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BY

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Towards a High-Fidelity Virtual Reality

Atrial Fibrillation Simulator for Surgery Training

Thesis submitted as a requirement for the degree of Bachelor of Engineering in Mechatronic Engineering

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ORIGINALITY STATEMENT

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ABSTRACT

Atrial fibrillation is the most common cardiac arrhythmia and currently no extensive simulator for surgical treatments exists. This project focuses on the development of a high-fidelity virtual reality training simulator for atrial fibrillation ablation surgery and seeks to provide a software framework to act as the foundations of further work. This report provides an outline on the integration of electromagnetic tracking technology with virtual reality and medical simulation applications.

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NOMENCLATURE

2D	Two Dimensional
3D	Three Dimensional
AF	Atrial Fibrillation
AR	Augmented Reality
ASCII	American Standard Code for Information Interchange
CI	Confidence Interval
CRC	Cyclic Redundancy Check
DICOM	Digital Imaging and Communications in Medicine
HMD	Head Mounted Display
MR	Mixed Reality
RMS	Root-Mean Squared
SCU	System Control Unit
TCP	Transfer Control Protocol
UI	User Interface
VR	Virtual Reality
XR	Extended Reality

1 INTRODUCTION

1.1 Extended Realities

Extended realities (XR) cover a variety of different interactive mediums that range from fully immersive experiences to digital overlays of unobstructed vision. XR technologies are seeing rapid innovation and applications in medical practice are becoming more common place.

1.1.1 Virtual Reality

Virtual Reality (VR) provides a fully immersive experience, completely obscuring the real world. The user wears a head mounted display (HMD) which occludes normal vision and replaces it with a digital environment. The digital world is displayed to the user via two screens (one for each eye), with focusing lenses for each to allow for true stereoscopic vision. The images are either sent to the HMD via a cable connected to a computer like the HTC Vive (HTC, Taoyuan City, Taiwan), or included in an all-in-one solution such as the Oculus Quest 2 (Oculus, California, United States). These immersive experiences are used in a variety of applications, including entertainment, business, and as training and educational tools.

1.1.2 Augmented Reality

Augmented Reality (AR) is a non-immersive medium which provides a digital overlay of normal vision. This digital overlay is typically not interactive and displayed on a 2D display. AR utilises cameras and live object tracking to determine virtual placement of the digital entities being displayed. It has been used in areas such as mobile phone gaming (Pokémon Go, Niantic, Inc.), advertising, and education. It provides limited functionality in terms of interaction. However, AR provides an enhanced method of displaying 2D and 3D information, intersected with the physical world.

Figure 1: (Left) AR Pokémon Go (Right Top) VR Oculus Quest 2 (https://www.oculus.com/quest-2/) (Right Bottom) MR Microsoft HoloLens (https://www.microsoft.com/en-us/hololens/buy

1.1.3 Mixed Reality

Mixed Reality (MR) combines AR and VR into an unobstructed experience with interactable digital overlays or holograms. Like AR, MR headsets utilise outward facing cameras to track the user's environment and anchor digital information/displays to them. The biggest difference between MR and AR is the ability to interact with the 3D environment using the user's hands. The same cameras track the user's hands and allow them to be used to control and manipulate the digital display. The Microsoft HoloLens 2 (Microsoft, Washington, United States) is an example of an MR head mounted display that has been used in many different fields, utilising see-through displays to enhance the world around the user.

XR technologies are seeing further use in medical practice with each passing year. They have been used in pre-operative planning, have open surgery applications, and have been widely adopted in the training and education space. Atrial Fibrillation (AF) is a key example where XR technologies could be applied to increase the efficacy of non-pharmacological therapies.

1.2 Atrial Fibrillation

AF is the most common form of cardiac arrhythmia (irregular heartbeat). This irregular heartbeat is caused by abnormal electrical activity in the top chambers of the heart, causing the top chambers of the heart (atria) to spasm out of rhythm with the bottom chambers (ventricles). AF reduces the hearts ability to pump blood properly and is a contributing risk factor for ischemic stroke [1] and often coexists with heart failure. AF can be paroxysmal, persistent, long-standing persistent, or permanent. Paroxysmal refers to cases which resolve spontaneously within 7 days, while persistent and long-standing persistent last for over 7 days or over 12 months, respectively. Permanent AF occurs when treatment is no longer sought by the patient or physician. The worldwide prevalence of AF increased by 33% between 1997 and 2017, with the estimated incidence rate also increasing by 31% over the same period.

There are two primary methods of treatment for AF. Pharmacological therapy methods consist of a variety of drug choices with goals in either maintaining rhythm control or rate control. [2] Non-pharmacological treatments involve different surgeries such as catheter ablation, the maze procedure, or permanent pacemaker implantation. Although treatment choices vary depending on patient circumstance, studies have shown that in cases where heart failure was present, catheter ablation and cryoballoon ablation are superior initial therapy choices for paroxysmal AF. [3, 4] AF ablation surgery is a complex, minimally invasive procedure. There currently exists no virtual simulation to prepare and train surgeons for this procedure, despite its increasing prevalence worldwide, affecting 0.51% of the global population in 2017.

AF ablation surgery costs approximately $18,151 CAD [5] ($\cong 19{,}812\ AUD$), and with success rate of 73% with one procedure, it can be costly if multiple procedures are required. This project aims to develop a realistic constructive simulation using VR technology to assist surgeons in improving this initial success rate.

The initial phase of the project had an exploration and education focus, identifying and developing the skills required to begin development. Despite this, once the production phase began, time was still allocated to discovering different methods and approaches to the same issues to better identify the most effective technique. The work achieved can be split into three sections:

- Development of a custom API
- Development of the TCP server/client pair
- Construction of Unity scenes

The first step was developing an understanding of the related topic and how the issue had been approached already.

2 LITERATURE REVIEW

2.1 Preoperative Planning

XR technologies have revolutionised access to 3D information in a 3D format, rather than on traditional 2D screens. Better visualisation assists in making more informed decisions and better overall preparation for surgery.

Planning and understanding a procedure before it is undertaken is an important process in any surgery. This can be enhanced with the innovative use of VR and 3D imaging [6], and allows the surgeon to better visualise the process and assess any potential risks or challenges. [7] outlines one such tool that is used for planning and testing different ablation strategies for the treatment of arrythmia such as AF. FaMaS-VR utilises individual patient data to create a virtual environment which can be manipulated in real time. This allows the interventionalist to assess the most appropriate approach for any given patient. FaMaS-VR is built from the IMHOTEP framework designed by Pfeiffer et al. [8] which is a virtual reality framework developed specifically for surgical applications.

