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Building a Virtual Reality Simulator for Transcatheter Aortic Valve Implantation

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

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ORIGINALITY STATEMENT

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Abstract

Transcatheter Aortic Valve Implantation (TAVI) is a minimally invasive procedure for treating aortic stenosis, requiring precise catheter navigation to position a replacement valve. This project aims to develop a virtual reality simulator for TAVI using the Meta Quest headset, providing an immersive training environment that overlays a virtual heart onto a physical model. By integrating an NDI-tracked catheter, users can manipulate the tool in real time within the virtual heart, enhancing spatial awareness and procedural accuracy. Our findings suggest that while the simulator is effective for basic interaction, further improvements in calibration are essential for medical training applications.

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1 Introduction

Immersive technology is experiencing rapid growth worldwide, driven by ongoing research and advancements in both hardware and software. Immersive technology includes virtual, augmented, and mixed reality. The applications of this in the field of medicine, specifically cardiology, range from medical training, to patient care and surgical procedures. It provides realistic visualisation and simulations in a cost-effective, accessible format. In this report, we explore the intersection of immersive technology and transcatheter aortic valve implantation (TAVI) with the goal of developing a mixed reality simulator to enhance procedural accuracy and training for this critical, minimally invasive technique.

1.1 Overview of Immersive Technology

Immersive technologies—comprising virtual reality (VR), augmented reality (AR), and mixed reality (MR)—offer unique advantages for visualizing complex anatomical structures and practicing surgical techniques in a controlled, interactive environment. VR, AR, and MR each provide distinct interactive capabilities that make them valuable tools in medical applications.

Virtual Reality (VR) is a 3D simulated environment that a person can experience through the use of a head-mounted display (HMD), sensors, and controllers. The user is placed inside an alternate reality which they can interact with via sensors and controllers. Currently, consumers have access to VR headsets such as Meta Quest, HTC Vive, and Playstation VR.

Augmented Reality (AR) is an immersive experience where digital information is overlaid on top of normal reality. This can be in a 3D head-mounted display such as the Apple Vision Pro, or a 2D display such as a phone or tablet. An example of augmented reality is Snapchat Lenses, which allow users to place 3D filters on objects while taking a photo or video. AR enables people to enrich their physical environment with digital information.

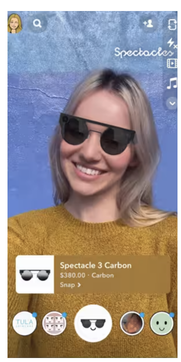

Figure 1: Snapchat AR Lens (Snapchat For Business, 2024) [1]

Mixed Reality (MR) blends both augmented and virtual reality. This allows users to be in a simulated environment while interacting with the real world at the same time. MR requires the use of a headset, such as the Microsoft HoloLens or Apple Vision Pro, to create this immersive experience.

Figure 2: Meta Quest (Meta, 2024) [2]

While initially popularized through gaming and entertainment, immersive technology is expanding rapidly in fields like medicine, retail, and education, demonstrating strong potential in improving training, diagnostic, and procedural methods. In cardiology, VR, AR, and MR are already contributing to enhanced training and simulation, with broader applications in patient care and surgical procedures expected.

1.2 Registration

A major challenge in implementing mixed or augmented reality in medical procedures is achieving accurate alignment between the virtual and physical worlds, a process known as registration. Currently, there are three primary approaches to registration: marker-based, marker-less, and surface-based methods. All three methods require a precise 3D reconstruction to be made prior to alignment.

In marker-based registration, fiducial markers are strategically placed on specific anatomical landmarks, which are then tracked by a camera or sensor. The tracking system, often supported by computer vision algorithms or optical tracking software, detects these markers and captures their spatial coordinates. This data is then transformed to map the physical coordinates onto the virtual environment, allowing the virtual model to be accurately overlaid onto its real counterpart.

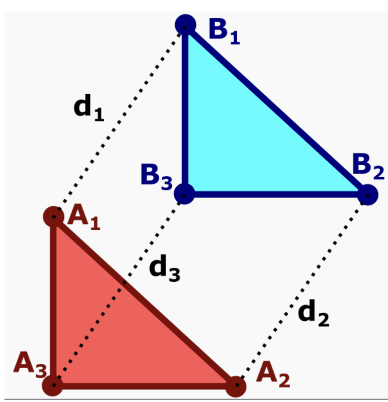

Figure 3: Marker based registration algorithm (Oncology Medical Physics, 2017) [3]

In marker-less registration, the camera or sensor detects predefined anatomical landmarks or distinctive shapes instead of physical markers. These features, chosen for their recognizability and stability, act as reference points. Once these landmarks are identified, the same process follows: transforming the detected coordinates to align the physical and virtual spaces, enabling accurate overlay. This approach eliminates the need for physical markers, making the setup less invasive while still relying on stable, fixed reference points, although it can be less accurate.

