Imperial College London

MEng Individual Project

Department of Computing

Imperial College of Science, Technology and Medicine

A Virtual Volumetric Screen

Author:
Robert Searby Buxton

Supervisor:
Dr Nicole Salomons

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Abstract

TODO

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I would like to thank **in order of importance**:

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- My loving family who still think I am studying physics for some reason.

Contents

Chapter 1

Introduction

1.1 Motivations

A volumetric display is a type of graphical display device that can provide a visual representation of objects natively in 3D. They can be viewed from any angle without the need for special visual apparatus by multiple people simultaneously [11]. These displays differ from more traditional virtual reality devices in that they are not immersive, but rather they are a window into a virtual world (See Fig 1.1.1 and Fig 1.1.2). There is no real consensus on what exactly constitutes a volumetric display, let alone the best way to build one. As we cover in the background section there are currently many different approaches being attempted by research groups both academic and industrial to create these displays.

Figure 1.1.1: One of Columbia University's passive optical scattering based volumetric displays [23]

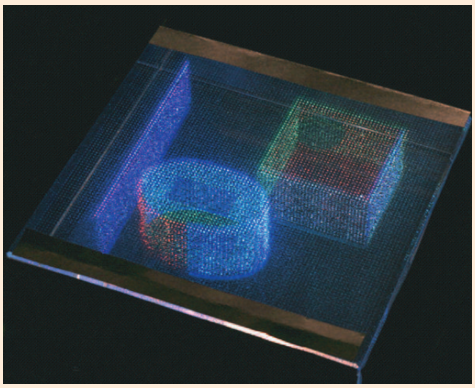
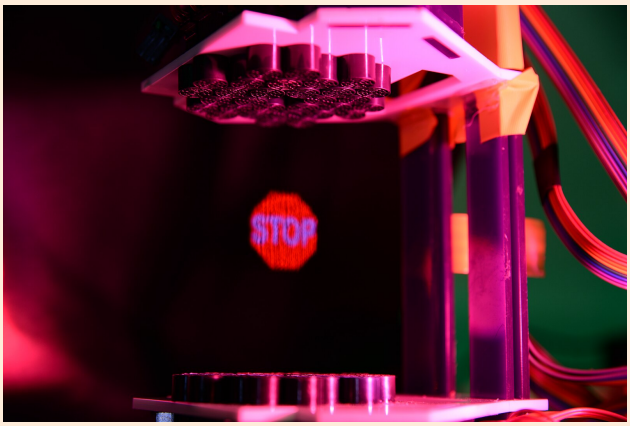


Figure 1.1.2: One of Bristol University's acoustic trapping based volumetric displays [14]



At the time of writing it is difficult to conduct human-computer interaction (HCI) research into the field of volumetric displays because these devices are not widely available, expensive and difficult to manufacture, and have extreme bandwidth requirements which makes it difficult to conduct user studies and experiments. People have created virtual simulations of volumetric displays before to try and solve this problem, but these solutions are often complicated and expensive to replicate.

1.2 Objectives

With the conclusion of this project, we aim to produce a cheap, multi-platform, lightweight and simple platform for simulating volumetric displays through the use of a Fish tank virtual reality (FTVR) device (See background). We hope that this will reduce the barrier to entry for researchers who wish to conduct HCI research in the field of volumetric displays. We aim to make the following contributions:

1.2.1 Volumetric Simulator

We plan to create a platform for simulating volumetric displays that is:

- **Multi-platform**: We have packaged our platform in the Nix package manager [7] which allows it to be easily run and ported to any platform and hardware that Nix supports.
- **Lightweight**: We use simple rending algorithms in OpenGL [26] to create our virtual volumetric display allowing our software to be computationally cheap to run compared to more fully-fledged rendering/games engines that might be used typically for HCI research like Unity.
- **Cheap**: By relying on only a generic depth camera and a standard display our software requires minimal hardware to run, making research conducted on our platform cheap and easy to run.
- **Reproducible:** By building with Nix we can guarantee that any experiments conducted using this platform will be completely reproducible. (See background)

1.2.2 User experiment

We plan to conduct an HCI user study to demonstrate the utility of our volumetric display simulation platform. We will conduct the user study to compare the relative effectiveness of using hand tracking to interact directly with an ethereal/incorporeal volumetric display compared to a via teleoperation with a corporeal/tangible display (See evaluation).

Chapter 2

Ethical Discussion

2.1 User Study

We ran a user study to evaluate our simulator titled ”A Virtual Volumetric Screen User Study”. We undertook Imperial College London’s ”Science Engineering Technology Research Ethics Committee process” which was reviewed by the ”Research Governance and Integrity Team” and the head of the computing department. We gained approval on the 2nd May 2024 and ran our study between May and July find first and last date of participants.

2.1.1 Human participants

As we ran our study on human participants we had to ensure we conducted our study in an ethical way. We consulted the Equality Act 2010 to make sure we did not exclude any participants ToCite . We were also careful to not use any participants that might feel perceived pressure to participate or might feel influenced by the researchers conducting the study. Participants were presented with an information sheet and a consent form before the study began.

2.1.2 Data collection

While collecting data for our study we were careful to comply with the local regulations (**GDPR**) ToCite . All data was stored on a secure computer on campus and was only accessible by the researchers, or was stored on Imperials secure cloud network. We also made sure to anonymise the data when presenting it in our report. Data will be retained until 30th June 2034.

2.2 Volumetric Simulator

2.2.1 Military applications

This technology in theory could be used for military applications, however, we believe is unlikely to be used for such purposes, and if it was, it would not be directly used in combat and would be no more dangerous than other existing technologies.

2.2.2 Copywrite Limitations

Open Source

We will be using the Azure Kinect SDK which is licensed under the MIT license. We will also be using the Nix package manager which is licensed under the LGPL-2.1 license. Furthermore, we will also be using the Nixpkgs repository which is licensed under the MIT license. We will also be using the `dlib` library which is licensed under the Boost Software License 1.0 (BSL-1.0). We will also be using the OpenGL library which is licensed under the open-source license for the use of sample Implementation (SI). Furthermore, we will also be using the GLFW library which is licensed under the zlib license. We will also be using the GLM library which is licensed under the MIT license. We will also be using the OpenCV license under the Apache License.

Proprietary

Furthermore, we use Microsoft's proprietary depth engine designed to work with the Azure Kinect SDK which is not open source.
Add other libraries we use

Chapter 3

Background

3.1 Nix/NixOS

3.1.1 Introduction to Nix

Nix [7] is an open-source, ”purely functional package manager” used in Unix-like operating systems to provide a functional and reproducible approach to package management. Started in 2003 as a research project Nix [6] is widely used in both industry [1] and academia [5] [21] [4], and its associated public package repository `nixpkgs` [13] as of Jan 2024 has over 80,000 unique packages making it the largest up-to-date package repository in the world [22]. Out of Nix has also grown **NixOS** [8] a Linux distribution that is conceived and defined as a deterministic and reproducible entity that is declared functionally and is built using the **Nix** package manager.

Nix packages are defined in the **Nix Language** a lazy functional programming language where packages are treated like purely functional values that are built by side effect-less functions and once produced are immutable. Packages are built with every dependency down to the `ELF` interpreter and `libc` (C standard library) defined in nix. All packages are installed in the store directory, typically `/nix/store/` by their unique hash and package name as can be seen in Fig 3.1.1 as opposed to the traditional Unix Filesystem Hierarchy Standard (FHS).

Figure 3.1.1: Nix Store Path

```
/nix/store/sbldylj3clbkc0aqvjjzfa6slp4zdvlj-hello-2.12.1
Prefix      Hash part                       Package name
```

Package source files, like tarballs and patches, are also downloaded and stored with their hash in the store directory where packages can find them when building. Changing a package's dependencies results in a different hash and therefore location in the store directory which means you can have multiple versions or variants of the same package installed simultaneously without issue. This design also avoids ”DLL hell” by making it impossible to accidentally point at the wrong version of a package. Another important result is that upgrading or uninstalling a package cannot ever break other applications.

Nix builds packages in a sandbox to ensure they are built exactly the same way on every machine by restricting access to nonreproducible files, OS features (like time and date), and the network [29]. A package can and should be pinned to a specific NixOS release (regardless of whether you are using NixOS or just the package manager). This means that once a package is configured to build correctly it will continue to work the same way in the future, regardless of when and where it is used and it will never not be able to be built.

These features are extremely useful for scientific work, CERN uses Nix to package the LHCb Experiment because it allows the software ”to be stable for long periods (longer than even long-term support operating systems)” and it means that as Nix is reproducible; all the experiments are completely reproducible as all bugs that existed in the original experiment stay and

ensure the accuracy of the results [4].

To create a package Nix evaluates a **derivation** which is a specification/recipe that defines how a package should be built. It includes all the necessary information and instructions for building a package from its source code, such as the source location, build dependencies, build commands, and post-installation steps. By default, Nix uses binary caching to build packages faster, the default cache is `cache.nixos.org` is open to everyone and is constantly being populated by CI systems. You can also specify custom caches. The basic iterative process for building Nix packages can be seen in Fig 3.1.2.

Figure 3.1.2: Nix Build Loop

1. A hash is computed for the package derivation and, using that hash, a Nix store path is generated, e.g `/nix/store/sbldylj3clbkc0aqvjjzfa6slp4zdvlj-hello-2.12.1`.
2. Using the store path, Nix checks if the derivation has already been built. First, checking the configured Nix store e.g `/nix/store/` to see if the path e.g `sbldylj3clbkc0aqvjjzfa6slp4zdvlj-hello-2.12.1` already exists. If it does, it uses that, if it does not it continues to the next step.
3. Next it checks if the store path exists in a configured binary cache, this is by default `cache.nixos.org`. If it does it downloads it from the cache and uses that. If it does not it continues to the next step.
4. Nix will build the derivation from scratch, recursively following all of the steps in this list, using already-realized packages whenever possible and building only what is necessary. Once the derivation is built, it is added to the Nix store.

3.1.2 Example of a Nix package

To give an example of what a Nix package might look like. We have created a flake (one method of defining a package) in Listing 3.1.1 that builds a version of the classic example package ”hello”.

Listing 3.1.1: flake.nix

```
{
  description = "A flake for building Hello World";
  inputs.nixpkgs.url = "github:NixOS/nixpkgs/nixos-23.11";

  outputs = { self, nixpkgs }: {
    defaultPackage.x86_64-linux =
      let
        pkgs = nixpkgs.legacyPackages.x86_64-linux;
      in
      pkgs.stdenv.mkDerivation {
        name = "hello-2.12.1";
        src = self;
```

```
13          # Not strictly necessary as stdenv will add gcc
14          buildInputs = [ pkgs.gcc ];
15          configurePhase = "echo 'int main() { printf(\"Hello World!\"); }' > hello.c";
16          buildPhase = "gcc -o hello ./hello.c";
17          installPhase = "mkdir -p $out/bin; install -t $out/bin hello";
18        };
19    };
20 }
```

To dive deeper into what each line does we have given a breakdown below for the `flake.nix`

- **Line 2:** We have specified that we want to build our flake with the stable **nix channel** `nixos-23.11`, the most recent channel at the time of writing. This ”channel” is just a release branch on the `nixpkgs` GitHub repository. Channels do receive conservative updates such as bug fixes and security patches but no major updates after the initial release. The first time we build the hello package from our `flake.nix` a `flake.lock` is automatically generated that pins us to a specific revision of `nixos-23.11`. Our built inputs will not change until we relock our flake to either a different revision of `nixos-23.11` or a new channel entirely.
- **Line 5:** Here we define `outputs` as a function that accepts, `self` (the flake) and `nixpkgs` (the set of packages we just pinned to on line 2). Nix will resolve all inputs, and then call the `output` function.
- **Line 6:** Here we specify that we are defining the default package for users on `x86_64-linux`. If we tried to build this package on a different CPU architecture like for example ARM (`aarch64-linux`) the flake would refuse to build as the package has not been defined for ARM yet. If we desired we could fix this by adding a `defaultPackage.aarch64-linux` definition.
- **Line 7-9:** Here we are just defining a shorthand way to refer to x86 Linux packages. This syntax is similar if not identical to Haskell.
- **Line 10:** Here we begin the definition of the derivation which is the instruction set Nix uses to build the package.
- **Line 14:** We specify here that we need `gcc` in our sandbox to build our package. `gcc` here is shorthand for `gcc12` but we could specify any c compiler with any version of that compiler we liked. If you desired you could compile different parts of your package with different versions of GCC.
- **Line 15:** Here we are slightly abusing the configure phase to generate a hello.c file. You would usually download a source to build from with a command like `fetchurl` while providing a hash. Each phase is essentially run as a bash script. Everything inside `mkDerivation` is happening inside a sandbox that will be discarded once the package is built (technically after we garbage collect).
- **Line 16:** Here we actually build our package
- **Line 17:** In this line we copy the executable we have generated which is currently in the sandbox into the actual package we are producing which will be in the store directory `/nix/store`.

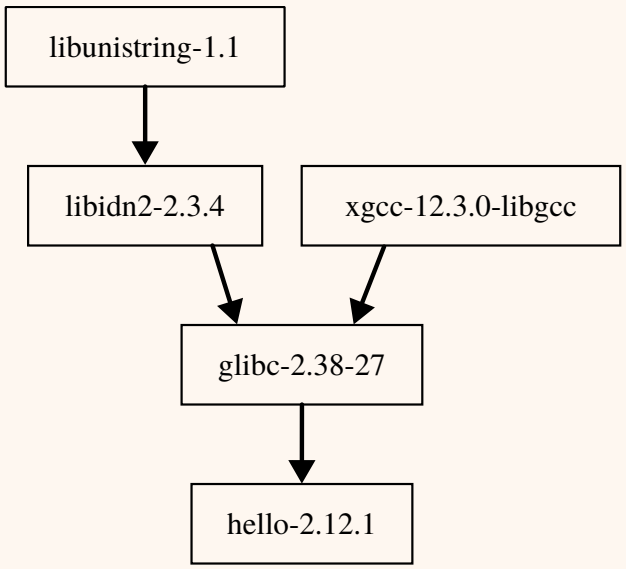
Below we have given some examples of how to run and investigate our hello package in Listing 3.1.2.

