some time for a prototype to figure out a Selenium based or otherwise technique to create general purpose tests that would ideally need as little change as possible on running. (See 4.2 for more details)

As for the process of creating the application, The student believes that the tech stack selected was a good choice even if there were some limitations.

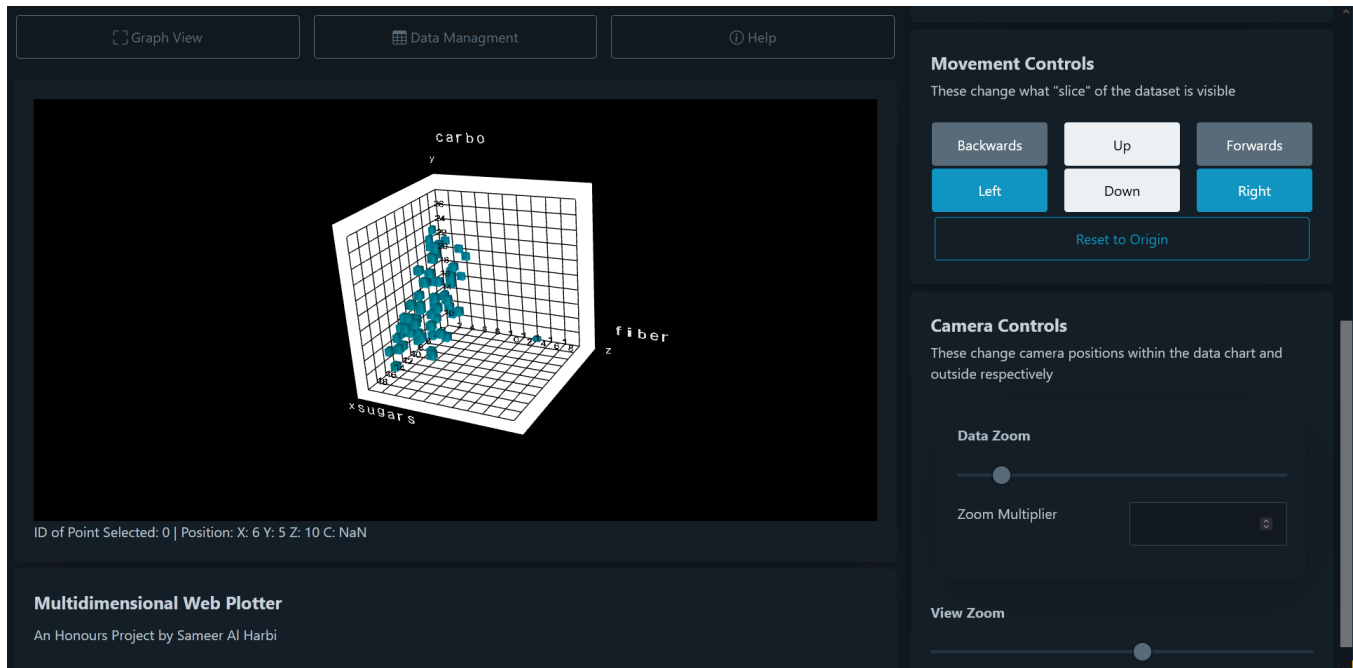


Figure 23: Graph View - Final App Version

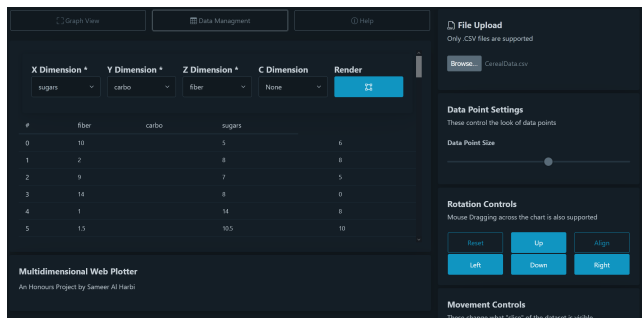


Figure 24: Data Management View - Final App Version

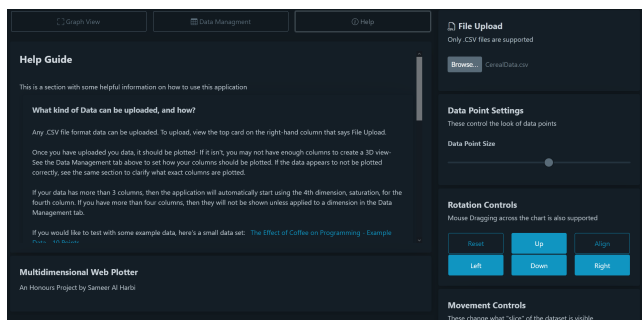


Figure 25: Help View- Final App Version

- WebGL was a good choice for a rendering API- It was highly performant and it's flexibility gave greater freedom to explore novel techniques and rendering designs. It's only

downsides would be mixed support by Apple devices [10] which limited the applications device accessibility.