In surface-based registration, the process focuses on matching the contours or surfaces of anatomical structures rather than relying on markers or fixed landmarks. A camera or sensor captures the surface geometry of the patient's anatomy in real-time, generating a 3D point cloud or mesh of the relevant area. Algorithms such as the Iterative Closest Point (ICP) can be used to align the 3D point clouds to get the overlay. This method is useful specifically for non-rigid registration, where objects may deform or shift, but is more computationally intensive.

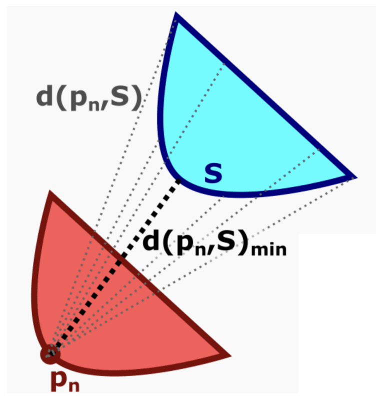

Figure 4: Surface based registration algorithm (Oncology Medical Physics, 2017) [3]

Manual registration can serve as an alternative or supplementary approach to initial registration methods, necessitating user input to modify the position, scale, and rotation of the virtual model. Although manual registration provides flexibility, especially when automated techniques cannot be used, it can be time-consuming and is less accurate, as its precision largely depends on the user's expertise [Andrews et al., 2020].

Accurate registration—aligning virtual and physical elements—is essential in mixed reality applications for surgery. Methods such as marker-based, marker-less, and surface-based registration each offer advantages and challenges in achieving the alignment precision necessary for high-stakes procedures like TAVI.

1.3 Transcatheter Aortic Valve Implantation

Transcatheter Aortic Valve Implantation (TAVI) is a procedure used to replace a damaged aortic valve without open-heart surgery. In TAVI, a replacement valve is placed inside a stent (small mesh tube) and guided into the heart using a catheter, which is inserted from the femoral artery in the groin or another part of the body.

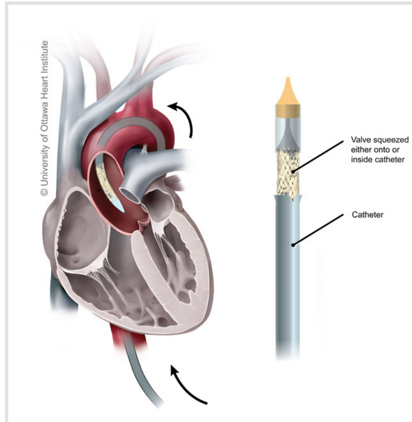

Figure 5: TAVI procedure (University of Ottawa Heart Institute, 2024) [4]

This procedure is for patients suffering from aortic stenosis, a condition where the aortic valve opening narrows over time. Aortic Stenosis is the third most frequent cardiovascular disorder for people over the age of 60 [Halapas et al., 2023], and the mortality rate goes up to 50% in 2 years after symptoms occur. The occurrence is 2-5% in patients aged over 75 [Litmanovich et al., 2014]. Due to an aging population, the prevalence of this disease is increasing.

Surgical intervention is not always possible because patients in this age range often have other comorbidities and are higher risk patients. In this case, TAVI has a similar level of effectiveness to surgery, with less risk [Thyregod et al., 2024].

Surgeons plan TAVI procedures using imaging techniques such as echocardiography, which is an ultrasound of the heart, angiography which uses a dye to visualize the blood vessels in the body, or multidetector computed tomography (MDCT), which is a computerized X-ray procedure. These imaging procedures create a static 2D image or a 3D image on a 2D screen display.

Current training methods, such as desktop simulations or reviewing case studies, do not provide the hands-on practice needed for optimal procedural success. As the prevalence of aortic stenosis grows, so does the need for advanced, immersive training solutions that provide realistic practice environments.

This project seeks to address the training limitations for TAVI by creating an immersive mixed reality simulator that enables medical professionals to visualize and practice catheter placement within a virtual heart model. By integrating electromagnetic sensor data into Unity, the project aims to create a responsive, accurate simulation that mirrors real-life procedural requirements, ultimately supporting improved accuracy and precision in TAVI training.