Listing 3.1.2: Terminal

```
[shell:~]$ ls
flake.lock  flake.nix

[shell:~]$ nix flake show
└──defaultPackage
   └──x86_64-linux: package 'hello-2.12.1'

[shell:~]$ nix run .
Hello, world!

[shell:~]$ nix path-info .
"\nix\store\sbldylj3clbkc0aqvjjzfa6slp4zdvlj-hello-2.12.1"

[shell:~]$ tree $(nix path-info .)
"\nix\store\sbldylj3clbkc0aqvjjzfa6slp4zdvlj-hello-2.12.1"
└──bin
    └──hello

[shell:~]$ nix-store --query $(nix path-info .) --requisites
/nix/store/s2f1sqfsdi4pmh23nfnrh42v17zsvi5y-libunistring-1.1
/nix/store/08n25j4vxyjidjf93fyc15icxwrxm2p8-libidn2-2.3.4
/nix/store/lmidwx4id2q87f4z9aj79xwb03gsmq5j-xgcc-12.3.0-libgcc
/nix/store/qn3ggz5sf3hkjs2c797xf7nan3amdxmp-glibc-2.38-27
/nix/store/sbldylj3clbkc0aqvjjzfa6slp4zdvlj-hello-2.12.1
```

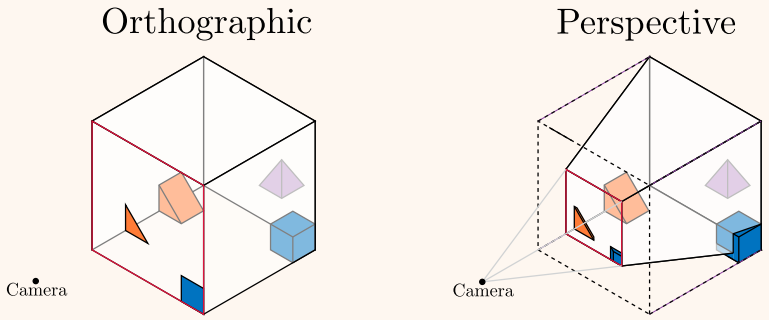
In Fig 3.1.3 we can see the package dependency graph of our `hello` package. We are only dependent on 4 packages `libunistring`, `libidn2`, `xgcc`, `glibc` all of which Nix have installed and configured separately the rest of the non-nix system (assuming we are not on NixOS).

Figure 3.1.3: Dependency graph



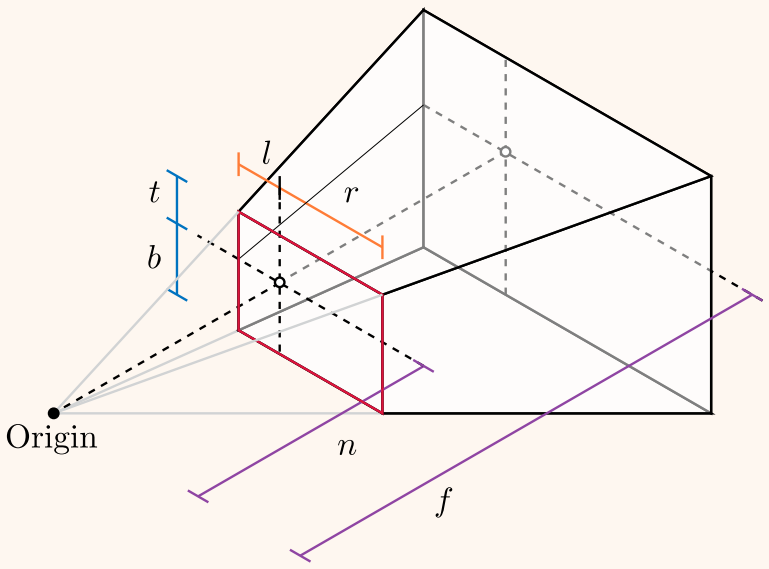
3.2 Perspective Projection

Figure 3.2.1: Orthographic and perspective projections



To represent 3D space on a 2D surface OpenGL supports two types of projections: perspective and orthographic as seen in Fig 3.2.1. Orthographic features parallel projection lines (orthogonal to the projection plane), which means that it does not depict the effect of perspective. Distances are preserved, making it useful for technical drawings where measurements need to be precise and not skewed by perspective (For example all diagrams in this report are from the orthographic perspective). Unlike orthographic projections, perspective projections simulate the way the human eye perceives the world, with objects appearing smaller the further away they are from the viewpoint as the projection lines converge at a vanishing point on the horizon. If we wish to create the illusion of volumetric display in this project we must use a perspective projection.

Figure 3.2.2: Using frustum to generate a perspective projection



OpenGL provides the `frustum` function as seen in Fig 3.2.2 which can be used to construct the perspective matrix (it is worth noting that OpenGL uses homogeneous coordinates so the matrix is 4x4):

$$\begin{bmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

This maps a specified viewing frustum to screen space (with intermediate steps handled by OpenGL) [16]. This viewing frustum is specified by six parameters: l, r, b, t, n and f which represent the left, right, bottom, top, near, and far extents of the frustum. These parameters define the sides of the near-clipping plane, highlighted in red, relative to the origin of the coordinate system. These parameters do not represent distances or magnitudes in a traditional sense but rather define the vectors from the center of the near-clipping plane to its edges.

The l and r parameters specify the horizontal boundaries of the frustum on the near-clipping plane, with the left typically being negative and the right positive, defining the extent to which the frustum extends to the left and right of the origin. Similarly, the b and t parameters determine the vertical boundaries, with the bottom often negative and the top positive, expressing the extent of the frustum below and above the origin.

The n and f parameters are scalar values that specify the distances from the origin to the near and far clipping planes along the view direction. Altering the value of n will change the angles of the lines that connect the corners of the near plane to the eye, effectively changing the "field of view". Changing the value f affects the range of depth that is captured within the scene but not the view.

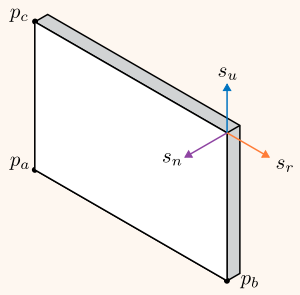
If we can track the position of a viewer's eye in real time then we can create the illusion of a 3D scene behind and in front of a display using this `frustum` function. This can be done fairly trivially following Robert Kooima's method he sets out in "Generalized Perspective Projection" to calculate f, l, r, b, t, n as the viewer's eye changes position [20].

3.2.1 Generating the perspective projection

The first step we must take is to record the position of the screen we are projecting onto in 3D space relative to the coordinate system of the tracking device, "tracker-space". To encode the position and size of the screen we take 3 points, p_a, p_b and p_c which represent the lower-left, lower-right and upper-left points of the screen respectively when viewed from the front on. These points can be used to generate an orthonormal basis for the screen comprised of s_r, s_u and s_n which represents the directions up, right and normal to the screen respectively as seen in Fig 3.2.3. We can compute these values from the screen corners as follows:

$$s_r = \frac{p_b - p_a}{||p_b - p_a||} \quad s_u = \frac{p_c - p_a}{||p_c - p_a||} \quad s_n = \frac{s_r \times s_u}{||s_r \times s_u||}$$

Figure 3.2.3: Defining a screen in 3D space



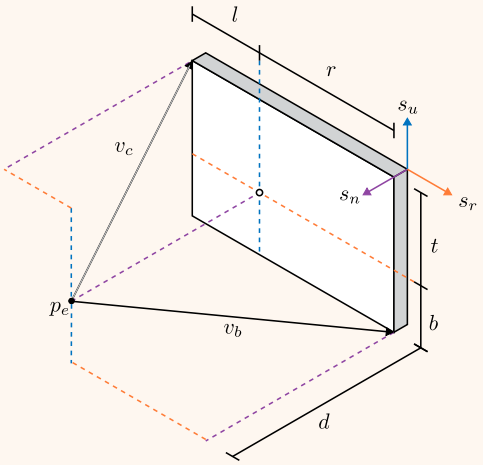
Next, we introduce the viewer's eye which we will refer to as p_e. We can draw 2 vectors v_b, v_c from the viewer's eye p_e to the corners of the screen p_b, p_c as seen in Fig 3.2.4. In the diagram, we also have labeled the components of each of these vectors in the basis of the screen. We can compute these as follows:

$$v_a = p_a - p_e \quad v_b = p_b - p_e \quad v_c = p_c - p_e$$

To calculate the required values for our `frustum` OpenGL function we must first find the point where a line drawn perpendicular to the plane of the screen that passes through p_e strikes the screen. We refer to this point as the *screen-space-origin*, it is worth noting that this point can lie outside the screen (the rectangle bounded by p_a, p_b, p_c). We can find the distance of the *screen-space-origin* from the eye p_e by taking the component of the screen basis vector s_n in either of the vectors v_b and v_c. However, as s_n is in the opposite direction we must invert the result. Similarly, we can calculate t by taking the component of v_c in the basis vector s_u, b by v_b in s_u, l by v_c in s_r and lastly r by v_b in s_r. We can compute these as follows:

$$d = -(s_n \cdot v_a) \quad l = (v_c \cdot s_r) \quad r = (v_b \cdot s_r) \quad b = (v_b \cdot s_u) \quad t = (v_c \cdot s_u)$$

Figure 3.2.4: Screen Intersection with view

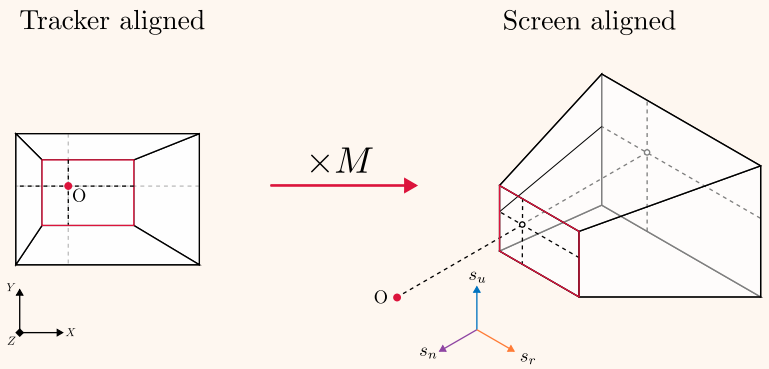


We can now generate a projection matrix by calling `frustum` using d as our near-clipping plane distance n with an arbitrary value for the far-clipping plane f depending on our required scene

depth. We have now successfully generated our viewing frustum but we still have a few issues. Firstly our frustum has been defined in tracker space so it is aligned with the direction of our camera not the normal of our screen. We can remedy this by applying a rotation matrix M to align our frustum with s_n, s_u and s_r, the basis of our screen as seen in Fig 3.2.5. M is defined as follows:

$$\begin{bmatrix} v_{rx} & v_{ry} & v_{rz} & 0 \\ v_{ux} & v_{uy} & v_{uz} & 0 \\ v_{nx} & v_{ny} & v_{nz} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

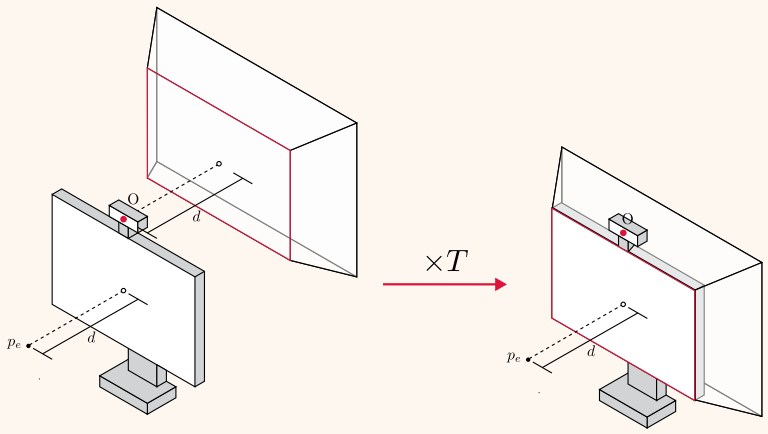
Figure 3.2.5: Rotating the frustum from tracker space alignment into screen space alignment



The second problem we have is that we want our projection matrix to move around with the viewer's eye however the mathematics of perspective projection disallow this, with the camera assumed to be at the origin. To translate our viewing frustum to our eye position we must instead translate our eye position (and the whole world) to the origin of our frustum. This can be done with a translation matrix T as seen in Fig 3.2.6. T can be generated with the OpenGL function `translate` where we want to offset it by the vector from our Origin to the viewer's eye p_e. T is defined as follows:

$$\begin{bmatrix} 1 & 0 & 0 & -p_{ex} \\ 0 & 1 & 0 & -p_{ey} \\ 0 & 0 & 1 & -p_{ez} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 3.2.6: Translating the viewing frustum to sit inside the screen

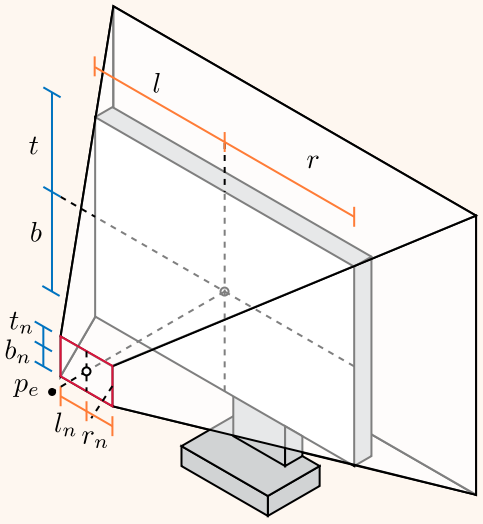


We now have a working method for projecting virtual objects behind our screen onto our screen however it is also possible if we desire to project objects in front of our screen onto the screen as well as long as they lie within the pyramid formed between the edges of the screen and the viewer's eye. We can scale the near-clipping plane from the plane of the screen to a small distance n from our eye as seen in Fig 3.2.7 giving us scaled-down values of t, b l and r we can use for our new viewing frustum which we call t_n, b_n l_n and r_n. They are defined as follows:

$$l_n = (v_c \cdot s_r)\frac{n}{d} \quad r_n = (v_b \cdot s_r)\frac{n}{d} \quad b_n = (v_c \cdot s_u)\frac{n}{d} \quad t_n = (v_b \cdot s_u)\frac{n}{d}$$

So our final viewing frustum takes in the frustum extents t_n, b_n l_n and r_n and n and f defining the distances to the near and far clipping plane.