- Using plain HTML for writing the view was not the best choice. Though in the context of this project it made sense to not bring in a UI framework, The student was already using many tools they haven't worked with before so it helped keep things simple- The agile approach also contributed to uncertainty on how useful a framework would be due to limited design done before development started. The Student would recommend future projects to consider options such as svelte or react to simplify UI development and simplify UI state bugs.

8.2 Future Work

The application as is has potential for future development. Both in improving upon what the current application is already capable of doing and preparing it for further additions and expansions. The User testing 2 feature set and further improvements 2 feature set in particular (See 14 and 15 respectively) are a great place to start for debugging and polishing up the current functionality. Beyond that, there are also a number of 'Under the hood' issues that would be helpful to address for future development

- Optimize rendering- There remain a lot of opportunities to optimize shaders and rendering in general. For instance, changing the default cube model (used to render data points) to something with less geometry could considerably speed up rendering. There is also opportunity to rework some aspects such as labels to focus more on saving memory vs cpu performance based on how Font + Model is made to interact. (See 5.2) There may also be opportunity to refactor

the application to use WebGPU, which is a yet unreleased high-performance low-level graphics standard for the web inspired by Vulkan which should help increase performance even further. [55] [34]

- Refactor UI rendering- As seen during User Testing 2 (See 6.2.2), the application UI has reached a level of complexity where the lack of a supporting UI library/Framework is starting to affect the quality of user experience as a consequence of more complex development. Any future UI work will benefit greatly from integrating a UI framework to handle components and state in particular. The Students recommendation would be React due to it's leading popularity among developers at the time being. [43]
- There is currently a limitation on what kind of controls can be done with the data. When data is uploaded, it is stored in memory as a variable. This means that the maximum amount of data directly depends on how much RAM the user's device has- and with the store being a simple variable, controls such as searching for a point cannot be optimized with database engine techniques such as indexing. This is probably at the moment the biggest hurdle holding back further big data support. A high-performance database would be ideal, either embedded into the application or as a server side component- with the server-side option providing better potential performance due to an independence from what the users hardware can handle. Though these additions will require greater care to ensure that the application is compliant with data security laws (See 4.6).

Addressing these limitations would open up opportunities to effectively develop further additions for the project, some ideas by the student are as follows:

- Address Velocity property of big data [7] This will likely involve creating an API interface for the Application to connect to sensors or a rapidly changing database and optimizing the application to render as updates come in.
- Study further design techniques to reduce cognitive complexity of Multidimensional data. It's easy to add and render more dimensions but it's difficult to make it understandable enough to easily extract patterns. This point was looked at during the research phase, see 2.1.3.
- Add new chart types to visualize different data or the same data in another way, Radar charts were identified as a possible option during this project. (See 2.1.4)

8.3 Personal Development Appraisal

The Student believes that this was a very productive project. learning wise, this project was the largest and longest piece of continuous they ever done and proved quite unique in the freedom it provided to plan and work as decided- which did in some cases prove challenging with the large amounts of decisions that came with it. The technologies used were all new for the student (Except for HTML, CSS and Python) and this project was the first time they used them. WebGL is particular was a huge departure from previous high Level API's used by the student and took considerable learning to grasp- Though taking the Graphics Module in Semester 1 which taught OpenGL greatly sped up the learning process. With the completion

of this project the student feels they have gained extensive practical experience in frontend, graphics development and more generally a better ability to manage and plan their work.

8.4 Acknowledgments

The student would like to thank all testers who took the time to complete the questionnaire assigned to them in either of the two testing phases, the students supervisor and everyone else who helped organize the honours project module. The Student would also like to acknowledge the following sources that helped create this project:

- All Open source tools used as per section 4.1, the use of Diagram.net for helping create UML Diagrams [30], mybib for helping form citations [38] and Overleaf for creating some project documents [44].
- The following learning materials [14] [5] [2] [35], of which some snippets of code were copied or inspired from as further labelled in the Application source code.