2 Literature Review

Immersive technology within cardiology finds diverse applications, encompassing surgical training and education, pre-operative planning, and intraoperative use.

2.1 Surgical Training and Education

In settings where clinical exposure and teacher availability are limited, VR simulations provide an alternative pathway for students to gain essential practical experience.

Early research in the use of simulation to train medical students began with desktop simulations. Romero et al. [2006] developed a web simulator for cardiac life support, which demonstrated improved student performance, while Berry et al. [2008] developed a carotid artery stenting simulator. Since the technology at this point was still at a nascent stage, early research indicated that students at a novice level had a positive learning experience. However, such simulations were not helpful for training more experienced clinicians and would instead be a supplement to regular learning. Surgeons who wish to gain experience in a new field, such as endovascular procedures, could also use simulation training at an early learning stage to improve their understanding of the domain and procedure [Aggarwal et al., 2006].

Given limited teachers and practical clinic opportunities, simulations allow students to gain similar practical experience, as well as gain more interest at a novice level. Some studies have focused on virtual reality simulators for teaching cardiac life support, as an alternative to training on a patient substitute such as a manikin. The VR simulation is a cheaper, accessible alternative that provides a similar learning experience to face-to-face training and also provides feedback to the trainee allowing them to improve their technique. Receiving this type of feedback is not possible with a manikin [Vankipuram et al., 2014].

Understanding cardiac anatomy is critical for medical students interested in cardiology. However, the complexity of the structures involved make it a challenging topic to teach. Virtual reality allows students to interact with the heart in a three-dimensional environment. Maresky et al. [2019] compared the performance of students who used a VR simulation of a heart for learning to those who used traditional learning methods. Those who went through the immersive cardiac VR experience performed higher on the quiz relative to the control group.

A study compared the proficiency of students learning how to do a mitral valve annuloplasty, which is a surgical procedure performed to repair the mitral valve in the heart, on porcine models. They compared students who learnt in a wet lab, dry lab, virtual reality lab and a control group without training. While the wet lab trainees did show the highest scores, the virtual reality simulation was also able to get students to meet the requirements of the course for all the major outcomes, while the control group was not able to do so. This demonstrates that virtual reality can be a cost-effective and more accessible solution for students to gain experience in various different procedures [Valdis et al., 2016].

Research has also shown the possibility of using VR simulation in Percutaneous Coronary Intervention (PCI), a procedure that requires removing blockages from coronary arteries with a stent. Perez-Gutierrez et al. [2020] created an immersive and non-immersive virtual reality simulation of the procedure, allowing medical students to select various instruments such as a catheter, needles, and wire-guide, and interact with a patient. The immersive experience used an Oculus headset and controllers. The simulator offers a guided tutorial and gives users feedback on how they perform each step of the procedure. Conventional training methods for students pose elevated risks and expenses, relying on live patients or cadavers, which limits the amount of time they can practice. VR simulators allow them to have a highly user-friendly experience where they can learn without any time or resource constraints. However, the learning curve for the immersive experience was higher than that of a simulation on a phone screen. This study was only conducted with ten students, so a larger sample size is required to accurately assess the usability and learning impact of the simulator.

Li et al. [2021] developed a similar simulator for PCI using personalized clinical data. This simulation aimed to create a more realistic environment for trainees compared to the previous study. The use of personalized clinical data allows students to be exposed to various training cases and understand the nuances of each cardiac patient. Trainees in this simulator manipulated real intervention instruments rather than a VR controller. The system gave real time response and feedback, with high accuracy of the tracking algorithm and haptic feedback hardware. Participants in the study reported that this simulator would be useful for novice PCI surgeons. In terms of adaptation, interface quality, fidelity and learning, participants preferred the virtual reality simulator to desktop simulators. This study is significant because it allows students to experience a diverse range of realistic cases without the time and expense required in a wet lab or hospital setting.

Cardiological procedures involving the use of various instruments such as catheters and guidewires require a high level of practice to gain precision in using the tool. Virtual reality systems can provide this training, and provide the trainee with the visual and haptic feedback they need to be able to guide the catheter to the target area while using the correct amount of force. The simulator can provide the feeling of friction and collision with the vascular system, providing a higher fidelity experience. However, this modelling of the catheter has been done inside a rigid vessel system rather than a human vascular system, which is a more complex task to achieve [Savir et al., 2023]. The combination of this catheter simulation placed within the previously outlined virtual reality environments of a complete procedure would create a very realistic training experience for aspiring surgeons, but such a simulation has not yet been built.