Figure 3.2.7: Extending the near plane to not clip out objects in front of the screen



Following these steps, we can create an accurate projection providing the perspective we would

expect to see if there was a scene in front and behind our screen.

3.2.2 Sample code

Below in Listing 3.2.1 we have given an example of a function implementing the process we have just described in C++.

Listing 3.2.1: projection.cpp, Sample code for creating the 3D illusion projection

```cpp
#include <glad/gl.h>
#include <glm/glm.hpp>
#include <glm/gtc/matrix_transform.hpp>

using namespace glm;

mat4 projectionToEye(vec3 pa, vec3 pb, vec3 pc, vec3 eye, GLfloat n, GLfloat f)
{
    // Orthonormal basis of the screen
    vec3 sr = normalize(pb - pa);
    vec3 su = normalize(pc - pa);
    vec3 sn = normalize(cross(sr, su));

    // Vectors from eye to opposite screen corners
    vec3 vb = pb - eye;
    vec3 vc = pc - eye;

    // Distance from eye to screen
    GLfloat d = -dot(sn, vc);

    // Frustum extents (scaled to the near clipping plane)
    GLfloat l = dot(sr, vc) * n / d;
    GLfloat r = dot(sr, vb) * n / d;
    GLfloat b = dot(su, vb) * n / d;
    GLfloat t = dot(su, vc) * n / d;

    // Create the projection matrix
    mat4 projMatrix = frustum(l, r, b, t, n, f);

    // Rotate the projection to be aligned with screen basis.
    mat4 rotMatrix(1.0f);
    rotMatrix[0] = vec4(sr, 0);
    rotMatrix[1] = vec4(su, 0);
    rotMatrix[2] = vec4(sn, 0);

    // Translate the world so the eye is at the origin of the viewing frustum
    mat4 transMatrix = translate(mat4(1.0f), -eye);

    return projMatrix * rotMatrix * transMatrix;
}
```

3.3 Volumetric displays

Volumetric displays [11] provide a three-dimensional viewing experience by emitting light from each voxel, or volume element, in a 3D space. This approach enables the accurate representation of virtual 3D objects while providing accurate focal depth, motion parallax, and vergence. Vergence refers to the rotation of a viewer's eye to fixate on the same point they are focusing on. Moreover, volumetric displays allow multiple users to view the same display from different angles, providing unique perspectives of the same object simultaneously.

3.3.1 Swept Volume Displays

Swept volume displays are one prominent category of volumetric displays. They employ a moving 2D display to create a 3D image through the persistence of vision effects. This is achieved by moving the 2D display through a 3D space at high speeds while emitting light from the display where it reaches the position of each corresponding voxel. Common techniques for achieving this include using a rotating mirror [12], an emitting screen, typically an LED-based [15], or a transparent projector screen [19]. There currently exist commercial products that implement this technique as can be seen in Fig 3.3.1 and Fig 3.3.2.

Figure 3.3.1: The VXR4612 3D Volumetric Display, a projector-based persistence of vision display produced by Voxon Photonics. [31]

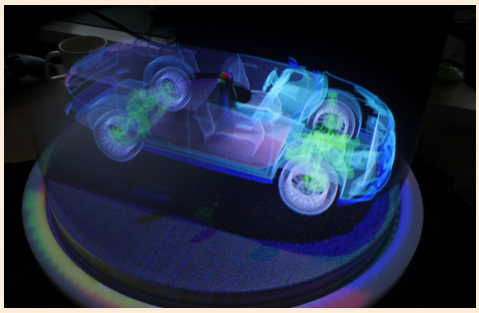


Figure 3.3.2: A Volumetric Display / Holographic Signage, an LED-based persistence of vision display produced by Brightvox Inc. [3]

3.3.2 Static Volume Displays

Static volume displays are another category. They employ a static transparent medium that when interacted with creates a 3D image. The result is that light is emitted from the display at each point in a 3D space. Techniques for achieving this range from using a 3D array of LEDs [27], lasers and phosphorus gas [32], or a transparent laser-induced damaged medium that can be projected into [23]. There has been research into photon-activated dye [24] and even quantum dot-based displays [18].

3.3.3 Trapped Particle Displays

Acoustic Trapping Displays displays are a relatively new category of volumetric displays. They employ a 3D array of particles that are suspended in air using acoustic levitation. [14] [17] This is achieved by using an array of ultrasonic transducers to create a standing wave that can trap particles in the nodes of the wave. By moving the nodes of the wave through a 3D space and illuminating the particles with light, a 3D image can be created. This technique is still in its infancy and can struggle to provide a convincing persistence of vision effect. Another direction some researchers have taken is to use a photophoretic trap to trap particles in air [28]. The advantage of this sort of display is that space that is not being used to display an object is empty and can be passed through. This is in contrast to swept volume displays/most static volume displays where the space not being used to display an object is filled with the display's hardware.

3.3.4 Issues

Volumetric displays often require custom/cutting-edge hardware (e.g. extremely high refresh rate projectors, transparent micro LEDs, complex laser systems) which makes them expensive, difficult to manufacture and calibrate and not widely available. For example, the Voxon VX1, one of the few if only commercially available volumetric displays costs, $11,700 USD [25] per unit.

Volumetric displays are also held back by their inherent high bandwidth requirements: To render objects in real-time at equivalent resolutions to current 2D displays while taking a raw voxel stream (as opposed to calculating voxels on hardware from primitive shapes) has an extremely high bandwidth requirement. If we want to render at `60fps` on a $4096 \times 2160 \times 1080$ voxel display with `24 bit` color, it would require a bandwidth of 1.37×10^3 bits per second/13.7 terabits per second which is orders of magnitude higher than what a normal display requires. To achieve that currently would require about 170 state-of-the-art Ultra High Bit Rate (UHBR) (80 gigabit) DisplayPort cables simultaneously. It was predicted in 2021 [2] that due to these limitations and based on the historic trends of bandwidth in commercially available displays, volumetric displays will only become feasible in 2060 at the earliest. There are ways to reduce this bandwidth requirement through compression and other techniques [35] but this still provides a major issue.

3.3.5 Volumetric Screen Simulations

Because of these issues, there has been some research into simulating volumetric displays. One commonly used method is the so-called fish tank virtual reality (FTVR) display [33] which has been commonly used to simulate volumetric displays, [10], [34]. A FTVR comprises a singular or set of 2D displays that are positioned in front of a user. The viewer's eyes are tracked in 3D space and the image on the displays is adjusted accordingly so that there appears to be a 3D image present in front of them. This is a relatively cheap and easy way to simulate a volumetric display, but it has some major drawbacks. The user is limited to a single focal depth and is limited to a single vergence (This can be fixed by wearing glasses to filter different images to

each eye providing a stereo view [30]). This system is also limited to just a single user at a time unless image filtering is used.
Another approach that has been taken is to take advantage of virtual reality (VR) headsets. VR headsets are a relatively cheap and easy way to simulate a volumetric display. They are also able to provide a stereo view and can be used by multiple users at once [9].

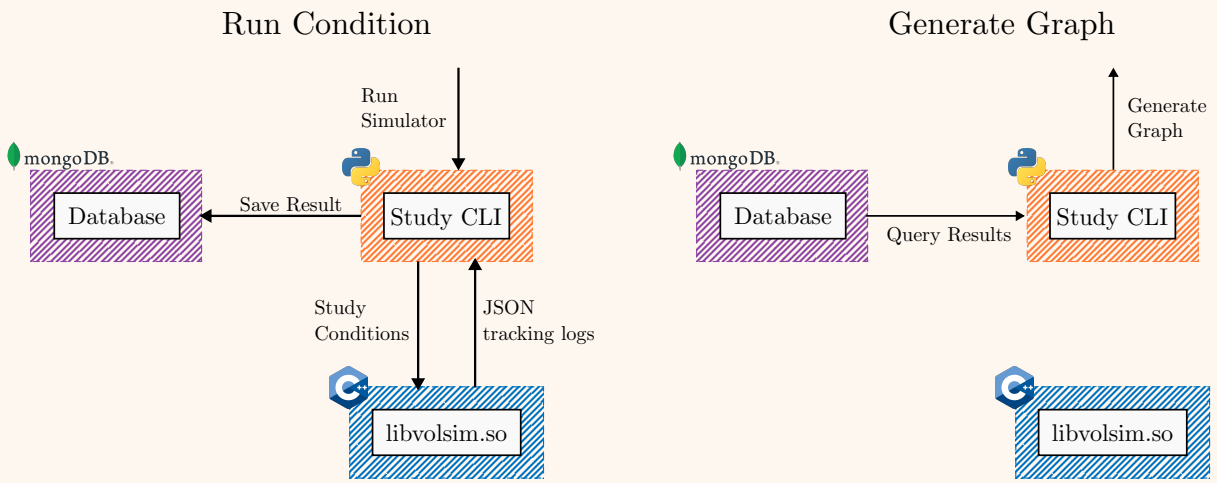
Chapter 4

Implementation

4.1 Overall System

Our system comprises two main components, the simulator and the user study cli. We use the study cli written in python to orchestrate running simulations by calling the simulator shared library `libvolsim.so` written in c++. Once the simulator has run it returns it's logs to the user study cli (in JSON form) which then stores the results in a mongodb database. The user study cli can then be used to analyse the results.

Figure 4.1.1: Two examples of using our system



4.1.1 Build System

The build system plays a crucial role in compiling the simulator and rendering system, as well as running the user study. This complex system requires the compilation of C++, CUDA, and Python code, and the management of large ML models and object files for rendering, as well as managing things like camera drivers. Portability is essential to ensure the user study can be conducted on various systems. Given our previous experiences, the build system often presents a significant bottleneck in the development process. To address these challenges, we have chosen nix for its declarative nature and ease of dependency management, including the capability to modify packages globally using overlays.

Overview

1. Draw a diagram of the build system (simplified)
2. The build system is split into two parts the simulator, and the user study.
3. Show how the simulator is compiled as a shared library and called from the user study.

The build system provides two main functionalities compiling the simulator (written in c++) as a shared library, and providing development environments for running the user study (written in python). This functionality is all available through a `nix flake` interface as can be seen in List 4.1.1.

Listing 4.1.1: Terminal

```
[VolumetricSim]$ nix flake show
git+file:///home/robbieb/Projects/VolumetricSim
├──devShells
│   └──x86_64-linux
│       ├──default: development environment 'volumetricSim'
│       ├──start-mongodb: development environment 'mongodb-shell'
│       └──userstudy: development environment 'userstudy-shell'
└──packages
    └──x86_64-linux
        └──default: package 'volumetricSim-0.0.1'
```

libvolsim.so

You can build our simulator as a shared library using the following simple command in List 4.1.2:

Listing 4.1.2: Terminal

```
[VolumetricSim]$  nix build
```

Although this might look like a simple command, it is doing a lot of work behind the scenes. Firstly it will go and fetch all the dependencies required to build the simulator, from source (or a public binary cache). You do not need to have any of the dependencies installed on your system, as nix will manage all of this for you.
Our packages configures:

1. **CUDA:** As we use CUDA in our simulator, we need to build the CUDA toolkit. Luckily nix allows you to build it in a more fine grained way, so you can build just pick and choose the parts you need. We use CUDA Deep Neural Network library (cuDNN), CUDA Basic Linear Algebra Subprograms library (cuBLAS),CUDA Random Number Generation library (cuRAND), CUDA Dense Linear Solver library (cuSOLVER) along with the required libaries to interact with them. We override and recompile OpenCV and Dlib to be CUDA enabled. ToCite

2. **MKL:** We use the Intel Math Kernel Library (MKL) for some of our linear algebra operations as it significantly faster than the default BLAS library. We override and recompile OpenCV and DLIB to use the MKL BLAS libaries. ToCite

3. **Azure Kinect Sensor SDK:** We use our own nix package for the Azure Kinect SDK, as it was not packaged. This package provides the required drivers and stubs for the Azure Kinect camera to run. ToCite

4. **OpenGL:** We download and configure `GLFW` (Light weight OpenGL utility library) and `GLAD` (Hardware specific OpenGL drivers) for OpenGL. ToCite

5. **Tracking models:** We download and configure Dlib and MediaPipe machine learning libraries that we use for our tracking models. We also automatically download the re-

quired two required models for DLIB (`shape_predictor_5_face_landmarks`,`mmod_human_face_de` from the internet (verified by hash). We also download and build OpenCV for managing our images. ToCite

Once all the dependencies are built, the simulator is compiled written into the nix store as package with a shared library `libvolsim.so` and all the files the simulator depends on (tracking models, obj files, shaders). This shared library can be called from the user study to run the simulator. An overview of the final package contains can be seen in List 4.1.3.

Listing 4.1.3: Terminal

```
[VolumetricSim]$  tree result
/nix/store/gasc1x5y75rz6qdjz33jq1ffid3az9q7-volumetricSim-0.0.1/
├── bin
│   └── libvolsim.so
└── data
    ├── challenges
    │   ├── demo1.txt
    │   ├── demo2.txt
    │   ├── task1.txt
    │   ├── task2.txt
    │   ├── task3.txt
    │   ├── task4.txt
    │   └── task5.txt
    ├── mediapipe
    │   └── modules
    │       ├── hand_landmark
    │       │   ├── handedness.txt
    │       │   ├── hand_landmark_cpu.binarypb
    │       │   ├── hand_landmark_full.tflite
    │       │   ├── hand_landmark_landmarks_to_roi.binarypb
    │       │   ├── hand_landmark_model_loader.binarypb
    │       │   ├── hand_landmark_tracking_cpu.binarypb
    │       │   └── palm_detection_detection_to_roi.binarypb
    │       └── palm_detection
    │           ├── palm_detection_cpu.binarypb
    │           ├── palm_detection_full.tflite
    │           └── palm_detection_model_loader.binarypb
    ├── dlib
    │   └── modules
    │       ├── face_detection
    │       │   └── mmod_human_face_detector.dat
    │       └── face_landmark
    │           └── shape_predictor_5_face_landmarks.dat
    ├── resources
    │   ├── materials
    │   │   └── scene.mtl
    │   └── models
    │       ├── cube.obj
    │       ├── cylinder.obj
    │       └── sphere.obj
    └── shaders
```

```
├── camera.fs
├── camera.vs
├── image.fs
└── image.vs
```

Dev Environments

To run our user study, we have created a development environment that contains all the dependencies required to run the user study and sets up an alias that allows you to run the study via a CLI easily as can be seen in List 4.1.4.