8.5 Summary

This paper highlights a project undertaken by the student to develop a web-based, client-side scatterplot visualization application for Multidimensional data using graphics rendering technology (WebGL). The development process is shown from the beginning where the project background and initial concept (to create an accessible, Big data capable application) was formulated followed by formal specification and design decisions that drove an agile based, user testing driven development phase over the course of 3 months. A final review and analysis of the developed application follow with the created Applications limitations and suggestions for future development opportunities.

9 APPENDICES

The following is a list of referenced appendices in the report. Please find the corresponding files in the submission.

- 9.0.1 A1. Notes on market competitors / similar applications on the market
- 9.0.2 A2. Analysis on different graph types and their application to 3D+ Data.
- 9.0.3 A3. Initial Requirements brief created by the student standing in for the Client.
- 9.0.4 A4. All testing datasets created for the project
- 9.0.5 A5. Latest HTML source code for testing instructions webpage, link to hosted page shared with testers and link to github repository
- 9.0.6 A6. User testing questionnaire questions and responses.
- 9.0.7 A7. Software source code, Latest Production branch
- 9.0.8 A8. Software source code, Production branch tested during User Testing 1
- 9.0.9 A9. Software source code, Prototype 2
- 9.0.10 A10. Software source code, Prototype 1

9.0.11 A11. User Manual, How to use the application and where to access it

9.0.12 A12. Meeting Minutes with advisor

9.0.13 A13. Ethics Declaration Form. Including the information sheet and a blank consent form.

9.0.14 A14. Risk Assessment Form

9.0.15 A15. Mid-term project progress report

9.0.16 A16. Project demonstrations material, includes a Poster

9.0.17 A17. UML diagrams

REFERENCES

- [1] StatCounter Global Stats [n.d.]. *Desktop Browser Market Share Worldwide*. StatCounter Global Stats. <https://gs.statcounter.com/browser-market-share/desktop/worldwide/#monthly-202110-202110-bar> (Accessed 4/12/2023).
- [2] [n.d.]. Home. <http://www.opengl-tutorial.org/> (Accessed 4/23/2023).
- [3] v8.dev [n.d.]. *V8 JavaScript engine*. v8.dev. <https://v8.dev/> (Accessed 4/12/2023).
- [4] webassembly.org [n.d.]. *WebAssembly*. webassembly.org. <https://webassembly.org/> (Accessed 4/12/2023).
- [5] [n.d.]. *WebGL Fundamentals*. <https://webglfundamentals.org/> (Accessed 4/23/2023).
- [6] Ravikant Agarwal and David Umphress. 2008. Extreme Programming for a Single Person Team. In *Proceedings of the 46th Annual Southeast Regional Conference on XX* (Auburn, Alabama) (ACM-SE 46). Association for Computing Machinery, New York, NY, USA, 82–87. <https://doi.org/10.1145/1593105.1593127>
- [7] Syed Mohd Ali, Noopur Gupta, Gopal Krishna Nayak, and Rakesh Kumar Lenka. 2016. Big data visualization: Tools and challenges. In *2016 2nd International Conference on Contemporary Computing and Informatics (IC3I)*. 656–660. <https://doi.org/10.1109/IC3I.2016.7918044>
- [8] Amazon. [n.d.]. *What is Java? - Enterprise Java Beginner's Guide - AWS*. Amazon Web Services, Inc. <https://aws.amazon.com/what-is/java/> (Accessed 4/12/2023).
- [9] Apple. [n.d.]. *Apple Developer Documentation*. <https://developer.apple.com/documentation/apple-silicon/porting-your-macos-apps-to-apple-silicon> (Accessed 4/13/2023).
- [10] Apple. [n.d.]. *Metal*. <https://developer.apple.com/documentation/metal/> (Accessed 4/13/2023).