Previous studies suggest that extended reality simulations are highly effective for training medical students, particularly at a novice level [Aggarwal et al., 2006, Vankipuram et al., 2014]. The effectiveness of these simulations grows with their realism; when simulations replicate the clinical environment accurately, learners can more easily transfer these skills to actual practice. Incorporating real-time haptic feedback from actual medical instruments, such as a catheter, is crucial for creating realistic simulations, especially given the importance of mastering catheter guidance in TAVI procedures. While several studies have developed intricate virtual models of the heart to visualize the cardiovascular system, comprehensive simulations specifically for TAVI are lacking.

Current mixed and virtual reality simulations provide highly detailed, high-resolution visuals and an immersive experience, making them well-suited for procedural training. However, without incorporating feedback from actual medical instruments, applying these simulations to complex procedures like TAVI remains challenging. An effective TAVI simulation would need to integrate both the vascular system and catheter manipulation within a surgical setting, offering users a complete, immersive experience of the procedure.

Another limitation of previous studies, such as by Perez-Gutierrez et al. [2020] and Li et al. [2021], is the sample size and cost of hardware in the experiments. These constraints limit the generalizability of the findings and make it challenging to replicate the studies on a larger scale. Furthermore, the high cost of hardware restricts accessibility, particularly in resource-limited settings, where advanced training simulations could be most beneficial. This project focuses on creating a cost-effective TAVI simulator that maintains a high level of realism while meeting practical constraints, making it easier for future research to adopt accessible and scalable components to achieve comparable educational outcomes.

2.2 Surgical Pre-Planning

Preprocedural planning is essential for cardiological procedures such as TAVI and PCI, as it enables surgeons to visualize the heart in detail before surgery. There has been an interest in using 3D printing to model a patient's heart prior to a procedure, which has been shown to improve the outcome of complex cases [Mao et al., 2024]. However, 3D printing is time consuming and expensive. It is also difficult to interact with a fixed size 3D model. Virtual reality offers a compelling alternative by enabling surgeons to engage with an accurate, scalable heart model from multiple perspectives, adding layers of detail that are difficult to achieve with physical models. In fact, a study by Ruyra et al. [2022] found that insights gained through virtual reality simulation led to revised procedure plans in half of the cases, underscoring VR's potential to enhance surgical planning.

Further studies have demonstrated the advantages of using VR as a planning tool for various surgical procedures. VR can be used to create 3D models from computed tomography (CT) scans, enabling clinicians to make appropriate decisions, such as predicting the most suitable valve for a patient. Clinicians can assess each patient's anatomy and suitably plan a procedure. For example, VR-based recommendations for a percutaneous pulmonary valve selection procedure showed a strong correlation with final clinical outcomes [Zablah et al., 2024]. Similarly, a VR model used in a TAVI procedure accurately predicted the presence or absence of paravalvular leak (PVL) in a group of 22 patients, matching the sensitivity and accuracy of 3D printing but with reduced time and cost [Chahine et al., 2024]. While these findings are promising, these findings require validation through larger studies to confirm the effectiveness of VR models in surgical planning.

A study comparing virtual reality and 3D printing for cardiac imaging in congenital heart disease found that VR has better visualisation of certain anatomical structures and connections, more consistency and was less error prone. Additionally, post-processing for VR models takes a few minutes, compared to over eight hours for 3D printed models. A limitation of the study was that the evaluation was conducted by a single heart surgeon, making the results harder to generalise [Raimondi et al., 2021].

Another application of VR in cardiovascular planning is in percutaneous valve-in-valve transcatheter mitral replacement (ViV-TMVR). Virtual reality modelling was used for a surgical candidate where traditional imaging found that the patient was at risk of left ventricular outflow tract (LVOT) obstruction which could cause heart failure. The surgical team was able to analyse the patient's anatomy from several angles and find an appropriate placement for the valve that would not cause any complications. The patient had no issues with the procedure 18 months post-surgery [Castellanos et al., 2022].

These studies indicate that virtual reality modelling can be a cost effective and efficient solution to surgical pre-planning, as an alternative to traditional imaging methods. However, due to the limited sample sizes, there is a need for larger-scale studies to fully validate VR's potential as a superior pre-planning tool, highlighting ongoing gaps and the necessity for further research.