Listing 4.1.4: Terminal

```
[~/VolumetricSim]$ nix develop .#userstudy
Type 'study' to start the user study application.
[VolumetricSim]$ study --help

  Command line interface for running the Volumetric User Study.

Options:
  --help  Show this message and exit.

Commands:
  add    [ user ]
  list   [ users | results ]
  run    [ debug | eval | demo | task | next ]
  save   [ user ]
  show   [ result | task | eval ]
```

As we also use out CLI to analyse the results of the user study, we have also created a development environment that contains all the dependencies required to run the analysis and completely reproduce the graphs and tables in this documents.

We also created a development shell to automatically launch and manage a local mongodb database for storing the results of the user study. This included gui tools for viewing the database editing the database (mongodb-compass). This can be activated by running the command you can see in List 4.1.5.

Listing 4.1.5: Terminal

```
[~/VolumetricSim]$ nix develop .#userstudy
```

4.1.2 Extra work

One of the major downsides of using nix is that if something is not already packaged by another user you have to package it yourself. Luckily almost everything we needed was already

packaged in nixpkgs, but we did have to package a few things ourselves. Usually if something is not packaged in nixpkgs, it is because it is not a widely used package, or it is a pain to package.

Azure Kinect Package

The first thing we had to package was the Azure Kinect SDK. This was not packaged in nixpkgs, and the only official package was a (not very well made) out of date Ubuntu package. To get it working in nix we have to manually patch the rpaths (run-time search path hard-coded in an executable file) in the file and fix some build and driver issues. Microsoft officially stopped supporting the Azure Kinect in August 2023 (ToCite) so we decided to package a fork of `https://github.com/microsoft/Azure-Kinect-Sensor-SDK` that fixed a lot of the issues we had. All in all this was quite difficult and took about a week. We haven't upstreamed this to nixpkgs yet but might do in the future.

Dlib package

The second thing we had to package was Dlib. Dlib was packaged in nixpkgs but we discovered the CUDA support had been added wrong. We were able to fix this locally using overlays (a functional method of globally mapping changes to all packages in nix). We decided to submit a PR ToCite to nixpkgs, to fix it for everyone. This took much longer than expected as ended up having to fix a lot of other things in the package that weren't a problem for us.

MediaPipe

The last roadblock we had was with MediaPipe. MediaPipe is a machine learning library that is built with Bazel ToCite . Bazel is a build system that is supported in nixpkgs, but is annoying to work with. To use it in our c++ project we had to convert MediaPipe to being a shared library by wrapping it in a c interface first before packaging it in Nix. This was quite time-consuming and annoying.

4.2 Rendering System

4.2.1 Introduction

The rendering system is responsible for rendering the 3D models and the environment. It is a crucial part of the system as it is the interface between the user and the system. It needs to be fast and responsive to preserve the illusion of 3D.

4.2.2 OpenGL

Because of requirements of our project we needed to implement a rendering system that could render 3D models in real-time at a low latency to preserve the illusion of 3D. We decided to use OpenGL ToCite because of its low-level control over the rendering pipeline and its cross-platform compatibility. We considered briefly using Unity or Unreal Engine but decided against it because of the large overhead and the lack of control over the rendering pipeline. We also used the GLM ToCite mathematical library for matrix manipulation and projections as it was sufficiently fast and integrated well with OpenGL.

4.2.3 Object Loading

Object loading support was added to the rendering system to allow for the rendering of complex 3D models. We used the library `tinyobjloader` ToCite to load .obj object files. We constructed our challenge for the user study by warping primitives such as spheres, cylinders, and cubes to create a task for the user to interact with.

4.2.4 Lighting

To help with the illusion of depth ToCite shadows help with depth? we added a simple lighting model to the scene. We used the Blinn-Phong lighting model which uses ambient, diffuse, and specular lighting. Ambient lighting is the light that is present in the scene regardless of the light sources. Diffuse lighting is the light that is reflected off the surface of the object. Specular lighting is the light that is reflected off the surface of the object in a mirror-like way. A comparison of the scene with and without lighting can be seen in Fig TODO .

4.2.5 Perspective

As covered extensively in background research, the perspective of the user is crucial to the illusion of 3D. To help with this we used the eye tracking system to render the scene from the perspective of the user. This was done by taking the position of the eye from the eye tracker and using it to render the scene from that perspective as can be seen in Fig TODO

4.3 Tracking System

4.3.1 Introduction

To be able to accurately produce a virtual volumetric screen, we need to be able to track the user's face and hands. This is so we can render the correct perspective of the screen to the user. Our tracking system had to fit the following requirements:

- **High resolution:** To be able to accurately track the user's face and hands smoothly.
- **High framerate:** To be able to track the user's face and hands smoothly.
- **Low latency:** To be able to track the user's face and hands in near real-time.

4.3.2 Hardware

Figure 4.3.1: Azure Kinect

Get Image from here https://deviestore.com/product/microsoft-azure-kinect/ source microsoft for the image.

For this project we used a Microsoft Azure Kinect camera ToCite Fig 4.3.1. The Azure Kinect camera has two sensors, a depth sensor (IR Sensor) and a colour sensor. For this project we have configured the camera to capture images at its widest field of view $90° \times 74.3°$, with the exposure time 12.8 ms and it's highest framerate 30fps. To be able to use these settings we had to compromise on the resolution of the images running the RGB camera at 2048×1536 rather than it's maximum resolution of 4096×3072 and the depth camera at 2×2 binned with a resolution of 512×512 rather than it's maximum unbinned resolution of 1024×1024. Because we use the depth camera in wide field of view mode $120° \times 120°$ rather than $75° \times 65°$ we compromised on the maximum operating range of the camera only being able to track hands up to 2.88m away rather than 5.46m.

4.3.3 Core Libaries

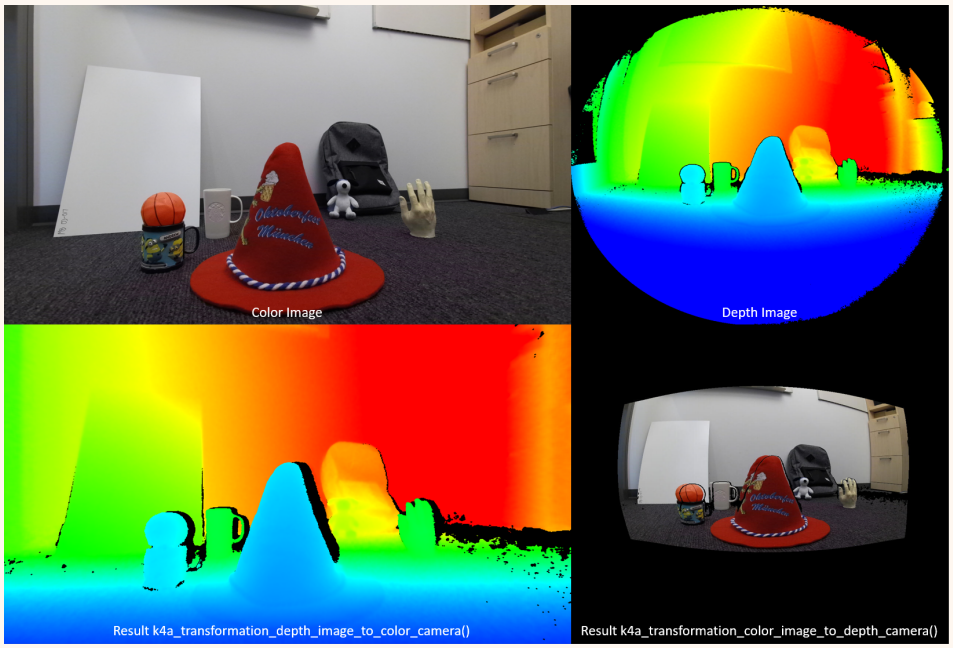
Figure 4.3.2: Core Libraries used for tracking

Cite libraries for the images

Azure Kinect SDK (K4A)

We use the Azure Kinect SDK (K4A) library to retrieve Captures from the Kinect and the handle the ”space” transformations you need to calculate the positions of points in 3D.

Figure 4.3.3: Different spaces changing Depth and Colour Images



The camera when polled with K4A returns a ”Capture” which is a struct containing a colour image, depth image and an IR image. We don’t use the IR image in our project so we ignore it. It is worth noting that the depth image is in a different space to the colour image as can be seen in Fig 4.3.3. The depth image is in the ”depth space” and the colour image is in the ”colour space”. To use the two images in conjunction we have to convert them into the same space.

Using a ”calibration” that is generated at the start of the program k4a lets you convert between

the 4 difference ”spaces”, ”Depth 2D”, ”Depth 3D”, ”Colour 2D”, ”Colour 3D”. There are interesting performance implications of using different spaces for different tasks. For example going from ”Depth 2D” to ”Depth 3D” is significantly faster than going from ”Colour 2D” to ”Colour 3D”.

Another interesting side effect of converting between spaces if because the IR and colour cameras are physically offset and diffract differently you get ”depth shadows” ToCite as can be seen in the Bottom Left image in Fig 4.3.3. Which can make it difficult when trying to track thin objects like fingers as you have a high probability of getting an invalid depth.

OpenCV

We use OpenCV to handle the images we get from the Azure Kinect SDK. OpenCV is a library that provides a comprehensive set of functions for image processing and computer vision. We use OpenCV to convert the images we get from the Azure Kinect SDK into a format that can be more easily used by Dlib and MediaPipe. We make use of OpenCV's GPU accelerated functions like to down scaling. To increase the performance of our tracking system. We also use OpenCV for debugging to render the images to the screen.

Dlib

We use Dlib to track the user's face. Dlib is a modern C++ toolkit containing machine learning algorithms and tools for creating complex software in C++ to solve real-world problems. We use Dlib's face tracking model ToCite to track the user's face. Dlib's face tracking model is a deep learning model that can track the user's face in real-time. We use Dlib's GPU accelerated functions to increase the performance of our tracking system. We initially used Dlib's CPU face tracking functionality but found that it was bottlenecking our system. We then switched to Dlib's GPU functions and found that it significantly increased the performance of our tracking system. Fill out more

MediaPipe

We use MediaPipe to track the user's hands. MediaPipe is a cross-platform framework for building multi-modal applied machine learning pipelines. We use MediaPipe's hand tracking model ToCite on colour images to track the user's hands. MediaPipe's hand tracking model is a deep learning model that can track the user's hands in real-time. Fill out more

4.3.4 Overall Tracking System Design

1. Diagram of how the system works.
2. Picture diagram of capture to tracking frame.
3. Mention how we track the hands and face seperately so two capture frames.

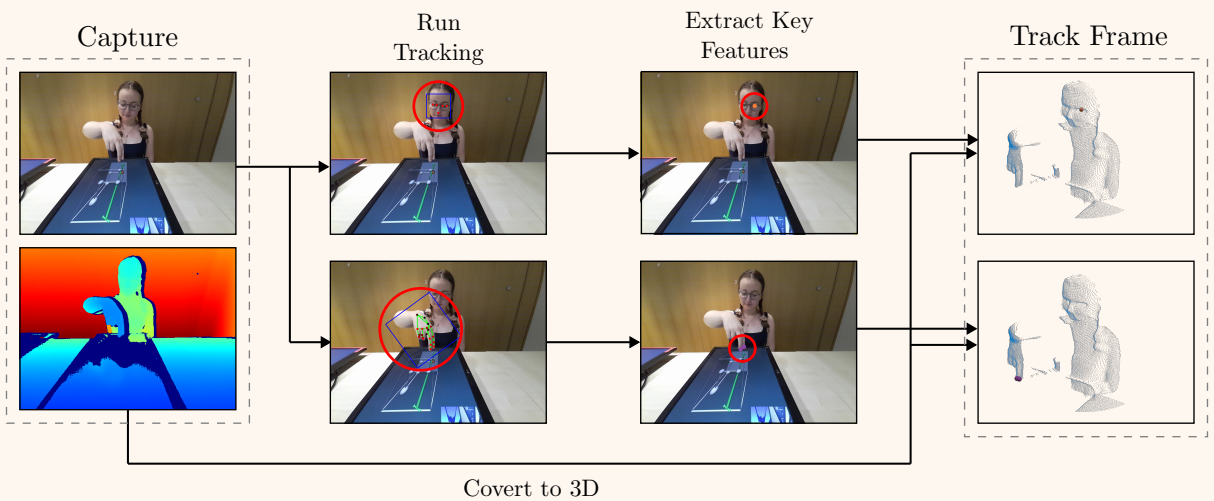
The purpose of the tracking system in brief strokes is to convert the Captures provided by the Kinect Camera into 3D point representing useful information from the render like the position of the users eye and fingers. The current system just returns the position of the left eye and

index and thumb tip on the closest hand to the camera. The system runs as the same speed of as camera (30fps) and feels smooth.

There were a number of different approaches we could have taken but in the end we decided to use a system that tracked the position of the users face and hands separately in 2D which we then converted into 3D. The main other approach we could have taken was to track the face and hands in 3D directly. In the end the main reason we decided against this approach was because although the rendering system was a key part of this project it was not the main focus. The main focus was the user study and the tracking system was just a means to an end. The ecosystem for tracking in 2D is much more mature (thanks in part to mobile phones) than in 3D and we were able to leverage a lot of existing work (Such as the previously described libraries Dlib, MediaPipe, and OpenCV). Another reason was that we were concerned about the performance of tracking in 3D. We were worried that tracking in 3D would be too slow to be able to track the users face and hands in real-time, however is suspect this probably would have been fine. There are a number of downsides that arise from tracking in 2D. For example, as we will talk about a bit more in the evaluation section, it is difficult to find the accurate positions of objects in 3D space that are occluded for example fingers behind other fingers. Because fingers are fairly small objects we also have to sample a vague area where we think it is and pick the closet point as if you only sample the predicted point you can miss the finger.