3D VR images have also been used in the planning of other cardiac surgeries. Sadeghi et al. [9, 10] used 3D VR images to assist surgeons in the planning and intraoperation stages of multiple different procedures. The 3D VR visualisation was found to be useful in creating or modifying the surgical plan. The original DICOM images obtained from the patients involved were converted to the 3D VR images using a VR software platform developed by MedicalVR, (Amsterdam, Netherlands), however there are several tools that have been developed for the same purpose. These tools allow the user to import traditional medical imaging formats such as MRI and CT scans and convert them easily into 3D models. The fact that these systems are readily available shows that the industry is moving towards a more intuitive, 3D approach to medical imaging, allowing better comprehension and understanding. VR is more suited to this application, placing the user in an immersive environment and providing clearer images than other XR technologies. The ability to manipulate the images shown in a VR experience provide new perspectives on traditional data, making it easier for decisions to be made. The next logical step with a lot of these applications is modifying them for use in open surgery, with access to live patient data.

2.2 Open Surgery

XR in live surgery generally leans towards the use of mixed realities. AR and MR maintain the user's awareness of their surroundings and keeps them in contact with the surgical team. The visual enhancement provided by MR can be beneficial during surgical procedures and has been utilised in various types of surgery. [11, 12] 3D models generated prior to surgery, using CT or MRI images, are superimposed on the surgeons view to provide improved spatial perception and safety [13]. Models generated prior to surgery only offer minor assistance however, as organ shift can cause discrepancies between virtual and actual positioning [14]. 3D transoesophageal echocardiography and Electroanatomic Mapping Systems (EAMS) have been used as a method to obtain real time information to then be transmitted to an MR headset as live visualisation aids [12, 15]. Live data is understandably preferable in open surgery and viewing information that is traditionally displayed in a 2D format in the form of a 3D hologram provides a unique and changeable view of the target area. The need to interpret 2D data into the 3D space can cause unnecessary strain on the surgeon and with the application of XR this strain is minimised.

A different approach to intraprocedural visualisation was explored by Marien et al. [14] with the extended functionality of real-time position tracking of surgical instruments. This novel system was designed to be used as a virtual targeting system for surgery and has promising applications in procedures where visualisation and targeting are typically difficult, like AF ablation surgery. However, it was found that the average error between the intended and actual targets were 16.9mm when targeting the prostate, and 12mm when targeting the kidney. In both cases much of this error came from the z-axis, or out of plane axis. This discrepancy was attributed to organ shift, likely caused by the operator pressing down on the target location during the initial puncture. It was identified that live organ tracking would improve the outcome as any deformation or shifting could be adjusted for using live data. Although this application does not use a VR or MR headset for visualisation, it utilises technology that is relevant and has potential future applications in both VR and MR.

Clearly MR and AR are generally more suitable for open surgery as it allows the surgeon to retain their perception of the procedure and stay in communication with supporting practitioners. VR is restrictive in this sense and has seen little to no use in open surgery with the technology currently available. Although it can create realistic and immersive environments, this is not necessary when in the operating room. However, VR can create models with higher resolution than possible with current MR technology, allowing for greater detail to be included which makes it a much more useful tool for education and planning purposes.

2.3 Surgical Training and Education

Due to the availability of a growing number of headsets and equipment, VR is more accessible and practical to be used in a wider range of applications, including education. XR has found particular use in teaching. [16, 17] A VR experience designed to better educate patients and medical residents on the AF ablation procedure-related knowledge was developed by Chang et al. [18] This experience is a narrated run-through of the entire AF ablation procedure and was found to improve self-efficacy and knowledge scores of residents and subsequently their patients. Although this experience is developing knowledge on the procedure, it does not allow surgeons to practice the actual performance of the operation. This type of simulation would work well when combined with a psychomotor skills-based simulator, similar to [19], where the virtual experience is directly linked to the physical component of the procedure. There currently exists no AF ablation simulator that trains these skills. Simulation education has always existed in medical practice to better prepare medical students for live surgery and there is a proven correlation between simulation performance and operating room performance as well as knowledge retention and overall skill development. [20-27] Most studies show the simulation trained group performing significantly better in most aspects of post training testing, clearly demonstrating the effectiveness of simulation training. [28] outlines the variety of simulators available. Most of the simulators used are custom-made (78%) and utilise custom designed hardware to recreate the physical

Figure 2: Stanford Virtual Heart (https://www.stanfordchildrens.org/en/innovation/virtual-reality/stanford-virtual-heart)

aspects of the simulated procedure. These simulators are often quite expensive to develop, which is also why commercially available simulators share this high price tag. This cost can be limited by incorporating much of the detail required by the simulation in the virtual space, simplifying the physical construction and setup of the system.

Voelker et al. [25] explored whether simulation-based training would improve procedural skills of beginners in interventional cardiology. It was found that the skill level of cardiology fellows in coronary interventions improved. The study made use of three commercially available simulators to ensure a more complete analysis into the effect of simulation training was performed. These were the Vist-C (Mentice, Gothenburg, Sweden), CathLabVR (CAE Healthcare, Guenette, Canada), and AngioMentor Express (Sim-bionix, Cleveland, Ohio). These simulators are used to train in the performance of a variety of operations depending on the modules in use. It is important to note that although these are considered VR simulations, they require custom designed tools for user input and can often require a large amount of space. A simulation which uses a standardised and readily available VR system (such as the Oculus Quest 2 (Oculus, Irvine, California)) could be designed to develop a variety of skills required for several diverse procedures.

Figure 3: Mentice Vist-G7 Simulator, successor to the Vist-C (https://www.mentice.com/vist-g7)

A recent review performed by the French Commission of Simulation Teaching identified a range of different simulation mediums used in cardiology [29], with VR and MR being the most recent modalities to be explored. One of the key advantages identified for XR simulators is the ability to avoid the purchase of multiple items of expensive equipment, however, to achieve high levels of realism within the simulation, more than just a HMD and controllers will need to be used. Purely virtual simulators generally focus on decision making and developing procedural knowledge. [18, 30] These simulators put the user in an immersive environment and test their ability to treat a patient created from real anonymised patient data. They focus largely on decision making while monitoring vital signs and wellbeing of the patient, emulating the real-life experience as closely as possible in the virtual space. Although there is a percutaneous element to these simulators do not simulate the physical aspect of surgery. However, they provide the user with a repeatable exercise that will create a familiarity with the procedure and the time sensitivity involved. MR is generally more limited in training for performing surgery and generally finds more use in visualisation steps during pre-operative planning and live surgery applications.

2.4 Limitations

Despite the obvious benefits of utilising XR technologies, there are several limitations preventing the technology from surpassing current practices. The current technology available makes compromises between cost, usability, and quality [31]. Often inexpensive VR headsets lack the high quality, detailed display required for effective simulation. Tethered headsets restrict movability, and often add to the headset's weight and size. Untethered headsets allow free movement but entail shorter usage times and have a reduced field of view. As technology improves, these compromises will be reduced.