2.3 Open Surgery

A few studies have integrated augmented or extended reality into a live surgery setting, however, it poses significant challenges, particularly in registration accuracy and the usability of head-mounted displays (HMDs).

The Enhanced Electrophysiology Visualisation and Interaction System (ELVIS) is a mixed reality simulator that places 3D projections of anatomy into the clinical work area to enable surgeons to perform cardiac electrophysiology procedures [Southworth et al., 2020]. Since this is a minimally invasive procedure, surgeons conventionally have to rely on data from 2D display screens to map out the position of their tools relative to the patient. The ELVIS system was found to display information at the same quantitative and qualitative level as a 2D screen, with no significant performance issues due to latency, battery or frame rate. However, there might be a learning curve to adjust to having a head mounted display on during surgery, which can cause discomfort, headaches, and reduced concentration. Additionally, there could be potential errors in perceiving the depth of virtual and real objects placed in the same visual scene. This system, while promising, reflects the current challenges in achieving both high registration accuracy and user comfort in live surgical settings.

Kasprzak et al. [2020] effectively demonstrated a percutaneous mitral balloon commissurotomy (PMC) procedure using a mixed reality display to provide real time data. 3D data was streamed into a HoloLens head mounted display which could be viewed by the interventionist and team in the clinical area. This data could be manipulated through voice commands and touchless gestures, allowing the seamless integration of a mixed reality display in a surgical setting. With further research, mixed reality headsets could become commonplace in minimally invasive procedures, since they allow for real-time visualisation and interaction with patient anatomy. However, achieving accurate alignment between virtual overlays and physical anatomy remains challenging, as current systems can experience registration errors, impacting the precision required in surgical contexts.

Sadri et al. [2024] developed an AR guidance system that would display 3D anatomical models of the heart that are customised for each patient. This system also uses a head mounted display (HoloLens) which allows users to interact with virtual models using gestures and voice commands. AR guidance allowed for the safe placement of cerebral embolic protection (CEP) devices during TAVI procedures. Performing this procedure on real patients demonstrated that an augmented reality headset does not undermine the safety of a clinical procedure while simultaneously increasing operator confidence.

A substitute for using a head mounted display is to overlay digital data on a patient using a movable screen that receives data in real time [Marien et al., 2015]. A percutaneous navigation system allowed surgeons to view the internal anatomy of a patient using a moving tablet display that had position tracking sensors. This provided an additional layer of information to the practitioner, allowing them to make intra-operative decisions more effectively without having to rely on multiple scans displayed on various screens. At the current stage, this technology has a high degree of error, due to organ shift and deformations in live patients or cadavers. Consequently, an organ tracking system is also required for the use of this system to be feasible in surgery.

Augmented reality offers an alternative approach for guiding and deploying stents in TAVI procedures. Presently, this task relies on fluoroscopic images, which are limited to two dimensions and exhibit lower fidelity. Moreover, the use of fluoroscopy exposes both patients and healthcare personnel to ionising radiation. The TAVI catheter can be tracked using a magnetic sensor, and its location can be overlaid onto real time ultrasound images on a monitor. This data can also be viewed alongside virtual models of the vascular structures to facilitate the procedure. The AR system achieves a similar result to using fluoroscopy [Currie et al., 2016].

A team investigated the use of 3D virtual image guided assistance for valve in valve procedures such as transcatheter heart valve (THV) implantations. They were able to demonstrate the implantation in two real procedures, using the virtual imaging process. In this study, they obtained 3D images of the aortic root from the CTA using custom software, and used a combination of feature based rigid registration and manual user input to align the virtual reconstruction with the 2D fluoroscopic images. The mean superimposition error was 1.1mm in this procedure [Soulami et al., 2016].

These examples underscore the critical issues of registration accuracy and user comfort in current mixed reality systems, which must be resolved before XR can be a feasible solution for live surgery. This project aims to develop a simplified, user-friendly calibration process as a proof of concept, demonstrating that a practical solution can be implemented in real-world settings without extensive computational resources. However, unlike the precision required for live applications, this approach does not address the complexities of non-rigid registration or organ deformation seen in actual patients. Instead, it is more suited as a training tool for use with fixed educational models.

2.4 Registration Methods

Numerous studies have examined the accuracy of various registration methods employed to align virtual and physical models in surgical settings. Some of these studies employ a combination of techniques to enhance precision.