Mention what happens when tracking fails (i.e only replace replace images in the frame if successful)

Figure 4.3.4: Tracker overview



As can be seen in Fig 4.3.4 the basic flow of the tracking system is as follows.

1. Retrieve the Capture from the Kinect Camera.
2. Run hand and head tracking on the colour image.
3. Extract the key 2D points from the hands (thumb and index tip) and face (left eye).
4. Use the depth image to convert the 2D points into 3D points and put these in a ”tracking

frame" to be sent to the rendered.

While it might seem strange at first as can be seen in the Tracking Frame in Fig 4.3.4 we actually keep a separate instance for the left eye and the thumb and index tips. This is because there is no guarantee that the tracker will be able to detect both the face and hands at the same time. For example if the user is holding their hand in front of their face the tracker will only be able to detect the hand. If this happens our system will just reuse the last known position which is a good approximation of faces position.

4.3.5 Tracking Models

Dlib

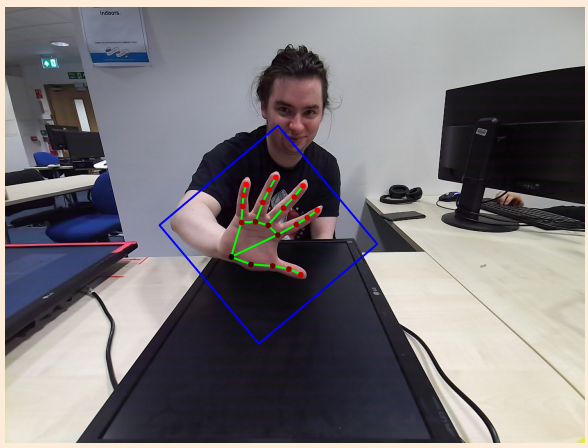
We use Dlib to track the eye using a two stage process. In the first stage we use a Max-Margin Object Detection model ToCite ToCite using a convolutional neural network (CNN) ToCite . Instead of training our own model we used a pertrained model provided by dlib ToCite called `mmod_human_face_detector`. The initial face detection was a bottlekneck for us, we chose to run our CNN on a GPU using CUDA accelerated functions.

Once we have detected our face we run the second stage of our facial landmark detection model. We chose to use a 5 landmark pose estimator called `shape_predictor_5_face_landmark` using dlibs implimentation of a method preposed in "One millisecond Face Alignment with an Ensemble of Regression Trees" ToCite https://ieeexplore.ieee.org/document/6909637 trained on the iBUG 300-W face landmark dataset ToCite . This pose estimator ran fast enough on a CPU that we didn't bother GPU accelerating it.

An example of the result of running the dlib two models can be seen in Fig **??**
Fix the issue with bad figure numbering for this below

Figure 4.3.1: Dlib Face Tracker

Figure 4.3.2: MediaPipe Hand Tracker



We use MediaPipe to track the position of two fingers on the users hand, also using a two step process. MediaPipe uses a two stage model to track the hands ToCite . The first stage is a palm

detection model that detects the position of the hand in the image. The second stage is a hand landmark model that detects the position of 21 points on the hand. MediaPipe provides a nice interface to for pushing our images in the form of a stream and abstracts away most detection logic for you unlike dlib.

We chose to track the position of the index and the middle finger as we found that this was more stable than tracking the thumb and index finger. Because we depth sample from the surface of the hand we chose to offset the positions by constant amount of make it feel like the point was inside the hand. An example of the result of running the MediaPipe two models can be seen in Fig **??**

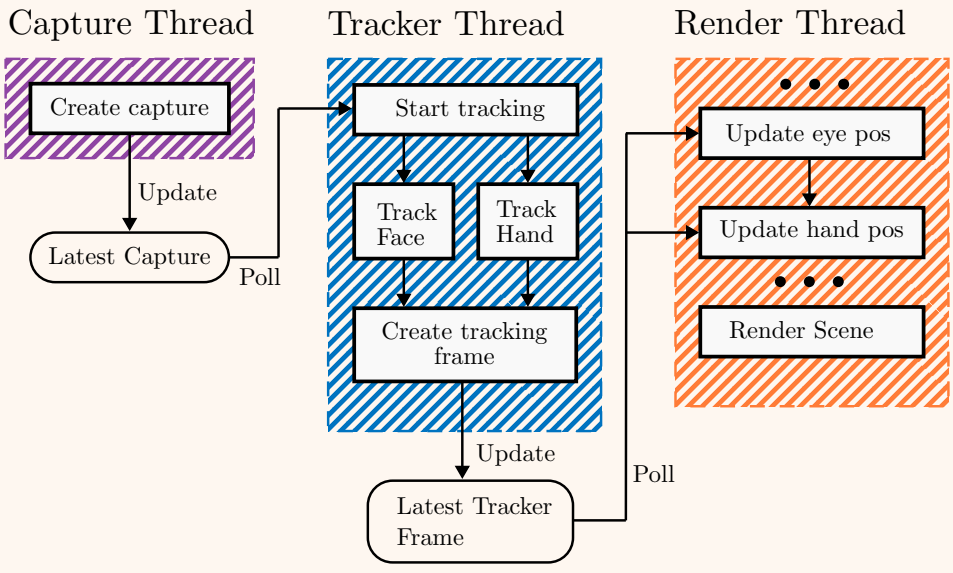
Downscaling

To make sure our tracking system runs at a high enough framerate we downscale the images we get from the camera. We found that we could downscale the images by a factor of 2 and still get accurate tracking results. This significantly increased the performance of our tracking system.

4.3.6 Multithreading

1. Seperate thread for tracking capturing and rendering
2. Increased framerate but did not change latency.
3. More wasteful in terms of resources but there is there are more than enough resources.
4. Talk about polling architecture and how we cache frames so we don't do redundant work.

Figure 4.3.5: Multi-threaded design

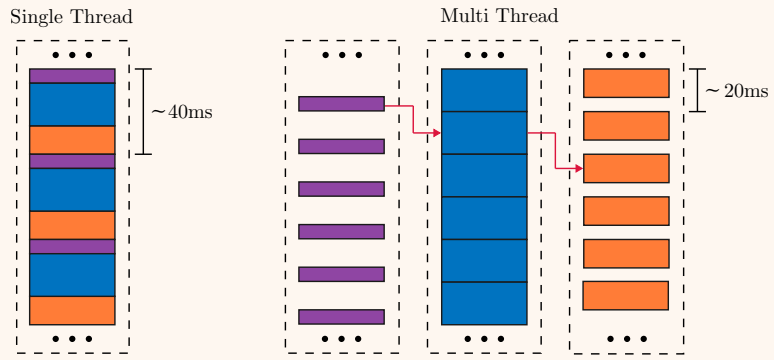


One of the more challenging aspects of this project was to make our tracking system run fast enough that it felt smooth. To achieve this we had to make use of multi-threaded design as can be seen in Fig 4.3.5. We used a separate thread for tracking, capturing, and rendering. This is a slightly wasteful use of resources as we effectively waste a thread waiting for captures however as the whole simulation is surprisingly light on resources this was not a problem it was worth it for the framerate gain it provided.

The purpose of this design choice is to make sure there is always a threading running the tracking models as these are by far the computationally most expensive part of the system. Using a multithreaded design does not reduce the latency (which we talk about more in evaluation) of the system but rather increases the throughput which in our case is the framerate of the application. As we are using a camera that runs at 30fps we need to be able to process an image every $\frac{100\text{ms}}{30\text{ms}} = 33\text{ms}$. As can be seen in Fig 4.3.6 by switching to a multi-threaded design we can increase the framerate of our whole tracking system to be the same as time required to run our tracking modules on our already retrieved captures. This also gives us the advantage of being able to run the simulation at an independent framerate to the tracker.

TO DO ADD KEY, also show how long each individual part takes. Also show that rendering happens multiple times a second

Figure 4.3.6: Single vs Multi threaded design



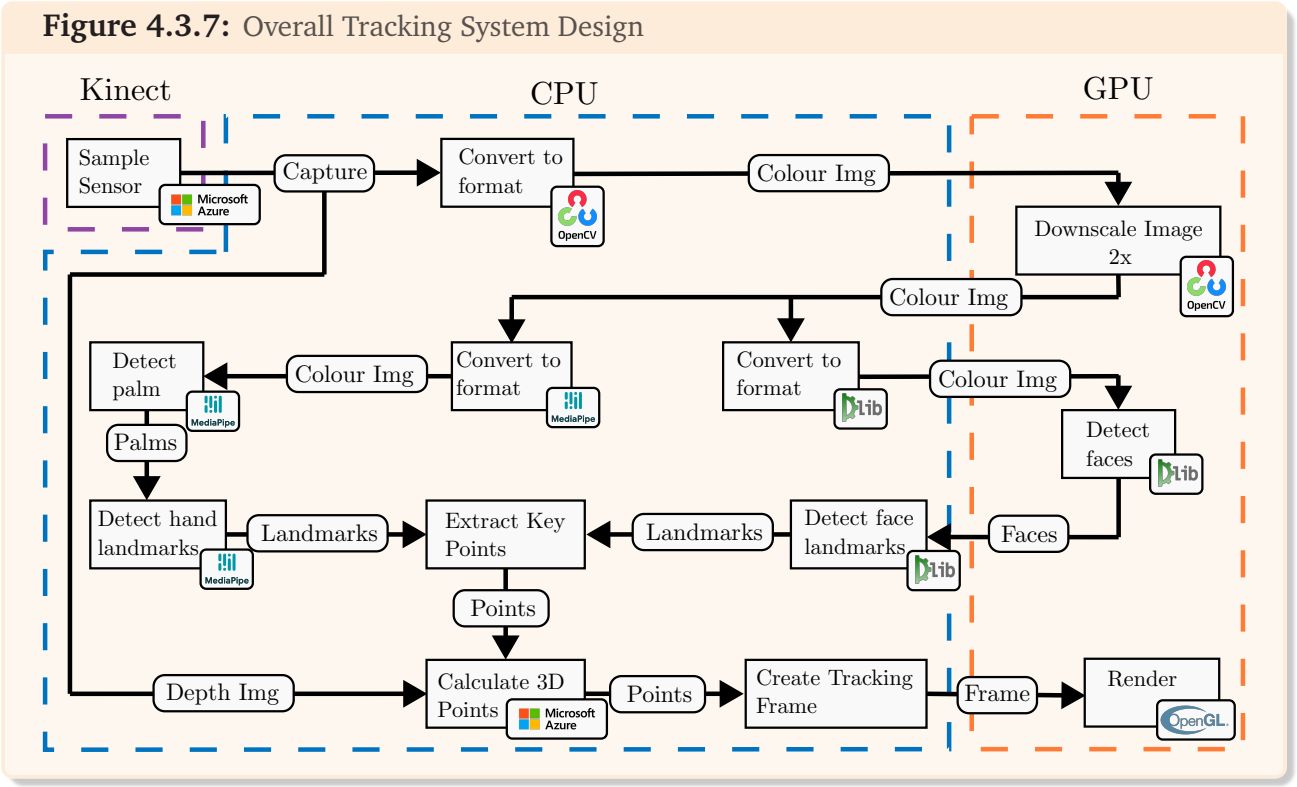
4.3.7 GPU Acceleration

Another method we use to increase the performance of our tracking system is to use GPU acceleration. Both Dlib and MediaPipe support GPU acceleration. We only used GPU acceleration in Dlib as we found that it significantly increased the performance of our tracking system. get actual stats for dlib gpu stats. We did not use GPU acceleration in MediaPipe as the CPU speed was already sufficient and the purported speedup of 12.27ms with GPU acceleration vs 17.12ms to cite https://ai.google.dev/edge/mediapipe/solutions/vision/hand_landmarker with cpu only didn't seem worth the effort of enabling CUDA in mediapipe after it already provided difficult to use (See build systems for more information) . We did not test the performance of MediaPipe with GPU acceleration as we did not have the time.

As you can see in Fig 4.3.7 we only used GPU acceleration for 3 parts of our tracking system.

We downscale our colour images using OpenCV's GPU accelerated pyramid down function as this is a highly parallel task and benefits from the acceleration. We also run the dlib cnn for detecting the face on the GPU. Lastly we run our rendering system on the GPU.

Figure 4.3.7: Overall Tracking System Design



1. Dlib and MediaPipe both support GPU acceleration. Only did it in DLIB. Get benchmarks from Mediapipe and DLIB
2. downscaling to increase performance has the downside of reducing precision/resolution but it was negligible.

4.3.8 Camera Positioning

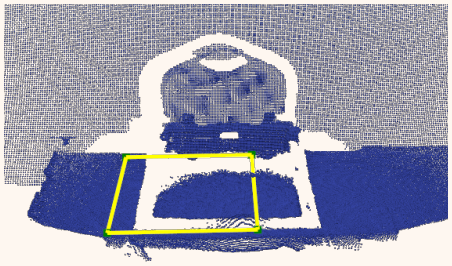
To set up the tracking system to be calibrated correctly such that the user can see the correct perspective with need to know the relative position of the camera to the screen, the orientation of the camera and the dimensions of the screen. We use a calibration system to set up the camera. The calibration system works as follows:

1. Camera is measured in 3D space and orientation is recorded. Screen is measured in 3D space.
2. Relative positions are given to the system
3. Predicted position of the screen in rendered in 3D.
4. Iteratively adjust the position of the screen until they line up.