Standard XR solutions also lack the ability to provide appropriate haptic feedback. This is a big contributor to the realism of purely virtual simulations used in education/training, and the technology in this field is still emerging [29, 32]. This is emphasised by a study by Coles et al. [33] which ascertains that surgical simulations require haptic feedback to provide a thorough, realistic experience for trainees. The limitation to the use of VR controllers (which do not emulate real surgical tools) is also restrictive and hand tracking is not always a viable option. Having a reduced or non-existent response from virtual stimuli reduces the realism and overall effectiveness of any training of psychomotor skills. Tactile feedback has been explored in surgery simulation before [34] however, is limited in its use. There are now more robust solutions available in the form of haptic gloves.[35] However, this technology has been developed recently and sees a hefty price tag as well as the addition of bulky equipment to the simulation setup.

Figure 4: Haptx Gloves DK2 (https://haptx.com/dk2-release/)

A critical area that restricts XR technology use in live surgery is the overall accuracy of augmented overlays and real-world bodies being simulated in the virtual space [15]. Tracking of controller movement can be achieved to the necessary accuracy with instruments such as NDI's Aurora [36], however, this comes at a high cost and requires supporting equipment. Live tracking of a patient's physical positioning is more difficult to achieve. The 3D visualisation technique employed by [14] uses pre-procedural scan data to generate the intra-corporeal anatomy. This led to unsatisfactory discrepancies between the desired position and actual position. Live organ tracking would improve accuracy however this area requires further development to be suitable for practice [37].

Ergonomic issues have arisen with the use of HMD's. Of 170 participants, 26 students suffered headaches and 17 felt nauseous and experienced eye fatigue or neck strain [38]. As the technology improves these issues may become negligible.

There are also various costs involved in the use of XR for medical simulation/enhancement. HMDs can cost as much as $1,399 USD, and VR ready computers can cost upwards of $2,100 USD. [39] Additional costs include accessories, such as hand controllers, the costs for the programs and necessary licensing to be loaded on to the devices, and the ongoing cost of repairs and upgrades [29]. These costs may be seen as limitations by some, yet compared to alternative simulation methods, they are of lesser concern.

MR and AR are generally more suitable for open surgery as they allow the surgeon to retain their perception of the procedure and stay in communication with supporting practitioners whereas VR is restrictive in this sense. However, MR technologies present the user with a more restricted field of view and are unable to provide the same amount of detail as VR alternatives. VR creates realistic and immersive environments; this is not necessary when in the operating room and proves more useful when simulating and training for surgery. VR can create models with higher resolution than possible with current MR technology, allowing for greater detail to be included. As the technology advances and new technologies are developed, the limitations outlined in this section will change, and largely diminish.

2.5 Future Direction

The role of extended realities in medical practice will develop as the technology improves and becomes more accessible. Research still needs to be performed to clarify and validate the ability of trainees to retain skills from extended realities training. As more authentic simulations and haptic capability are introduced, simulations will be developed to address more complex cardiac procedures and promoted by an established training curriculum [29, 40].

Access to live patient data will also prove to be a leap forward in intra-procedural applications. With live positioning data, like that which can be obtained from an EAMS, could be used in conjunction with XR technologies to provide enhanced visuals and important information while maintaining real world accuracy.

Hand tracking is an area that has seen little use in medical applications to date. It has the potential to blend physical environments with virtual details provided by an HMD in the form of a constructive simulation. VR headsets could be used to immerse the user in a realistic environment from anywhere in the world, and basic physical stimuli could be mapped to the virtual space to provide the user real objects to touch, and enhanced visuals to experience. This would allow for psychomotor skills to be applied within the simulation and for the surgeon practice the physical elements of the procedure.

3 METHODOLOGY

3.1 Overview

The process followed for the work completed had a logical progression. However, a cyclic approach was taken to the overall development of the project. This led to multiple components of the project being

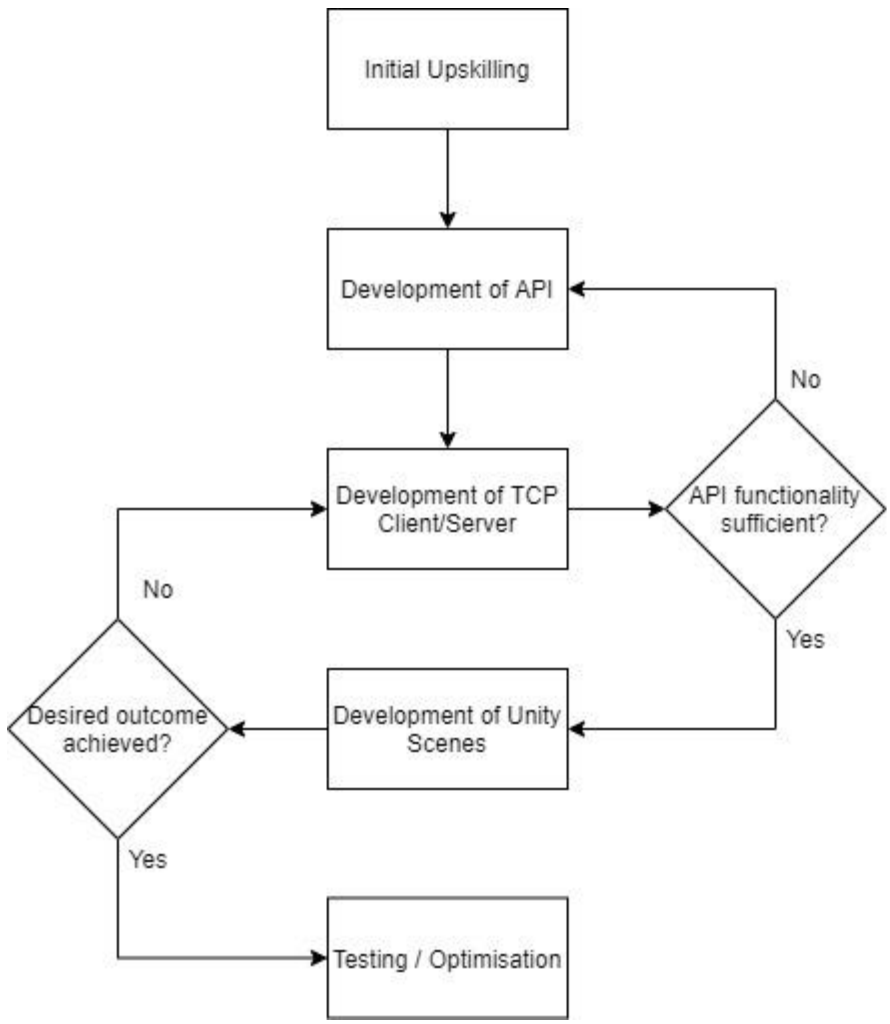

Figure 5: Project Workflow

developed at the same time. This process is outlined in Figure 5. However, if any issues were found with a component during the testing phase, this component would be revisited and modified until the output was satisfactory.

The project contains two primary Unity scenes which demonstrate the work completed to date. The calibration demonstration scene shows a method of aligning the virtual world with the real world with the use of the NDI Aurora system. Various calibration methods were tested and are outlined below. The practice scene allows the user to manipulate a simulated steerable sheath through a basic network of pipes. The physical properties of the sheath were experimented with, and the process is outlined in later sections.