- [11] BillWagner. 2022. A tour of C# - Overview. <https://learn.microsoft.com/en-us/dotnet/csharp/tour-of-csharp/> (Accessed 4/13/2023).
- [12] MDN Contributors. [n.d.]. *JavaScript*. <https://developer.mozilla.org/en-US/docs/Web/javascript> (Accessed 4/13/2023).
- [13] davidbritch. [n.d.]. *What is .NET MAUI? - .NET MAUI*. learn.microsoft.com. <https://learn.microsoft.com/en-us/dotnet/maui/what-is-maui?view=net-maui-7.0> (Accessed 4/12/2023).
- [14] Joey De Vries. 2019. *Learn OpenGL*, extensive tutorial resource for learning Modern OpenGL. <https://learnopengl.com/> (Accessed 4/23/2023).
- [15] Blender Foundation. 2019. *blender.org - Home of the Blender project - Free and Open 3D Creation Software*. <https://www.blender.org/> (Accessed 4/22/2023).
- [16] Robot Framework. [n.d.]. *Robot Framework*. <https://robotframework.org/> (Accessed 4/14/2023).
- [17] Morteza Ghobakhloo. 2020. Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production* 252 (2020), 119869. <https://doi.org/10.1016/j.jclepro.2019.119869>
- [18] GrantMeStrength. 2021. *Direct3D - Win32 apps*. <https://learn.microsoft.com/en-us/windows/win32/direct3d> (Accessed 4/12/2023).
- [19] Khronos Group. 2011. *WebGL*. <https://www.khronos.org/api/webgl> (Accessed 4/12/2023).
- [20] Khronos Group. 2016. *Khronos Releases Vulkan 1.0 Specification*. <https://www.khronos.org/news/press/khronos-releases-vulkan-1-0-specification> (Accessed 4/12/2023).
- [21] Khronos Group. 2022. *WebGL 2.0 Achieves Pervasive Support from all Major Web Browsers*. <https://www.khronos.org/blog/webgl-2-achieves-pervasive-support-from-all-major-web-browsers> (Accessed 4/22/2023).
- [22] TM/©Khronos Group. 2017. *The Official WebGL Logo*. https://commons.wikimedia.org/wiki/File:WebGL_Logo.svg (Accessed 4/13/2023).
- [23] W.S. Humphrey. 1996. Using a defined and measured Personal Software Process. *IEEE Software* 13, 3 (1996), 77–88. <https://doi.org/10.1109/52.493023>
- [24] Kaoru Ishikawa. 1985. *What is total quality control? The Japanese way*. Prentice-Hall.
- [25] Avita Katal, Mohammad Wazid, and R. H. Goudar. 2013. Big data: Issues, challenges, tools and Good practices. In *2013 Sixth International Conference on Contemporary Computing (IC3)*. 404–409. <https://doi.org/10.1109/IC3.2013.6612229>
- [26] Javed Khan, Izaz Rehman, Yawar Khan, Iftikhar Khan, and Salman Rashid. 2015. Comparison of Requirement Prioritization Techniques to Find Best Prioritization Technique. *International Journal of Modern Education and Computer Science* 7 (11 2015), 53–59. <https://doi.org/10.5815/ijmecs.2015.11.06>
- [27] Steve Klabnik and Carol Nichols. 2023. *The Rust Programming Language, 2nd Edition*. No Starch Press.
- [28] Tingting Liang, Shan Lu, and Quansheng Liu. 2020. *Data Visualization System Based on Big Data Analysis*. , 76-79 pages. <https://doi.org/10.1109/ICRIS52159.2020.00027>
- [29] Joy Lowe and Machdel Matthee. 2020. Requirements of Data Visualisation Tools to Analyse Big Data: A Structured Literature Review. In *Responsible Design, Implementation and Use of Information and Communication Technology*, Marié Hattingh, Machdel Matthee, Hanlie Smuts, Ilias Pappas, Yogesh K. Dwivedi, and Matti Mäntymäki (Eds.). Springer International Publishing, Cham, 469–480.
- [30] JGraph Ltd. [n.d.]. *Diagram Software and Flowchart Maker*. <https://www.diagrams.net/> (Accessed 4/23/2023).
- [31] MathWorks. [n.d.]. *3-D scatter plot - MATLAB scatter3*. <https://www.mathworks.com/help/matlab/ref/scatter3.html> (Accessed 4/22/2023).
- [32] Microsoft. [n.d.]. *TypeScript - JavaScript that scales*. <https://www.typescriptlang.org/> (Accessed 4/13/2023).
- [33] Microsoft. [n.d.]. *What is .NET? An open-source developer platform*. Microsoft. <https://dotnet.microsoft.com/en-us/learn/dotnet/what-is-dotnet> (Accessed 4/12/2023).