Schneider et al. [2020] compared manual and surface-based registration for laparoscopic liver surgery. In the manual registration process, a mouse or touch screen monitor was used to modify the position of the 3D model to an accurate position. In the surface-based method, a stereoscopic surface reconstruction algorithm was used to generate a point cloud, and the iterative closest point algorithm was used to match the 3D model with the patient liver. Their study found mean registration accuracies of 10.9 mm for manual registration and 13.1 mm for surface-based registration; however, the study's small cohort size limited the statistical significance of these results. Given this degree of accuracy, the method was suggested as a supportive tool for surgeons rather than a precise instrument. However, feedback indicated that surgeons found the augmented reality approach to be more user-friendly, suggesting that with improved accuracy, it could become a highly valuable technique.

An AR reconstruction of neurosurgery using a HoloLens head mounted display (HMD) tested three different manual registration methods, with a target registration error between 3-10mm. In the first method the user uses raycasting to place the model onto the right position, with an accuracy of 5.5mm. In the second method, they select three points to calibrate the alignment between the virtual and physical worlds, with an an accuracy of 10 mm. In the final method, the user adjusts the model's position using a keyboard, with an accuracy of 3.8mm. Similar to the previous study, these methods are more suited for use as supportive tools rather than meeting the exacting standards required for medical aids [Nguyen et al., 2020].

Current research on fiducial marker-based registration demonstrates varying accuracies across different studies, particularly in surgical applications. One study focused on cranial surgery, developing a calibration method for a HoloLens, which achieved an average root-mean-square error (RMSE) of 1.30mm when aligning a 3D-printed skull model with real-world landmarks [Sun et al., 2020]. Another study investigated the use of HMD-AR for guiding pedicle screw placement in spinal surgery, reporting a maximum average deviation of 2.5 mm during registration without real-time fluoroscopic guidance [Gibby et al., 2019]. Additionally, a study examining cardiac surgery indicated a target registration error (TRE) of 1.1 mm, utilizing initial registration alongside the simultaneous localization and mapping (SLAM) capabilities of the HoloLens 2 for continuous alignment on a porcine heart model [Doughty and Ghugre, 2022]. Lastly, research focused on percutaneous tumor ablation procedures utilized a combination of optical image targets and electromagnetic sensors localized with the HoloLens, achieving a mean RMS distance of 1.2 mm between fiducial markers, indicating the potential benefits of enhanced depth perception and spatial awareness in image-guided therapies. Collectively, these studies underscore the ongoing advancements and varying accuracies in marker-based registration techniques across different surgical contexts [Gadodia et al., 2022].

Research on surface based registration shows slightly more accurate results, with one study demonstrating a target registration error of 1.28mm for calibrating a virtual model onto kidney tissue during a laprascopic nephrectomy [Su et al., 2009a]. The usage of coherent point drift algorithm after iterative closest point algorithm enabled the error rate to decrease, and was more suitable for non-rigid registration since the real organs are soft and deformable. A similar study overlaying a 3D virtual model onto live video footage of a kidney found an accuracy of 1mm. This was achieved through an image based surface tracking software to detect the shape of the kidney tissue and the iterative closest point algorithm to complete the calibration. This demonstrates that without using an external navigation system or markers, using surface based registration is a promising technique [Su et al., 2009b].

Comparing these registration methods reveals that surface-based and marker-based techniques generally offer higher accuracy than manual registration. However, surface-based algorithms are computationally demanding, often requiring considerable processing time and, in some cases, additional training such as building a neural network to identify specific surfaces. The effectiveness of each method also depends on the complexity of the object being mapped, as simpler, fixed shapes are easier to calibrate accurately. In contrast, while fiducial marker-based methods can achieve high accuracy, they require extensive setup and precise marker placement, limiting their practicality for interactive VR applications and necessitating prior knowledge of the calibration target. The calibration techniques in this project are designed to accommodate the fixed nature of the heart model, as well as the computational constraints and latency limitations of virtual reality headsets, to deliver a responsive and effective solution.

2.5 Limitations of Immersive Technology

While VR shows significant promise in advancing cardiology, it also presents several challenges.

The use of a head mounted display in VR can cause physical discomfort after prolonged use. Li et al. [2021] found that extended VR use could lead to discomfort in users' eyes and heads, with common symptoms including motion sickness, eye strain, and neck pain.

Another challenge lies in the latency experienced in wireless headsets, which can impact user experience. Since medical procedures are time-sensitive, leaving minimal margin for errors, it is important for VR simulators to be built with low latency. Furthermore, wireless headsets have shorter usage times compared to wired ones, due to limited battery life.