3.2 Initial Upskilling

In preparation for the project, several online courses were taken to provide a familiarity and basic level of skill in the use of the Unity development software. Unity is a cross-platform game engine used by developers worldwide. The courses taken were provided by Unity and covered a variety of topics and skills. However, as development progressed, further knowledge was obtained as needed to achieve specific milestones or goals for the project. This was often done through YouTube, forums, and other free online mediums that allow publication of tutorials and answering of questions. The knowledge obtained was then applied more specifically to the project and cited where necessary. This process was the most efficient way to make quick progress in the project as the path taken was not straightforward and required re-evaluating decisions and optimising methods as the project progressed.

3.3 Software Architecture Outline

The application consists of three key components: the NDI tracking system, the TCP Server and the Unity application running on a Quest HMD. The NDI Aurora electromagnetic tracking system is used to obtain accurate transformation data from sensors which allows the precise tracking of physical tools to then be replicated in the virtual space. This transformation data needs to be interpreted and passed on to the Unity application.

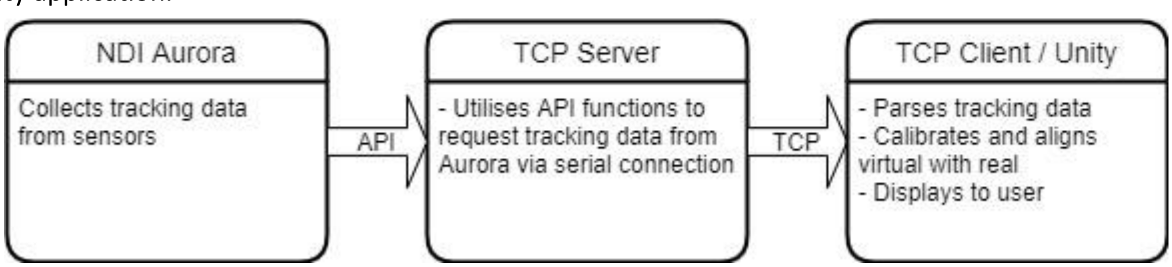

Figure 6: Project Architecture

The TCP server has a custom application programming interface which allows interaction between the NDI system and the console application. The data obtained by the TCP server is then broadcast to any client connected to it. As a result, when the Quest HMD runs the Unity application, this data is received by the client and interpreted appropriately. The following sections go into further detail as to how each of these elements were developed and the challenges that were overcome.

3.4 Development of API

An API was needed to allow for the TCP Server to send messages to and interpret responses from the Aurora SCU. The API was developed in C# based on a sample API provided by NDI alongside the hardware. It provides the TCP server with easy access to functions that allow communication with the Aurora system. The Aurora SCU utilises an RS-422 serial port to communicate with a connected computer. As such, the SerialPort class from the System.IO.Ports namespace is used to allow for simple serial socket management. A class was developed to simplify the setup and allow for user customisation of the serial port on start up. The project is being developed using the C# programming language, however the sample API provided by NDI was written in the C programming language. As a result, a custom API was developed in C# using the sample API as a guide. The custom API consists of a narrower set of functions designed specifically for this project. A custom class derived from the SerialPort class was incorporated into this API as the method of establishing a serial socket.

The API follows a procedure outlined by NDI for interacting with the SCU. The device must first be initialised using an "INIT" command. This is followed by the "PHSR" command which assigns port handles to any tools (or sensors) that do not already have one assigned. Without executing this command, the connected sensors will not provide any tracking data. The Aurora system must then be put into tracking mode with the "TSTART" command. Once tracking mode has started tracking data can be retrieved using the "TX" keyword. This returns the tracking data in ASCII form which allows for simplified parsing of the data. The server utilises this command in a loop, constantly requesting updated tracking data to be passed on to the client.

In its current state, the API provides a basic level of functionality to the TCP server. Rapid improvements can be made with further development including the addition of CRC error detection and the implementation of the "BX" tracking request mode which operates faster than the "TX" mode.

3.5 Development of TCP Client-Server

3.5.1 Overview

Both the server and client are based on a similar set of programs written by Dilmer Valecillos [41]. The TCP server program incorporates the custom API to communicate the Aurora SCU. The server retrieves the transformation data from the SCU and encapsulates the data in a message sent to the connected client. The server program is only necessary due to the wireless nature of the Quest headset. If a wired headset was used, then the Unity scene could integrate a script utilising the API which could directly handle the serial communication with the Aurora. The server runs a dedicated thread for requesting data from the Aurora system. Whenever new data is available it transmits this to the client on a separate thread, unique to the client instance.

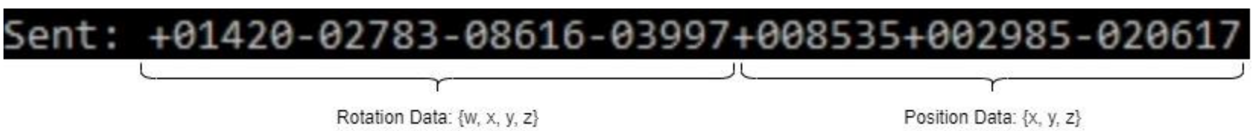

Figure 7: Transformation data segment

Since the server only acts as a relay between the client and the Aurora system, the client performs most of the data parsing and interpretation as it is the end of the line regarding data transmission. The client identifies the start point of a data segment, and extracts a substring based on the expected response length which is outlined in the Aurora system documentation. This substring is then split once more into individual float values which are subsequently assigned to their corresponding transformation variable.

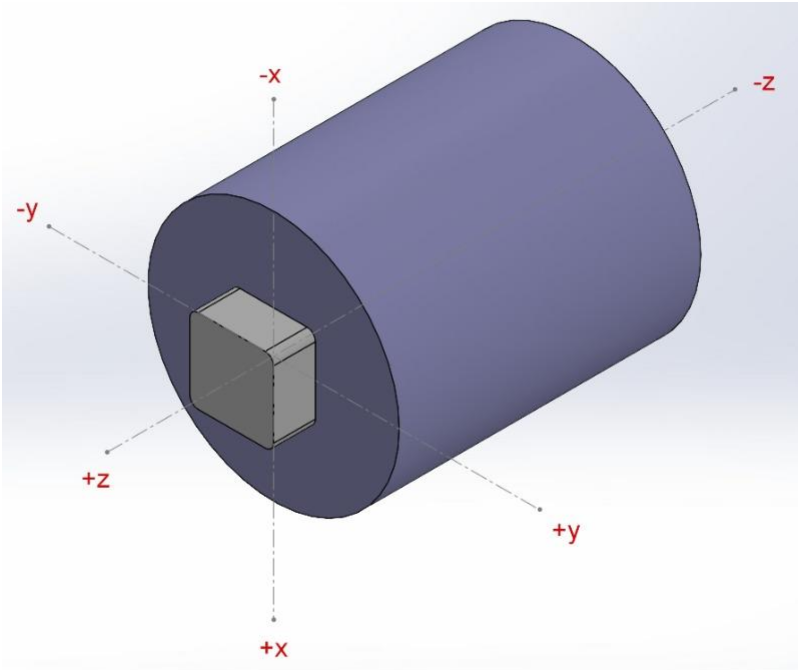

Figure 8: NDI coordinate system

Figure 8 shows the coordinate system used by the Aurora. Since this is a left-handed system, adjustments need to be made to the received values to ensure any offsets applied are being performed on the correct axis. The table below outlines the axis assignments required to ensure the positions and rotations will match the appropriate axis.