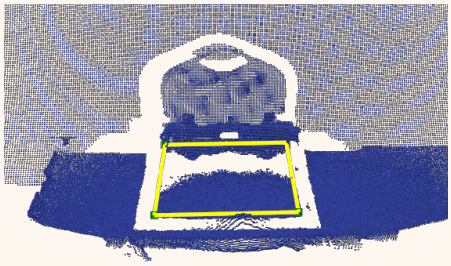
An example of a correct and incorrect calibration can be seen in Fig 4.3.8

Figure 4.3.8: Display Calibration

Incorrect Calibration



Correct Calibration



4.4 User Study

4.4.1 Introduction

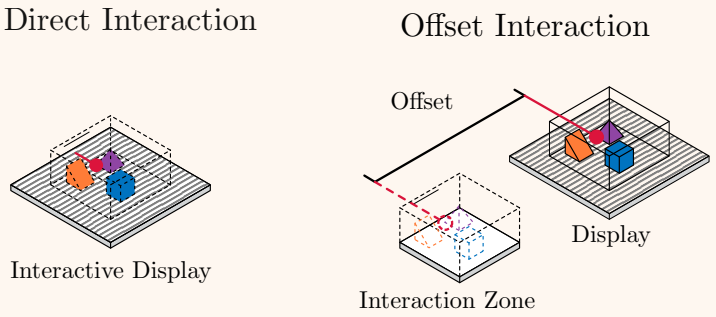
To validate the usefulness of our system we decided to conduct a Within-Subjects User Study. The user study was designed to show the capacity of the system for being used in research. The study was designed to test the effectiveness of users using volumetric displays under different conditions.

4.4.2 Experimental Variables

For this study we wanted to evaluate the difference in performance of participants in interacting with volumetric screens directly with their hands vs via teleoperation.
Our two independent variables which we varied over the study were:

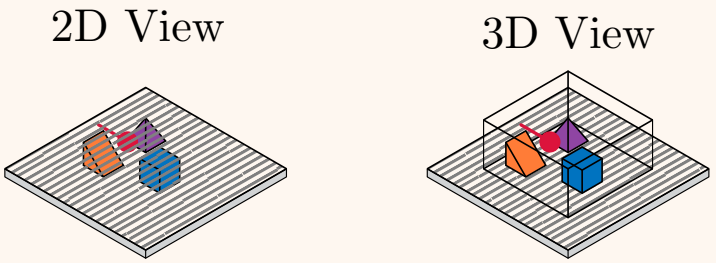
- **3D Perspective**: (On/Off). This controls if the system is able to use the eye tracking system to create the illusion of a 3D volumetric display as opposed to a fixed perspective on a standard monitor as can be seen in Fig 4.4.1.

Figure 4.4.1: Direct & Offset Interaction



- **Interaction Offset**: (On/Off). This controls if display is directly in front of the participant or if it is offset by a fixed amount as can be seen in Fig 4.4.2.

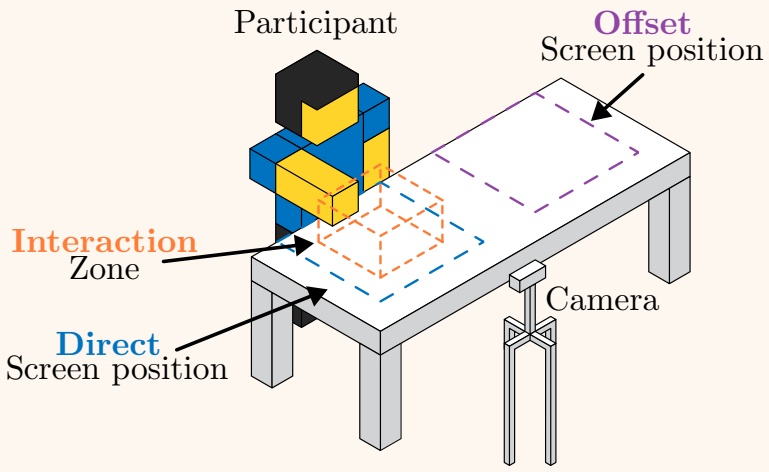
Figure 4.4.2: 2D & 3D



We made sure to control for the following variables: We made sure that the five tasks were the same in each condition. We also made sure that the position of the participant, the tracking

camera, and the zone of interaction were the same in each condition as can be seen in Fig 4.4.3. We were careful to ensure the lighting conditions inside the room did not change. When using an offset position we placed another display where the old display was to ensure tracking was consistent.

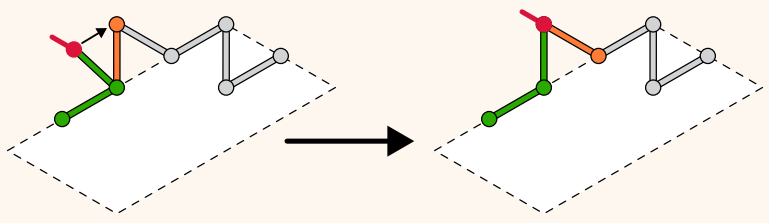
Figure 4.4.3: Test Setup



4.4.3 Tasks

In each of the 4 conditions the participant must complete the same 5 tasks. The tasks are designed to be simple but more difficult to complete if not in 3D. To complete a task a participant must trace the path between the points with their index and middle finger in the order the simulator presents to them. A green point is completed segment, an orange point represents the next point to be completed and a red point in the current position of the participants hand as can be seen in Fig 4.4.3.

Figure 4.4.4: Completing a task



The participants have a timeout of 1 minute to complete the task. If they do not complete the task in the time limit, the task is marked as incomplete. The time each point is completed is recorded as well as the position of the hand and eye throughout the minute. The 5 different tasks are shown in Fig 4.4.6 The participants are also given two demo tasks to get used to the system.

Figure 4.4.5: Demo Conditions

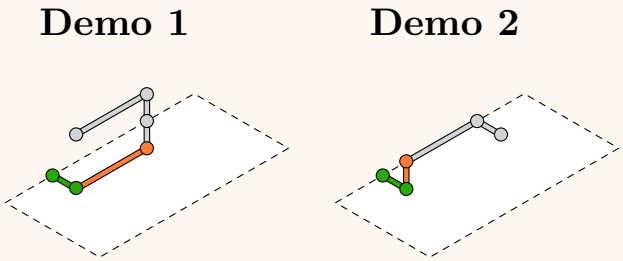
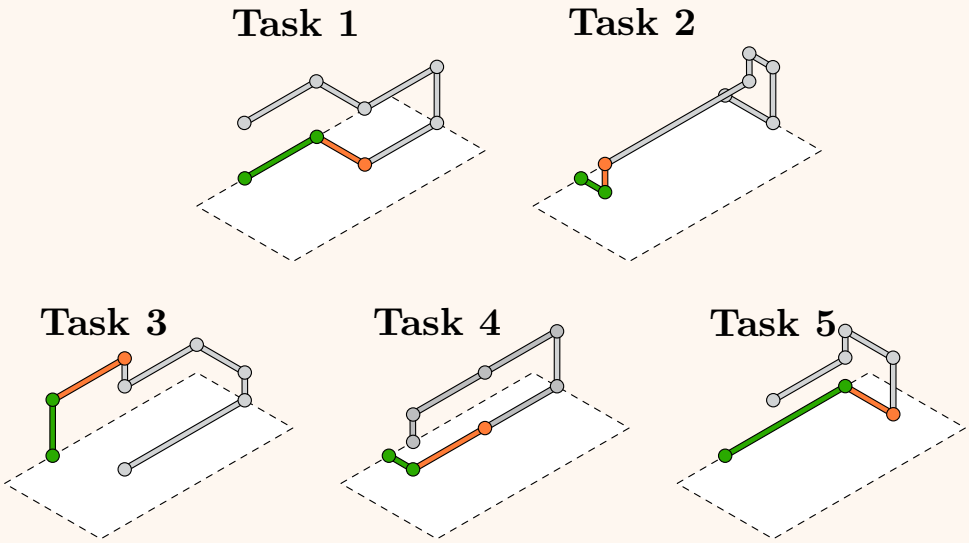


Figure 4.4.6: The 5 tasks



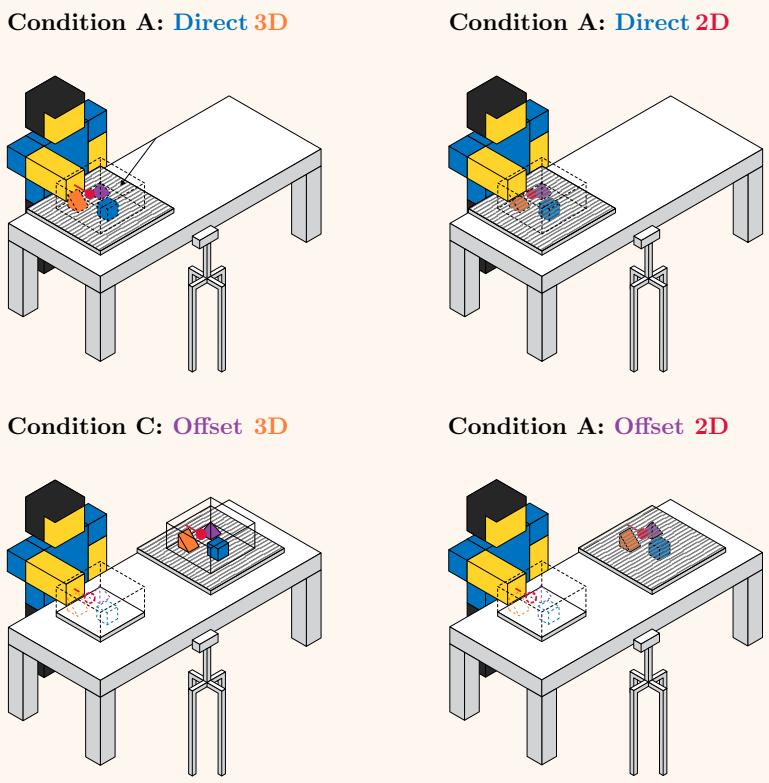
4.4.4 Participants

We invited participant to take part in the study via email and text using a standardized script. On arrival the participants were asked to fill out a consent form and a questionnaire about themselves to find out information that might affect the results, such as their age, handedness and previous experience with VR/AR.

They were next given a brief overview of the system and allowed to run through two demo tasks in each of the 4 different configurations to get used to the system. They were advised to keep their non-dominant hand on their lap, and place their dominant hand on the monitor face down at the beginning of each task to aid with tracking. They were allowed to do this up to three times.

When they were comfortable with the system they were entered into our system and were automatically assigned a random order of the four conditions that can be seen in Fig 4.4.7.

Figure 4.4.7: Study Conditions



Each condition consisted of the 5, 1 minute tasks that the participants had to complete in order. They were given an audio cue when the task was about to start and when it had finished. The participants were allowed to take breaks between conditions. After each condition they were asked to fill out a survey about the condition. At the end of the study they were asked to fill out a survey about the system as a whole.

4.4.5 Setup

The study was run on the groundfloor of the Huxley building in Room 218 at Imperial College London. As we knew we would be conducting the study over multiple days, we made care to set up the system in such a way it would be difficult to tamper with. As can be seen in Fig 4.4.1 we put our camera on a tripod and marked the positions of the legs on the floor. We also surrounded the camera with a barrier of tables to prevent it from being knocked over.

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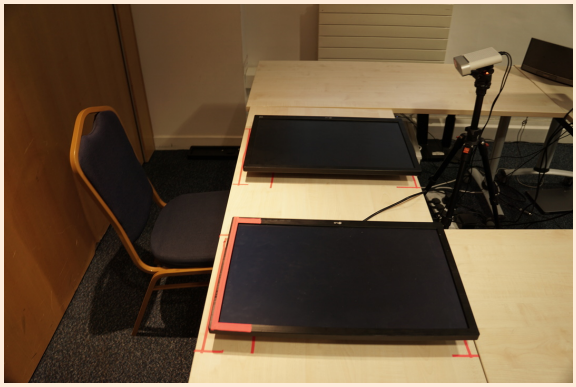
Figure 4.4.1: Study: Front View

Figure 4.4.2: Study: Side View



The displays we used for the study were $24''$ 1920×1200 `LG IPS LED 24EB23` computer monitors that we had taken off the stands and places horizontally on table. They were places with a gap of 25cm between the bottom of far monitor and top of the close monitor as can be seen in Fig 4.4.2. The camera was placed such that the head of the user would be approximately (it would vary with participant height) 1 meter away. The relative position of the interaction zone (on the far display) meant that the user would be interacting with scene at a range of distances from 30-70cm from the camera. Both of these distances were chosen to be in the observed tracking range of out system that we go more into detail about in our evaluation.

We setup two monitors on the other side of the camera to allow the study runner to control the system and monitor the participants as can be seen in Fig **??**. We chose to use two large monitors to block the view of the study runner from the participant to prevent any bias.

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Figure 4.4.3: Study: Control View

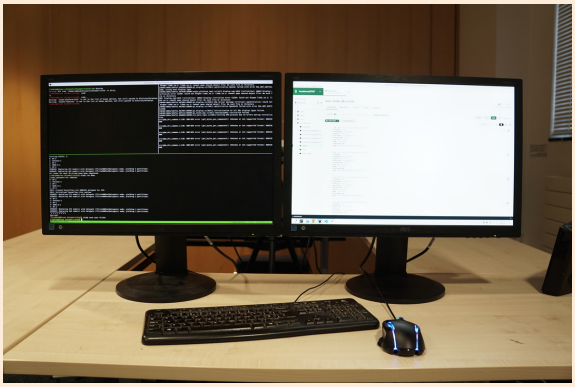
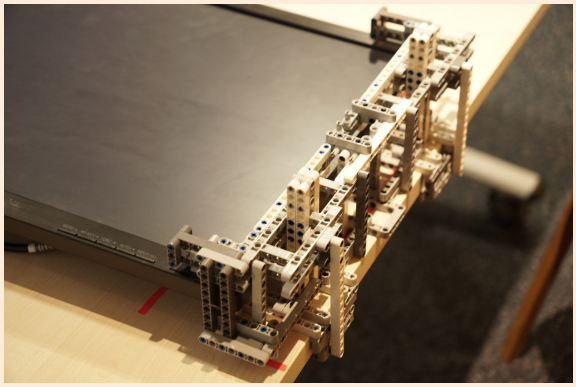


Figure 4.4.4: Study: Calibration Device



we also created a calibration device that can be seen in Fig 4.4.4 to re-align the displays. This was a simple device made from Lego Technic ToCite that allowed us to easily re-align the displays if they were knocked out of place by the participants during the study.