While studies indicate that VR simulators are highly effective for novice learners, experienced interventionists may not derive the same level of benefit. Novices, who often lack practical experience, may benefit greatly from the immersive and interactive nature of VR simulations, which provide a safe environment for learning and practice [Romero et al., 2006]. The degree of realism in VR simulations is a crucial factor in determining their utility for experts. For experienced practitioners, the fidelity of VR simulations must closely resemble real-world scenarios and procedures to be considered useful for skill refinement and proficiency maintenance.

Unlike traditional training methods that allow learners to physically manipulate instruments and feel tactile sensations, VR controllers often lack the capability to replicate these sensory experiences. As a result, trainees may find it challenging to develop a sense of touch and spatial awareness crucial for performing surgical manoeuvres accurately [Perez-Gutierrez et al., 2020]. Although VR systems with haptic feedback exist, they are often costly and less accessible than regular controllers, limiting their use in broader training contexts.

Furthermore, the lack of standardized protocols across VR studies presents a challenge. There are variations in experimental design, data collection methods, and analytical approaches. Most studies are performed on a small sample size and rely on differing, and frequently subjective, approaches to evaluate effectiveness. As a consequence, it becomes difficult to directly compare findings and draw meaningful conclusions.

Finally, the rapid advancement of XR technology creates an ongoing need for updates and adaptations. As investment drives improvements in realism and functionality, older VR systems can quickly become outdated, leading to a shorter shelf life for previous research. This fast-paced evolution underscores the need for ongoing development to ensure VR simulations remain effective and relevant in educational and clinical settings.

These limitations highlight areas where VR technology must advance to serve as a viable tool for surgical training. Minimizing user discomfort and reducing latency are essential, as these aspects greatly influence the effectiveness of immersive simulations in fast-paced medical settings. This emphasises the need for efficient, low-latency solutions and calls for computationally optimized VR designs that ensure real-time responsiveness while maintaining accuracy. Additionally, achieving reliable calibration that balances alignment precision with ease of use remains an open challenge in the field. Research that explores these aspects will contribute to developing VR systems that are not only technically advanced but also practical for real-world medical training applications.

3 Methodology

The primary objective of this project was to develop a virtual twin of a catheter and heart model within Unity. Using a VR headset (Meta Quest), users would experience the virtual model overlaid onto the physical one, enabling real-time visualization of the catheter's movement through the virtual heart.

This was accomplished using the NDI Aurora electromagnetic tracking system, which provides real-time tracking of micro sensors placed within a catheter (Figure 6). Live data from the NDI sensor was transmitted to an XR project in Unity, where a virtual replica of a 3D-printed left ventricle model was positioned in the scene. The catheter's movement was synchronized with the sensor's tracking, enabling coordinated movement within the virtual environment.

Figure 6: NDI Aurora Components (Northern Digital Inc, 2024) [5]

3.1 Physical System Setup

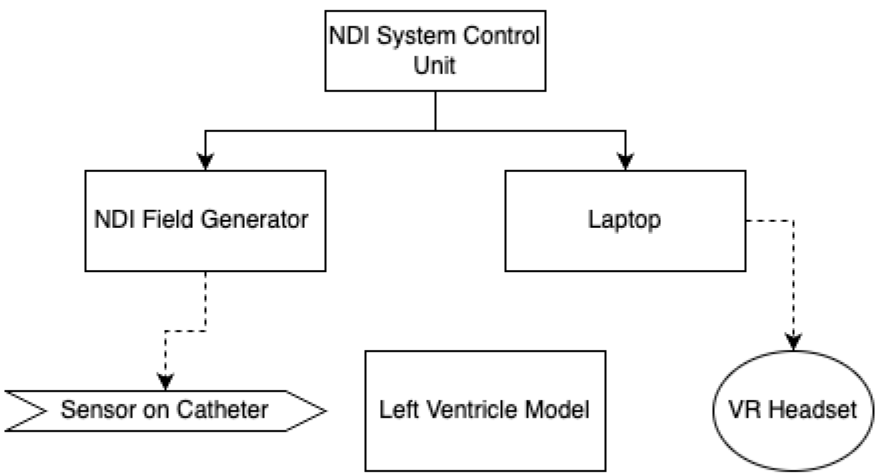

Figure 7: Setup of the system

The system consists of the NDI System Control Unit, field generator, catheter sensor, laptop, left ventricle model, and VR headset (Figure 7). The NDI System Control Unit serves as the central hub, coordinating data from the NDI Field Generator and the sensor on the catheter. The NDI Field Generator generates an electromagnetic field that enables precise tracking of the sensor's position on the catheter, allowing for accurate real-time monitoring.