Table 1: Coordinate Axis Assignments

Variable (in Unity)	Rotation (from Aurora)	Position (from Aurora)
x	x	-y
y	y	-x
z	-z	z
w	w	N/A

These assignments assume the field generator is positions such that it is facing the user and orientated about its z-axis as shown. If this orientation is changed, the axis assignments would need to be modified accordingly.

3.5.2 Calibration Methods

Three separate calibration methods are explored as part of the work completed. The efficacy of each method was tested using the same procedure to allow a comparison between them. When the virtual table is generated, a visual reference point is placed in the centre of the table, meanwhile on the physical table a piece of paper is placed with a point measured and marked to be the real centre of the table. Once calibration has been complete, the virtual tool was placed on the virtual centre, marking the paper. The

Figure 9: Virtual view of calibration testing (left), Real view (right)

calibration was performed multiple times to test the accuracy and precision of each method. The distance from each mark to the real centre was measured and the results were recorded in Table 2. Unfortunately, this method of testing does not indicate the error in the vertical (y) direction. However, a similar method could be used with a wall-like surface to indicate error in this direction. Since the offset in the y-direction is calculated in the same way as the values for the other axes, it is assumed that this error will be of a similar magnitude.

3.5.2.1 General Calibration Process

1. User starts program and selects begin
2. User places front of a controller/tip of index finger on the front left corner of their workbench and pulls the trigger/pinches.
3. Repeat 2 for the front right, and back right corners.
4. Calibration complete.

The above process assumes that the location of the NDI field generator is calibrated within the code snippet below. User settings can easily be added to the program to allow for flexibility in the table size / NDI Aurora field generator positioning. The live calibration method still utilises the process above, however, does not rely on the positioning of the field generator on the table for calibration.

A vector for the sensor origin is determined from the table corners determined by the user. For hand and controller calibration methods it is assumed that the NDI field generator is placed in the middle of the tables back edge. The table height, depth and width are calculated based on the corner positions provided by the user.

```
Vector3 sensorOrigin = new Vector3(table.tableCorners[0].x + (tableWidth / 2), tableHeight
+ 0.1f, table.tableCorners[0].z + tableDepth - 0.07f);
```

Figure 10: Calibration code snippet relying on specific placement of field generator

Assuming the field generator is placed as above, facing the user, then the calibration is performed as shown in Figure 11 which outlines the modifications required to align the two coordinate systems.

The posData array contains the tracking data {R_w, R_x, R_y, R_z, x, y, z} and tempData is a data structure used to temporarily store the tracking data before it is utilised by other scripts within the Unity scene. The only notable change in the rotation is that $Unity_z$ = -NDI_z. This is due to the NDI system using a left-handed coordinate system, while Unity uses a right-handed system. The adjustments made in the positional data values are outlined in Table 1 where the x and y axes are swapped and inverted, then offset by the related value from the sensor origin. The NDI z axis aligns with the unity z axis, so only the offset needs to be added.

```
tempData.rotation.w = posData[0];
tempData.rotation.y = posData[1];
tempData.rotation.x = posData[2];
tempData.rotation.z = -posData[3];
tempData.position.y = -posData[4] + sensorOrigin.y;
tempData.position.x = -posData[5] + sensorOrigin.x;
tempData.position.z = sensorOrigin.z + posData[6];
```

Figure 11: Calibration data assignment

3.5.2.2 Hand Tracking Method

The hand tracking calibration method requires the user to place their index finger on the corner of their worktable and create a pinching gesture with their index finger and thumb. The program detects this gesture and captures the location of the tip of the index finger. This process is performed for two more corners. These points are used as the base for generating a mesh for a basic cube to represent the table as well as providing the required values to determine the position of the Aurora Field Generator, which must be placed in a known, measured position on the table. When the virtual table is created, the location of the field generator is calculated and used to align the virtual sensor location with the actual sensor location. This method is inflexible as it requires specific knowledge about the real-world location of the field generator.

3.5.2.3 Controller Method

The controller method follows the same process as the hand tracking method using the Oculus Quest touch controllers instead of using hand tracking technology. This method still requires specific placement of the field generator.

3.5.2.4 Live Calibration Method

The live calibration method differs from the previously mentioned methods. The offset transformation is determined by fixing a sensor to one of the touch controllers and comparing the sensor tracking data with the transform values of the controller. This allows for constant updating of the offset value, however; the table location is still required and as such the controller method is still used for locating the corners of the table. The live calibration method outlined here is more flexible in that it does not require critical placement of the field generator.

3.6 Development of Unity Scenes / Physics Engine Challenges

3.6.1 Overview

The project consists of a total of four Unity scenes each with a specific function. The scenes which display the overall functionality of the work completed are the Calibration Demonstration scene and the Practice scene. The underlying functionality of each scene is detailed below, including the most significant C# scripts used to achieve it.

3.6.2 Start Scene

This scene is used as a launching pad to access both the Practice Scene and the Calibration Demonstration scene. It consists of two buttons which when selected take the user to the chosen scene. This is performed using generic UI scripts provided by Oculus to set up the controllers, in combination with a custom script (LoadScene.cs) which loads a designated scene based on the build index provided.

3.6.3 Table Calibration Scene

The table calibration scene is used to receive input from the user about the location of the worktable. This scene facilitates all the calibration methods mentioned in section 3.5.2. Two scripts are used to programmatically position two objects to be located at the tip of each index finger when hand tracking is