4.4.6 Evaluation Metrics and Collected Data

The evaluation metrics we used to evaluate the system were primarily the time taken to complete the task and the number of subtasks completed. We took a time stamp at the beginning of each task and at the end of each subtask.

We also logged through the task the position of the participants eye, and hand coupled with time stamps to allow us to analyse the data in more detail. This allowed us to visually plot the paths participants took to complete the study which can be seen in the evaluation section.

picture of consent form, put the whole survey in the appendix

4.4.7 Study Implementation

The study was run from a python based CLI using the Click library. The simulator was compiled as a shared library and called from the python CLI using a C-FFI (foreign function interface). The results and logs were received from python in json format and stored in a mongoDB database.
if have time include code CLI snippet, draw basic diagram with mongodb?

Chapter 5

Evaluation

5.1 User Study Evaluation

1. Look at the results.

5.1.1 Study Results

1. Use ANOVA test?
2. ????

1. For each task graph the distance of the points to it, see if people spend more time trying to be exactly precise.

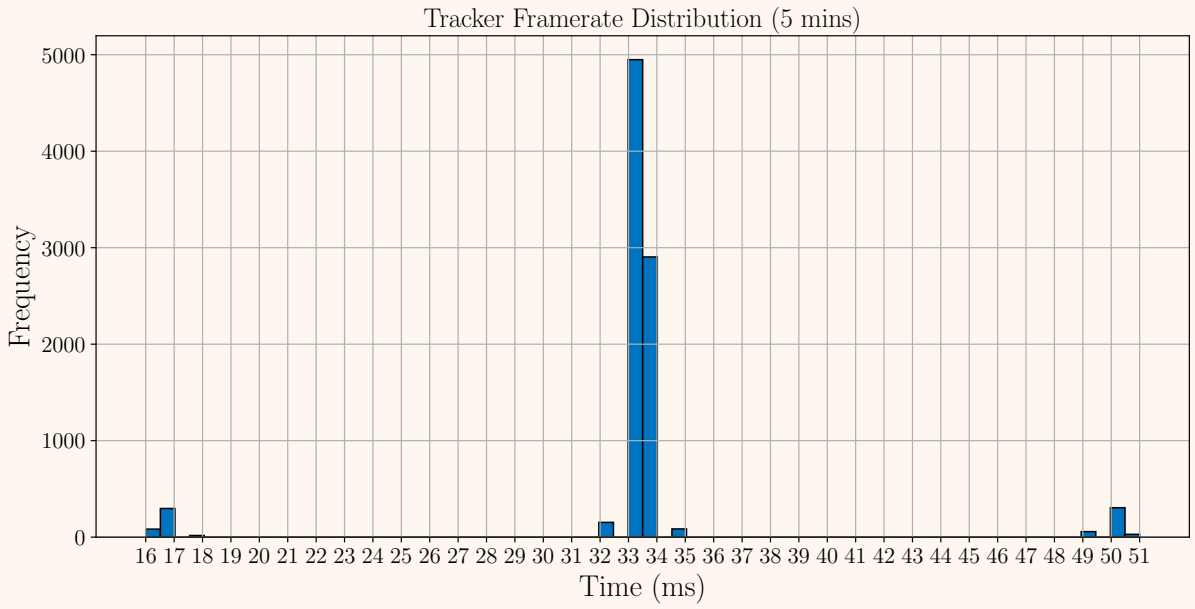
5.2 Simulator Evaluation

5.2.1 Overall System

1. Get benchmark of the system i.e GPU usage and CPU usage.

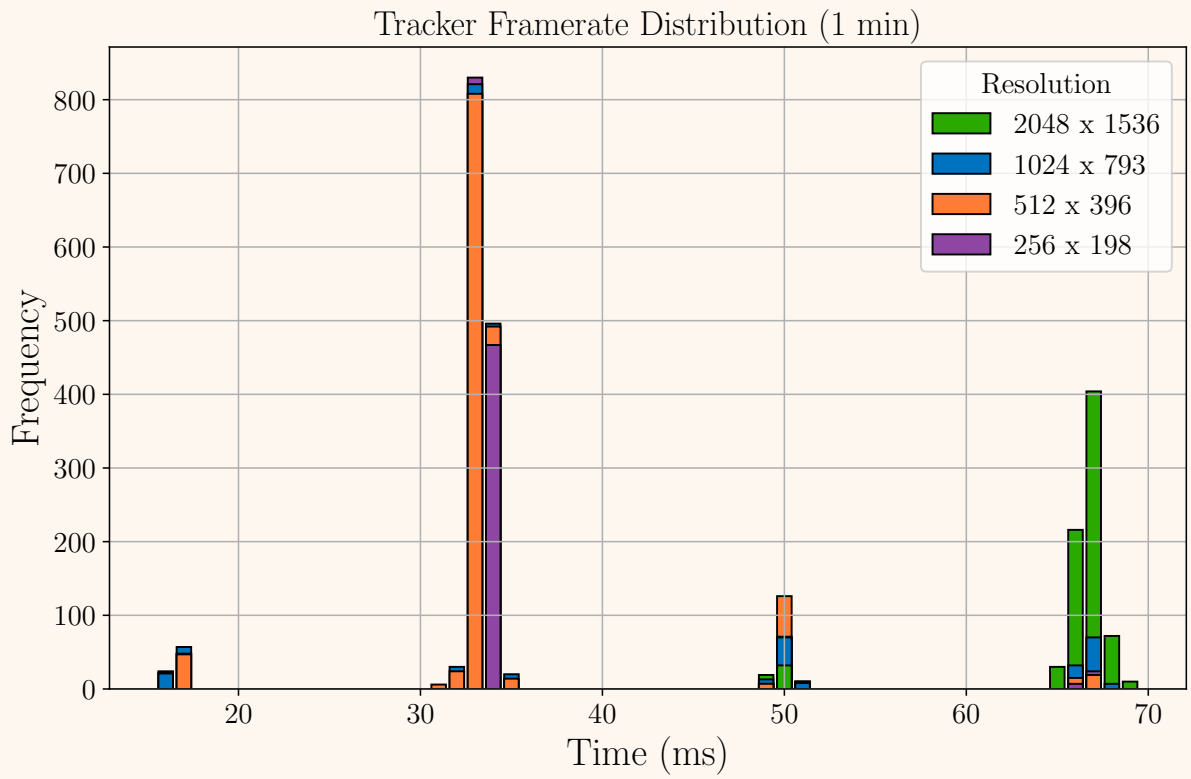
5.2.2 Tracking System: Frame Rate, Latency and Timings

Figure 5.2.1: Overall Framerate



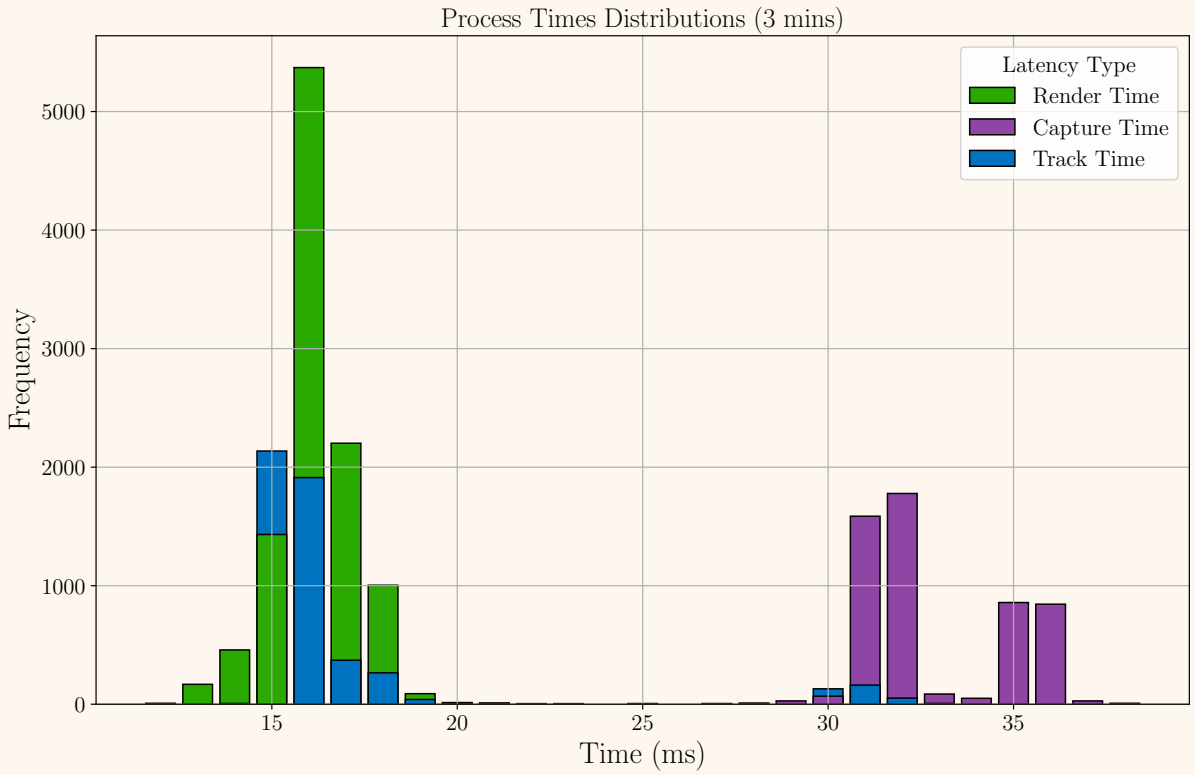
As can be seen in Figure 5.2.1, the framerate of the system is quite low. 90.83% of the time the framerate is between 30 and 35ms. There is what at first glance a strange phenomenon of a group of latencies at 16-18ms (4.46%) and 49-51ms (4.39%). This is due to the framerate of the renderer, as it lazily converted on request it basically chunked to the nearest 1000/60 = 16.666. Even though the tracker is running at 30fps, it is possible to have a latency of 16ms if the tracker fails to the meet the 30fps requirement for a frame buffering the result for the next frame. This means the next capture is already ready by the next frame so it makes it appear like the camera has a higher framerate than 30. rewrite this in a less shit way
We investigated down scaling the image to increase performance. We only found that down scaling it once was enough to get the performance we needed. Down scaling it further did not offer any significant performance increases and significantly decreased tracking quality. As can be seen in Figure 5.2.2, the performance of the system increases noticeably between going from 2048 x 1536 to 1024 x 793 but reducing the resolution further does not provide any speed benefit at all as we are already running at 30fps which is the cameras refresh rate.

Figure 5.2.2: Comparing Resolutions



As can be seen in Figure 5.2.3, of the three separate threads (captures from the Kinect camera, tracking the hand and eye, and rendering with OpenGL) which are running at the same time, the bottleneck is waiting for the inect camera to return the capture. This means there isn't any benefit to speeding up the tracking algorithm.

Figure 5.2.3: Comparing Processing Times



.

Estimate Latency, 12.8 exposure which you should cite, plus workout how the framerate effects it + 15 ms for tracking plus work out how the random chance of being selected during rendering works and compare to it similar systems like oculus quest and maybe fishbowl and vision pro?

5.2.3 Tracking System: Accuracy

We measured the effective tracking range of our system. The method we used for this was to sit in a chair and slowly wave your hand and move you your head side to side over a period of 30 seconds as can be seen in Fig 5.2.1. We took a variety of samples at different distances measuring the percentage of captures that were successfully able to detect a face or hand. The resolution of the colour camera was 1024 x 793.

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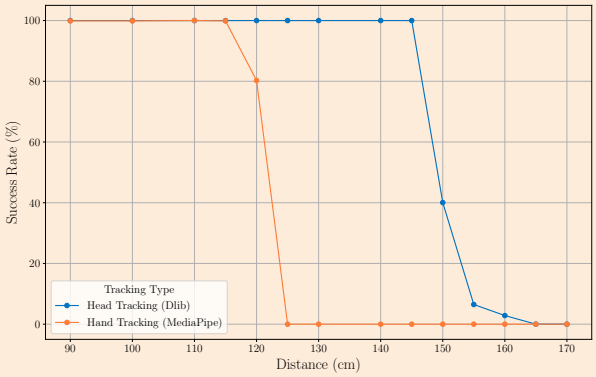
Figure 5.2.1: Setup for distance testing

Figure 5.2.2: Tracking success rate at different distances



As can be seen in our results for Fig 5.2.2 the success rate for MediaPipes hand tracking model rapidly deteriorates after about 1 meter to the point of being completely unable. We suspect this is probably due to the data it was trained on and the fact it was primarily designed as a model to track hands from a mobile phone camera ToCite .

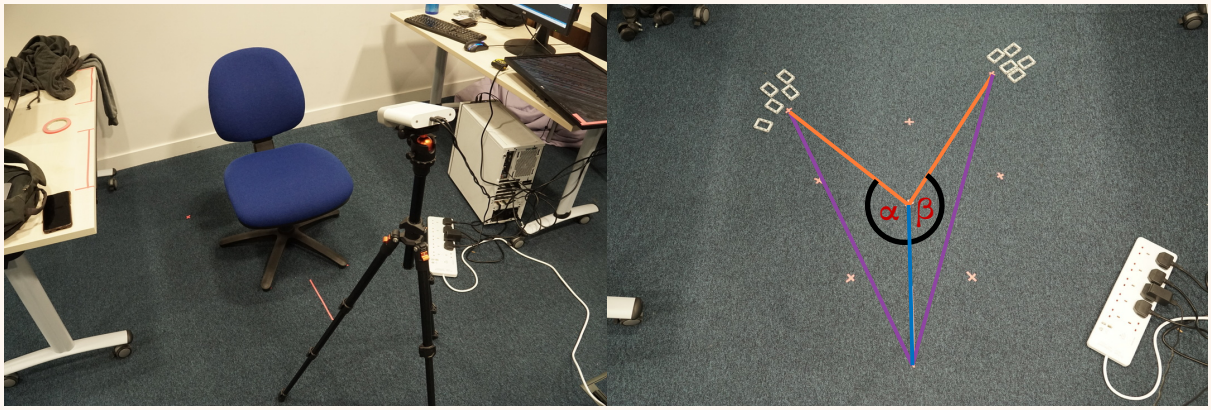
Dlib's headtracking model was better deteriorating at about 1.5 meters for suspected similar reasons to MediaPipes. We took these results into consideration while designing our user study positioning the camera so the users hand would be in the range of FIND OUT STUDY DISTANCE RANGE

Head Tracking

1. Test with glasses on?

One of the important aspects of the system is the head tracking. We wanted to evaluate how well the head tracking system worked. One important aspect of the head tracking system is the angle of the head at which it fails to detect a face. We create a fairly redumentary setup as can be seen in Fig 5.2.4 to measure the angle of the head at which the head tracking system fails. We used a swivel chair to rotate the user's body and head (we asked the participants to keep their body still and rigid). We measured the location of the midpoint of their feet when the tracking finished. Using GCSE trigonometry we were able to calculate the angle of the head at which the tracking failed.