- [34] Mozilla. [n.d.]. *WebGPU API - Web APIs | MDN*. https://developer.mozilla.org/en-US/docs/Web/API/WebGPU_API (Accessed 4/22/2023).
- [35] Mozilla. 2019. *MDN Web Docs*. <https://developer.mozilla.org/en-US/> (Accessed 4/23/2023).
- [36] Mozilla. 2019. *WebGL: 2D and 3D graphics for the web*. https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API (Accessed 4/12/2023).
- [37] mrdooob. [n.d.]. *three.js*. <https://github.com/mrdooob/three.js/blob/dev/README.md> (Accessed 4/13/2023).
- [38] MyBib. 2018. *MyBib - A New FREE APA, MLA, Harvard Bibliography Generator*. <https://www.mybib.com> (Accessed 4/23/2023).
- [39] Benjamin Nicoll and Brendan Keogh. 2019. *The Unity Game Engine and the Circuits of Cultural Software*. Springer International Publishing, Cham, 1–21. https://doi.org/10.1007/978-3-030-25012-6_1
- [40] Node.js. [n.d.]. *Node.js*. <https://nodejs.org/en> (Accessed 4/12/2023).
- [41] Ekaterina Olshannikova, Aleksandr Ometov, Yevgeni Koucheryavy, and Thomas Olsson. 2015. Visualizing Big Data with augmented and virtual reality: challenges and research agenda. *Journal of Big Data* 2 (2015), 22. <https://doi.org/10.1186/s4053701500312>
- [42] Oracle. [n.d.]. *What is Java technology and why do I need it?* Java.com. https://www.java.com/en/download/help/whatis_java.html (Accessed 4/12/2023).
- [43] Stack Overflow. 2021. *Stack Overflow Developer Survey 2021*. <https://insights.stackoverflow.com/survey/2021> (Accessed 4/12/2023).
- [44] the Online LaTeX Editor Overleaf. 2019. *Overleaf, Online LaTeX Editor*. <https://www.overleaf.com/> (Accessed 4/23/2023).
- [45] Mark Segal and Kurt Akeley. 2022. *The OpenGL® Graphics System: A Specification (Version 4.6 (Core Profile) - May 5, 2022)*. <https://registry.khronos.org/OpenGL/specs/gl/glspec46.core.pdf> (Accessed 4/12/2023).
- [46] Selenium. [n.d.]. *The Selenium Browser Automation Project*. <https://www.selenium.dev/documentation/> (Accessed 4/14/2023).
- [47] SmartBear. [n.d.]. *TestComplete | SmartBear Software*. <https://smartbear.com/product/testcomplete/> (Accessed 4/13/2023).
- [48] Smartbear. [n.d.]. *TestComplete Pricing | Automated Software Testing Tool*. <https://smartbear.com/product/testcomplete/pricing/> (Accessed 4/14/2023).
- [49] stevehwims. 2021. *Direct3D 12 programming environment setup - Win32 apps*. <https://learn.microsoft.com/en-us/windows/win32/direct3d12/directx-12-programming-environment-set-up> (Accessed 4/12/2023).
- [50] Bjarne Stroustrup. 1986. An Overview of C++. *SIGPLAN Not.* 21, 10 (jun 1986), 7–18. <https://doi.org/10.1145/323648.323736>
- [51] Unity Technologies. [n.d.]. *Unity - Manual: Graphics API support*. <https://docs.unity.cn/Manual/GraphicsAPIs.html> (Accessed 4/13/2023).
- [52] threejs.org. [n.d.]. *three.js docs*. <https://threejs.org/docs/index.html#manual/en/introduction/Installation> (Accessed 4/13/2023).
- [53] GOV UK. 2018. *Data Protection Act*. <https://www.gov.uk/data-protection> (Accessed 4/23/2023).
- [54] Johannes Unterguggenberger, Bernhard Kerbl, and Michael Wimmer. 2023. Vulkan all the way: Transitioning to a modern low-level graphics API in academia. , 155–165 pages. <https://doi.org/10.1016/j.cag.2023.02.001>
- [55] W3C. 2023. *WebGPU*. <https://www.w3.org/TR/webgpu/> (Accessed 4/22/2023).
- [56] OpenGL Wiki. 2022. *History of OpenGL - OpenGL Wiki*. http://www.khronos.org/opengl/wiki_opengl/index.php?title=History_of_OpenGL&oldid=14895 (Accessed 4/12/2023).
- [57] TM/©Microsoft. 2020. *Typescript logo* 2020. https://commons.wikimedia.org/wiki/File:WebGL_Logo.svg (Accessed 4/13/2023).