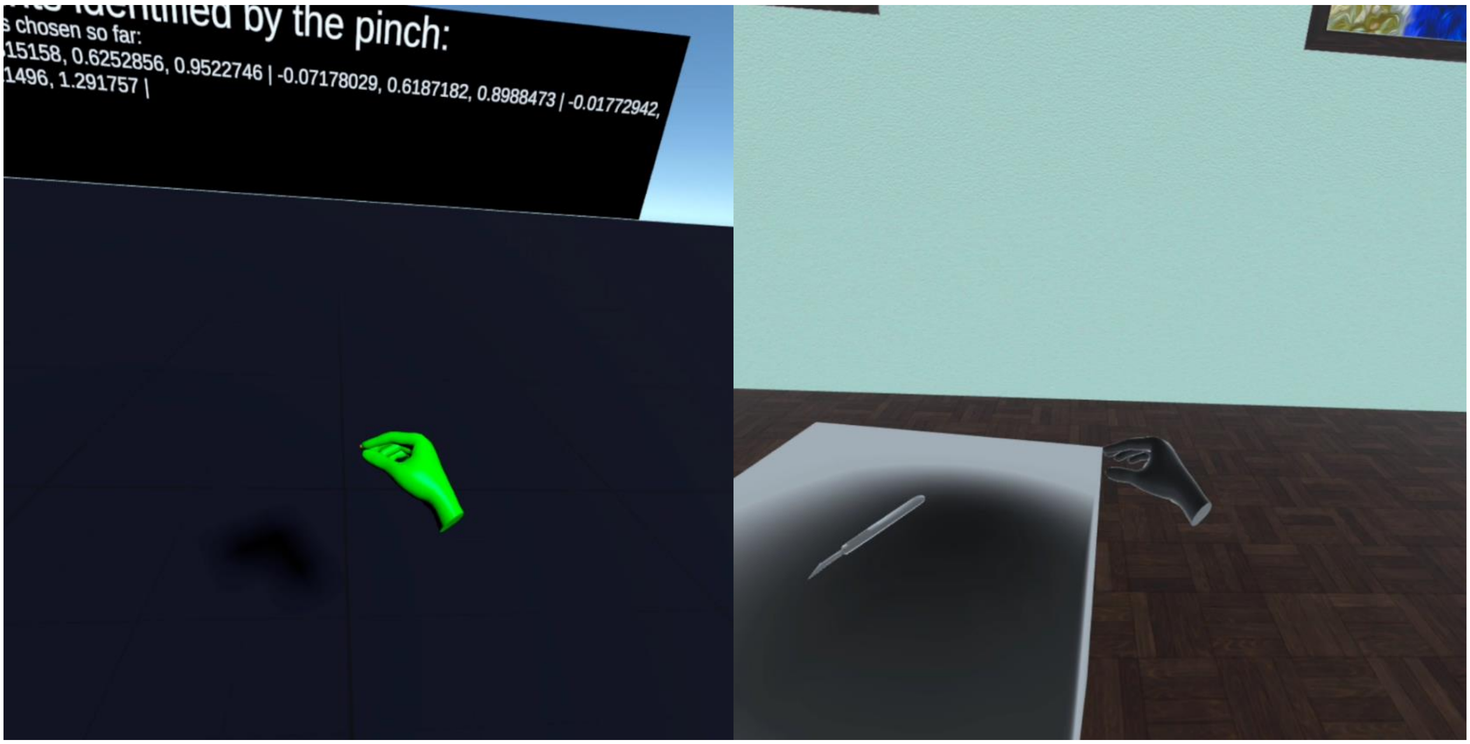

Figure 12: Calibration using hand tracking, performing third pinch

in use. This allows the user to see the exact point in virtual space which will be captured when a pinch gesture is performed. The TestPinch.cs script handles identifying which type of controller is active (either touch controllers or hand tracking) and modifies the method for logging a point accordingly. Once three points have been recorded, the next scene is immediately loaded.

3.6.4 Calibration Demonstration Scene

The calibration demonstration scene contains the scripts which allow the HMD to wirelessly connect to the TCP server and receive tracking data from the NDI system. While testing locally, a PowerShell script was required to allow the HMD to remotely connect to the TCP server. The script performs port forwarding [42] for the HMD, allowing the connection to take place on the specified port on the local computer. This step is critical in the operation of the project in its current state.

```
<#Connect headset to network#>
adb shell ip route
adb tcpip 5555
adb connect 10.0.0.16:5555
adb -s 10.0.0.16 reverse tcp:13000 tcp:13000
<#Start server#>
Start-Process -Wait -FilePath "TCPServer.exe" -WorkingDirectory
"C:\Users\Josh\Documents\Thesis\TCPServer\TCPServer\bin\Debug\net5.0"
adb kill-server
```

Figure 13: Port forwarding PowerShell script

The script requires modification if the HMD is connected to a new network or the TCPServer.exe file is ever located in a different folder. However, when not run locally the script will not be required as the TCP connection will be possible without port forwarding as the host computers public IP address would be used.

The data parsing performed by the TCP client is flexible and can function with multiple tools connected, separating the data and storing it so that it is easily accessible by another script within the scene. This script (SensorMove.cs) repositions its attached object to the location and rotation defined by the tracking data of the selected tool. This functionality provides the opportunity for easy testing of more complex calibration methods using multiple sensors. In practice, if a sensor was positioned at the tip of a guidewire or steerable sheath, the script would be placed on the virtual representation of the object it is modelling, causing it to mimic the physical tools movements. Figure 12 shows the transition from the Table Calibration scene to the Calibration Demonstration scene. After the final point is assigned, the new scene loads and generates the worktable identified by the provided points. The tool with sensor attached can be seen resting on this table.

3.6.5 Practice Scene

The Practice scene is a standalone scene which allows the user to use and experiment with a basic model of a flexible and steerable catheter sheath. The steerable tip was modelled in Blender and is made up of 6 bones. This allows the object to flex and bend with the use of another script (TipController.cs). This script