Figure 5.2.4: Angle Setup



We tested this with 5 different people and the results can be seen in Fig 5.2.3. The technique was not particularly precise so the results should be taken with a grain of salt. The angle at which the head tracking failed was typically between $120° - 150°$. This might result might see strange as at that angle the participant is very much facing away from the camera however the way the face tracking model works is it first detects a face and then maps a landmark to the face.

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Figure 5.2.3: Angle of failure for headtracking

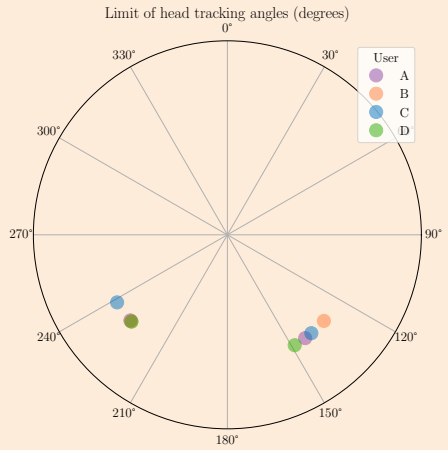
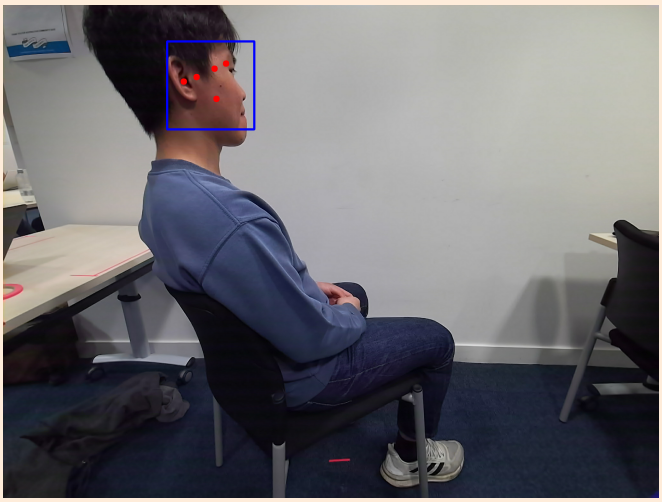


Figure 5.2.4: Incorrect Head Tracking



As can be seen in Fig 5.2.4 the face tracking model can still detect a face even when the face is not visible as it is detecting the side of this participants head. Acadotally the model seems to fail when it can only see hair. We would be interested to test this on a bald participant so see if it always detects a head no matter the rotation. Although this might seem like a problem at first glance it isn't. If the tracker cannot see the face then the face can't see the

display either, so it doesn't matter if the display is rendered incorrectly. It also has the added benefit of tracking the eyes in an approximate position to where they would be if the face was visible, so as the user turns their head and the face comes into view the display does not need to correct much and the user will not notice the correction.

Hand tracking

1. Estimate throughput via logging (unique points). Draw a bell curve like graph of the time between each result from the tracker.
2. Measure accuracy by moving head around and seeing how often it loses track at different distances. Change hand orientations
3. Mention occlusion issue.
4. Wall vs no wall issue.
5. The colour of the screen also affects the hand tracker.
6. Maybe should have added image segmentation model to make the hand tracker better.

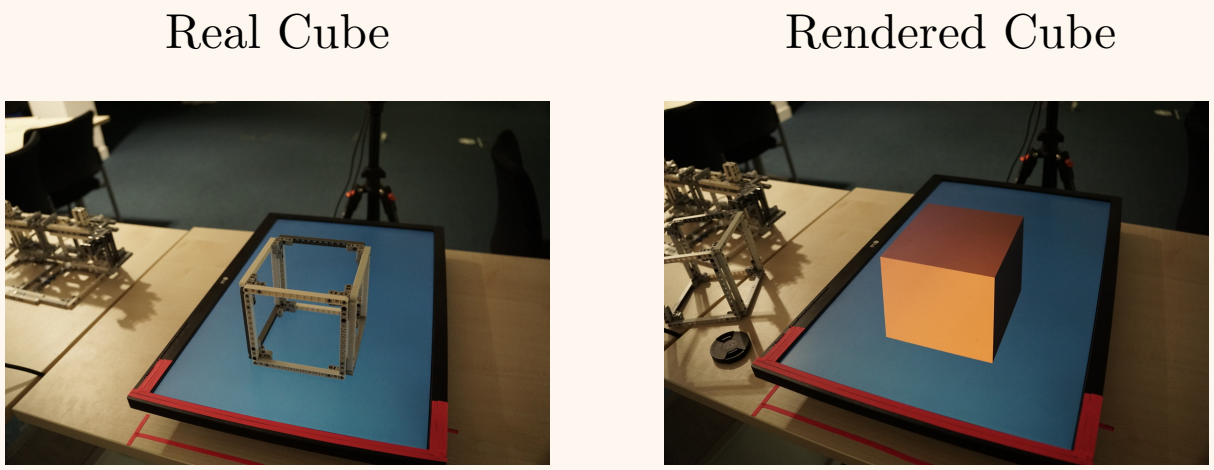
5.2.4 Renderer

TODO

1. Talk about and give an image of the rendering system displaying a complex scene.
2. Get framerate?

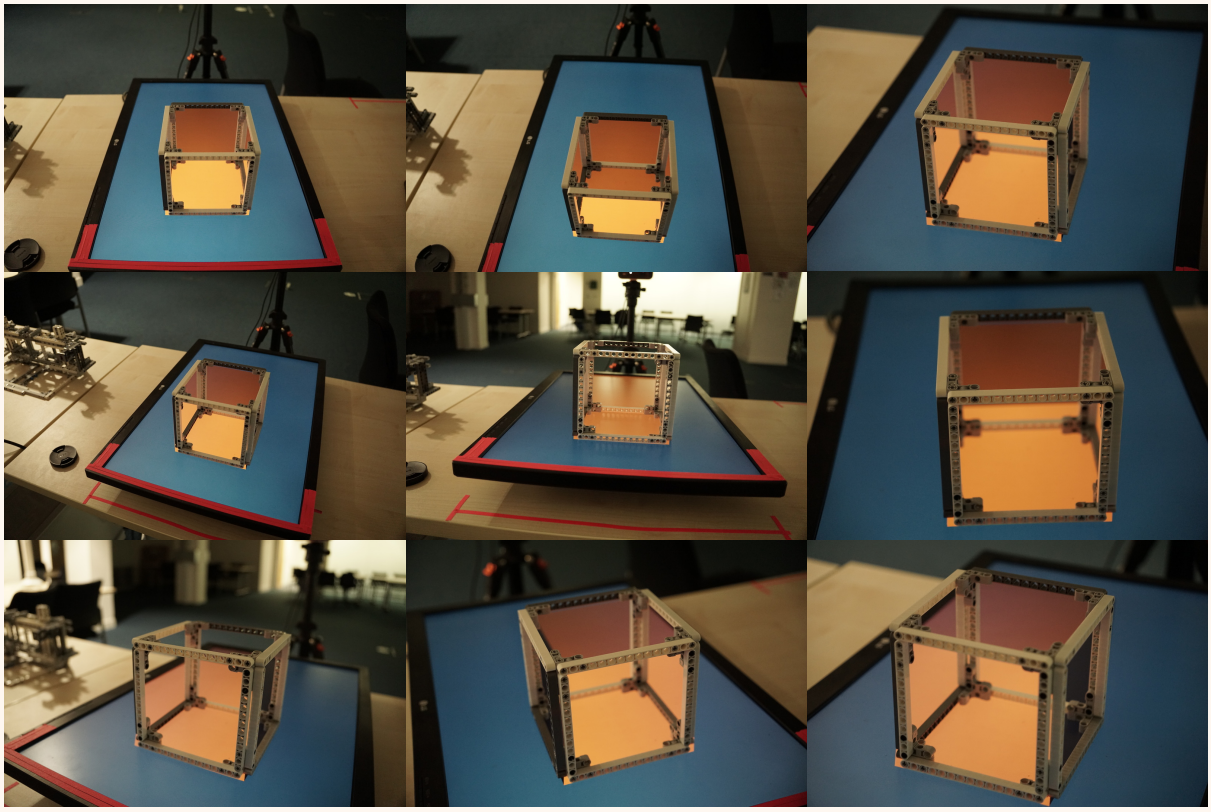
We wanted to evaluate how accurate our rendering system. As our rendering system propose is to create the illusion of 3D objects in the real world, we wanted to see how well it could recreate a real object. We chose a cube as it is a simple object that is easy to recreate. We created a physical cube out of lego and created a virtual cube in our simulator both with the same dimensions of 13.5cm x 13.5cm x 12cm as can be seen in Fig 5.2.5.

Figure 5.2.5: A real and rendered cube



Because the physical cube is hollow this allowed us to easily to compare the two cubes by superimposing them. We tested a variety of different perspectives and verified that the two cubes were indeed the same size and shape and completely overlapped. Some examples can be seen in Fig 5.2.6, it is worth noticing that the images might be slightly off as the system was tracking my eye and not the camera lense which was both below and about 10cm in front of my eye. This shows that our rendering system is accurate and can be used to create the illusion of 3D objects in the real world.

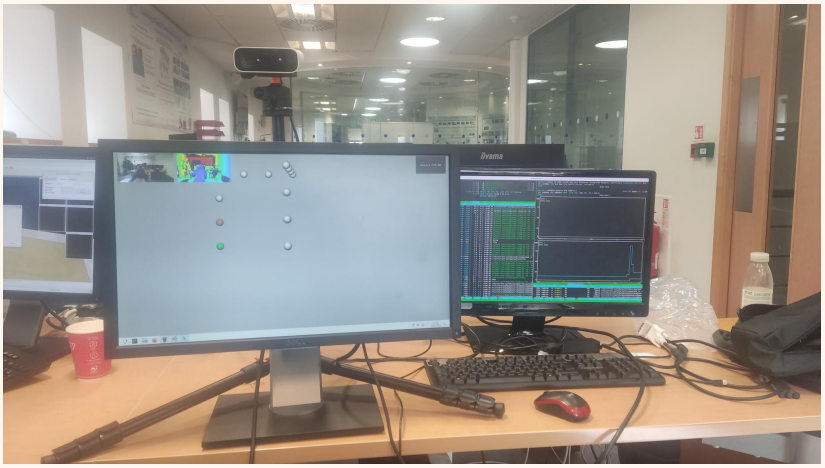
Figure 5.2.6: Superimposed real and rendered cube



5.2.5 Portability

One of the key aspects of the system is that it is portable and should be runnable from a fresh linux machine from scratch with a single command. We developed the system on a Linux Machine (NixOS) using an Intel i5 9600k, with a Nvida 2070 Super GPU. We tested the system on a different linux machine (NixOS) with an Intel i7 4770k and a Nvidia 1080 as can be seen in Fig 5.2.7. We were able to run the system on this machine with no issues first try. We also tested the system on a Windows machine using WSL2 TODO .

Figure 5.2.7: Running on a different machine



Chapter 6

Conclusions and Future Work

6.1 Conclusions

1. We have developed a novel system for visualising 3D data in a 2D space.
2. We were able to validate it with a user study.
   (a) Write about results form user study.
3. We are unaware of any other system that can do this with hand tracking.
4. We have built a system that is easy to use and intuitive and portable.

6.2 Future Work

- **Adapt to be compliant with OpenXR:** OpenXR is an open standard for virtual reality and augmented reality. It is supported by all the major players in the industry including Microsoft, Valve, Oculus, Google, and many more. It would be a good idea to adapt the project to be compliant with this standard, so it can load into any OpenXR compatible application. I am currently not sure how difficult this is or if it is even feasible.
- **Anaglyph 3D:** Anaglyph 3D is a method of displaying 3D images using filters typically red and green color filters and does not require special hardware. The 3D effect currently requires 1 eye to be closed so adding 3D support would make it a more immersive experience. I predict this task will take a day or two as I just need to duplicate the perspective per eye.
- **Realtime light detection:** Taking inspiration from what I have learned from advanced graphics this term, it might be interesting to add another camera, a fish eye lens and use that to generate a real-time light map. This would allow the virtual scene to be lit by real-world lighting. I have already talked to Prof Abhijeet Ghosh about this idea, and he thinks it is feasible. However, this is going in a slightly different direction with the project. I predict this task will take a week or two.
- **Improve compatibility:** Currently the project only works on Nvidia GPUs. It would be good to improve compatibility to work on AMD GPUs and Intel GPUs and also run without a GPU (albeit slowly). It would also be good to support different depth cameras other than the Kinect (Like Intels Intellisense) as this has been discontinued by Microsoft. This would require a lot of refactorings and would probably take a week or two.
- **Switch hand tracking model:** By a fairly significant margin, the hand tracking was the weakest part of the project. It would be good to switch to a more robust hand tracking model. I think it would be good to switch to a model that tracks using the depth image rather than the RGB image. This would probably be a fairly large undertaking as there is unlikely to be an off the shelf model that does this. I think implementing this paper may be promising ToCite . I predict this task will take a month or two.

6.3 Contributions

6.4 Novel Contributions

Once this project is complete we expect to have made the following novel contributions:

- A **volumetric display simulator** that is Multi-platform, Lightweight, Cheap, and Reproducible.
- A **user experiment** that compares the effectiveness of using hand tracking to interact directly with an ethereal/incorporeal volumetric display compared to a via teleoperation with a corporeal/tangible display.

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