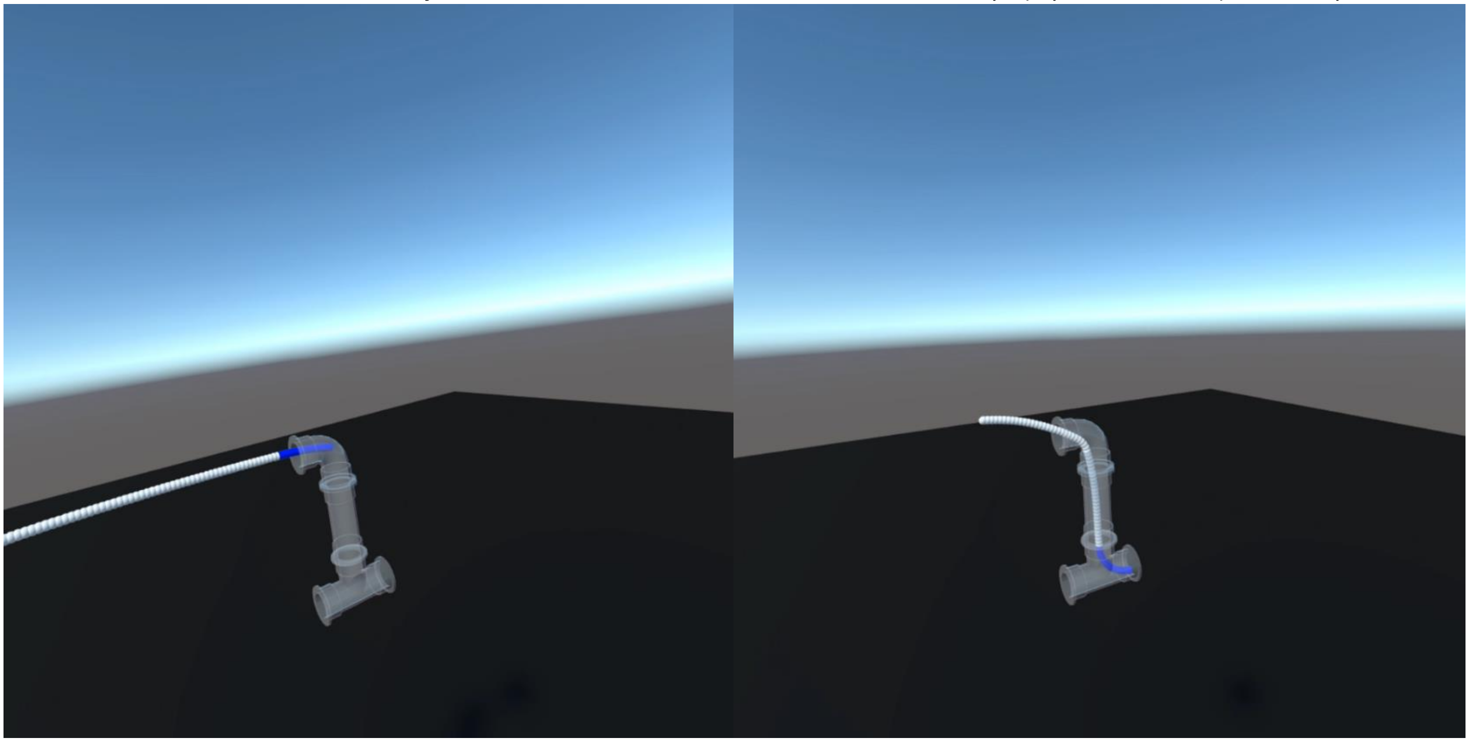

Figure 14: Steerable sheath passing through pipe network

adjusts the angle of each joint while a button is being pressed. This allows the user to control the angle of the tip and navigate the simple pipe network included in the scene. The shaft of the catheter is more complex, consisting of 57 sphere primitives, each with their own sphere collider. Each sphere is connected to the next using Unity's Configurable Joint. Each joint is configured in the same way, providing an approximate simulation of a flexible tube. However, none of the objects that constitute the steerable sheath are affected by gravity which can lead to unexpected behaviour.

4 RESULTS AND DISCUSSION

Various methods were experimented with when approaching each component of the project so far. These different methods were compared both qualitatively and quantitatively to achieve the best outcome. However, there are certainly other approaches that may be more suitable that are not discussed here.

4.1 Modes of Data Transmission

With the current implementation of the system, there are clear disadvantages that need to be addressed. A qualitative observation of the virtual tool shows that its movement lags that of the physical tool. This is due to the measurement rate of the NDI Aurora system being slower than that of the display hardware (Oculus Quest) refresh rate. The field generator used has a standard frame rate of 40 Hz, while the Oculus Quest utilises a standard 72 Hz refresh rate. This slower measurement rate paired with transmission delays encountered throughout the process cause this lag. The lag should be minimised to increase user comfortability as well as improve overall immersion in the virtual environment.

4.2 Calibration/Alignment of Virtual Space

Each calibration method that was tested was measured using the same procedure to allow a direct comparison of each method. The table below outlines four measurements, each made with the same tool by the same person. These measurements represent the linear distance between the centre of the worktable and the aligned virtual representation of the table centre as seen in the virtual space.

Table 2: Calibration error comparison

Method	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	Average (mm)
Hand Tracking	15	20	24	21	20
Controller Tracking	15	17	16	21	17.25
Live Tracking	4	8	4	8	6

The live tracking method is clearly the superior method of the ones described; however, each approach has limitations and none of the tested methods result in a desirable amount of error. The three methods all utilise either the hand tracking or the touch controllers to align the virtual table. As such, this element of each process introduces similar errors no matter which method is used. Both the hand tracking and controller tracking methods rely on critical placement of the NDI field generator. If this placement is even slightly off, then additional errors can develop which cannot be corrected programmatically.

The live tracking method mitigates this placement error and allows the field generator to be placed with more freedom by using the tracking data provided by the NDI Aurora which has a much lower RMS error.

Table 3: Aurora Sensor Technical Specifications (https://www.ndigital.com/products/aurora/)

	Aurora – Cube Volume		**Aurora – Dome Volume**	
Accuracy – 6DOF Sensor	RMS	95% CI	RMS	95% CI
Position (mm)	0.48	0.88	0.7	1.4
Orientation (degrees)	0.3	0.48	0.3	0.55

However, due to the nature of how the tracking data is obtained, the live tracking calibration method used has a critical flaw. Since the sensors provide tracking data via their interaction with the electromagnetic field generated by the field generator, other electrical devices can cause interference between the sensor and the field generator. As a result, rather than observing relatively constant tracking data, the values are observed to fluctuate around the expected value. This adds considerable error however, this can be minimised by allowing the user to select when to update the calibration with a button press.

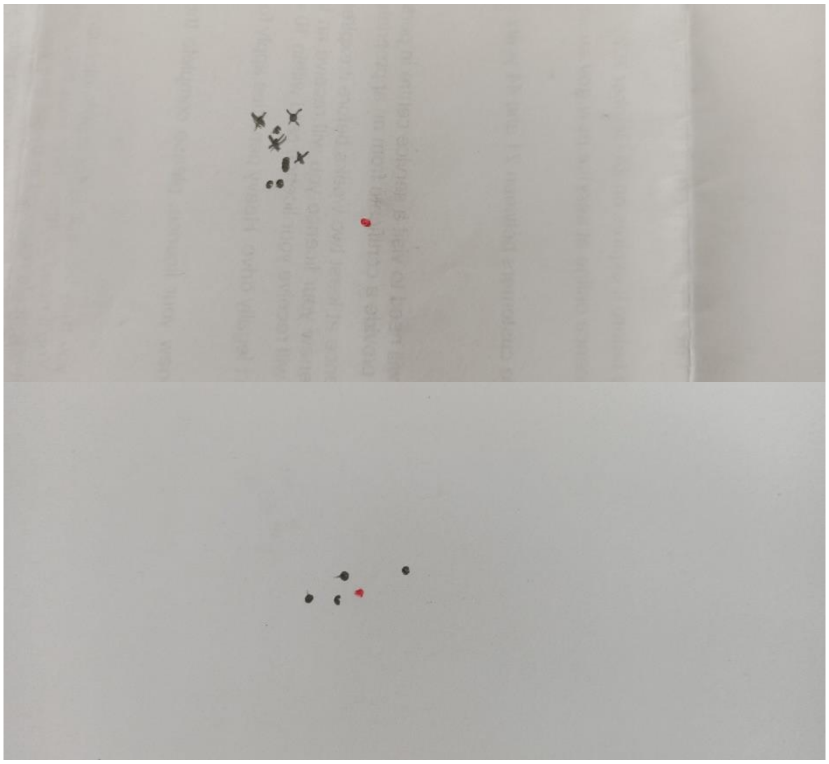

Figure 15: Hand tracking method & controller method (TOP), Live tracking method (BOTTOM)

There is also a matter of the placement of the sensor on the controller used for the live tracking method. Using visual tools within the Unity game engine the location of the controller's anchor point can be determined. However, this is only a visual inspection and not an accurately measured position which also adds inaccuracy to the results. Despite these additional sources of error, they are considerably smaller than the error introduced by incorrect placement of the field generator in the alternative methods already discussed resulting in a better performance overall.

4.3 Modelling Steerable Sheath

The modelling of the steerable sheath was an explorative procedure that involved considerable trial and error to achieve somewhat reasonable results. Two joints provided by the Unity game engine were trialled in the modelling of the sheath, the spring joint and the configurable joint.

4.3.1 Spring Joint

The spring joint provides a flexible characteristic to the connection between two rigid bodies. However, this joint only allows configuration of the linear behaviour of the spring. This is important but the angular behaviour in each axis is also relevant for this use case.

4.3.2 Configurable Joint

The configurable joint has a high degree of customisability. It has options to control the linear as well as angular motion allowed by the joint which can be manipulated to achieve many different behaviours. Unfortunately, the use of the configurable joint within Unity is not very well documented which lead to a trial-and-error approach to achieve suitable results.

The most relevant setting to achieve comparable behaviour were the Angular Limit Spring settings as well as the Angular Drive settings for each axis. The Angular Limit Spring settings dictate the behaviour of the joint when at or approaching the desired rotational limit around the designated axis. The Angular Drive for an axis configures how the joint will attempt to return to the desired position, for this use case this is a zero-rotation position. The values used in the current implementation were decided determined through extensive testing of various values and combinations to achieve a result that allowed the user to pass the simulated sheath through the basic pipe system without causing a structural failure of the model. Since the model is made up of many individual primitives, if a large force or velocity is applied the joints break apart.

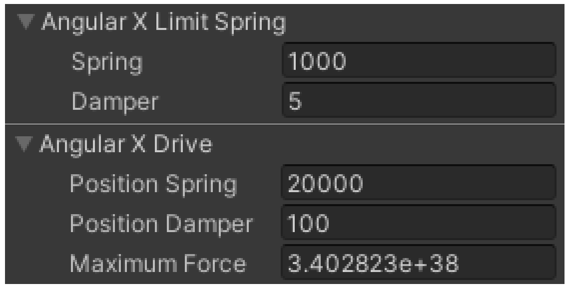

Figure 16: Configurable Joint settings

The final values used in the current implementation are shown in Figure 16, where the settings for the axes not shown use the same values. These settings let sheath flex and conform to a given shape while still holding enough rigidity to eventually return to a straight arrangement. All the rigid bodies that constitute the sheath are not affected by gravity. This does not replicate the conditions found in the physical world however, the joint behaviour changes drastically when this setting is enabled. The caveat of disabling gravity is the sheaths behaviour is floaty and does not simulate the true behaviour of the tool when in free space.

The tip of the steerable sheath functions excellently. The user can push a button to get the sheath to flex one way or the other. This lets the user steer the sheath and navigate the pipe system to a desired location. However, as the tip is created as a single body, there is no flexibility. This is a minor deviation from the expected behaviour and could be overlooked.

4.4 Future Work

There is considerable work to be done moving forward. The introduction of further physical elements to the simulation is an important and difficult step towards a high fidelity constructed simulation. Alignment is important and the tools and equipment used will need to be modified to be operable inside the virtual space. Having accurate and precise alignment is important in the effectiveness as well as the immersivity of the simulation.

With the addition of more physical aspects, the virtual models will need to become more precise and more realistic. The introduction of patient data to better simulate real anatomy will further improve the quality of the simulation and the ability for it to mirror real life as close as possible. The overall processes required to be followed are also important when constructing an educative tool such as this. Clinicians and experts must be consulted on the best practices during the procedure as well as the best ways to test and educate users of the simulation. Furthermore, the current functionality needs improving before taking further steps. The project currently has the beginnings of a strong foundation however this foundation needs to be built on and improved before further additions and features can be added.

4.4.1 Modes of Data Transmission

The NDI Aurora offers two possible methods for requesting tracking data. The "TX" command is what is currently implemented and provides the tracking data in an ASCII format. This makes the programmatical parsing of the data simpler and easier to manipulate and is why it was chosen. However, the alternative method ("BX") provides the means to request the data in a binary format. This format is much more efficient and allows for faster measurement rates when compared to an ASCII format. Utilising this method would also require a change in the parsing of the data. The binary data could be split into related segments when received by the TCP server so that only the relevant tracking data is passed on to the client improving the latency issue discussed above.

4.4.2 Calibration/Alignment of Virtual Space

A more robust alignment method still needs to be explored. One possible solution is utilising multiple NDI sensors to provide more accurate values for calculating the offset. Placement of sensors in known, measured locations on the table will allow the automatic generation of the table based on the tracking data provided and improve overall accuracy. The precision of the methods already discussed is reasonable however this will also be improved by improving the tools used for measurement. More accurate measurements will lead to more accurate results. Having sensors located on the table will also remove the interference introduced by sensors placed on controllers or other electrical devices.

4.4.3 Modelling Steerable Sheath

Further work needs to be done on the modelling of the virtual tool. The overall approach can change if there is a sensor located in the tip of the real steerable sheath. In the current implementation the base of the tool is the tracking point, however if the tip is also incorporated then the tubular midsection will have two known end points and will behave more realistically when being inserted into the pipe system or simulated anatomy. To achieve this, the Practice scene would need to be integrated with the calibration of the NDI sensors allowing them to be used this way.

5 CONCLUSIONS

Atrial Fibrillation is of growing concern and is the most common cardiac arrythmia. A simulation training method for the AF ablation procedure does not currently exist and has the potential to improve the initial success of the procedure. Extended Reality technologies have already been proven to be effective modes of interactive education however lack the easy access to the tactile response that is an integral component to performing surgery and more closely representing the worlds they try to emulate. Combining VR technology with an aligned physical environment can provide the tactile response that the virtual environment lacks, allowing the relevant psychomotor skills to be practiced, tested, and evaluated in a safe and controlled environment before live surgery is performed.

A key challenge of achieving this goal is aligning the virtual space with the physical space and tracking the movement of physical tools that need to be mobile in the virtual space. This is accomplished using the NDI Aurora electromagnetic tracking system and currently has substandard performance. Future work would see this alignment improved to better replicate the movements of the physical tool; however, the foundational functionality has been achieved in this project.

Wireless communication with the electromagnetic tracking system was attained using a TCP client server relationship. This process would be unnecessary with the use of a wired HMD; however, a cost-effective solution is preferable and currently most wired VR solutions come with additional overheads due to the need for a high-performance computer. Despite the success in achieving end-to-end communication using this wireless method, the efficiency of the accomplished work should be improved in future.

The work achieved throughout this project provides a foundation for future work on the development of a high fidelity constructed VR simulation for AF ablation surgery training. After further development, the solution will require testing and evaluation by clinicians to determine its efficacy and viability as a tool for improving the psychomotor skills of novice surgeons.

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