The sensor on the catheter provides positional data that is relayed to the laptop, which processes and visualizes the data within the Unity environment. The left ventricle model represents the heart structure used for reference in the simulation. The VR headset, connected to the laptop, allows the user to experience the virtual environment, where the catheter's movement can be viewed in real-time as it interacts with the virtual heart model. This setup creates a seamless integration of hardware and software, enabling an immersive and interactive simulation experience for training purposes.

3.2 System Architecture

This section describes the system architecture, detailing how data flows from the physical NDI sensor to the virtual environment in Unity.

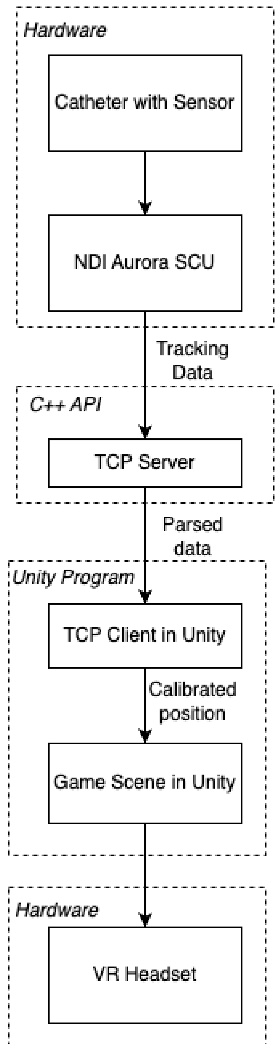

Figure 8: System architecture

The NDI Aurora SCU tracks the sensor's position and transmits this data to the TCP server, where it is formatted and sent via the TCP protocol to ensure reliable, real-time data transfer. Within Unity, the TCP client processes the data and calibrates the position of the GameObjects (the heart model and catheter) according to the sensor's readings, allowing the user to visualize the real-time interaction through a VR headset.

3.3 Initial Set Up

A prerequisite for the project was understanding how to develop in Unity as well as learning C++ to use the provided NDI sensors API.

Unity offers online learning modules that cover fundamental aspects of building a scene, such as creating game objects, implementing physics, and managing collisions. These tutorials, along with support from online forums, provided the necessary groundwork for undertaking this project.

Furthermore, there was a lot of trial and error involved in setting up the NDI API and building it correctly. The API comes with sample code that sends a small amount of tracking data to a CSV file, as well as visualisation software that displays the movement of attached sensors. The package includes drivers for multiple operating systems, along with installation and usage instructions. Despite these resources, the documentation is outdated, and there is limited online support or troubleshooting information available for working with the API.

The initial Unity setup involved creating a project with an Open XR Rig to ensure compatibility with various mixed reality headsets. Pass-through mode was enabled in the project, allowing virtual objects to overlay onto the real-world environment, an essential feature for achieving the immersive mixed reality experience required by this project.

3.4 Data Transmission from NDI Sensors to Unity

The initial goal of the project was to stream real-time data from the NDI sensors to a Unity-based client.

3.4.1 Server and API

To achieve this, a C++ program with a TCP server was developed. The server used existing NDI API functions to initialise the system and retrieve tracking data for each attached sensor, as well as error handling. It streams data continuously while managing connections with the Unity environment, ensuring synchronized and efficient data transmission.

The API transmits the following data to the client:

- `q0 qx qy qz`

  representing the tool's orientation in quaternion format.

- `Tx Ty Tz`

  representing the tool's position in millimeters.

The structure of this data is outlined in the Aurora system documentation.

3.4.2 Client

In the Unity environment, a TCP client was created to handle the connection to the TCP server. Coroutines were implemented to enable multithreaded network communication. Coroutines allow for non-blocking, asynchronous data handling. This approach ensures that tracking data is received continuously without disrupting the main thread's operations.

The Unity client is responsible for parsing incoming data and validating it. Upon receiving a data string from the server, the client extracts the coordinates and adjusts the NDI's right-handed coordinate system to align with Unity's left-handed system. Table 1 displays the mapping of Aurora rotation and position coordinates to Unity's coordinate system.

Unity Coordinates	**Aurora Coordinates (Rotation)**	**Aurora Coordinates (Position)**
x	x	-y
y	y	-x
z	-z	z

Table 1: Coordinate transformation between Unity and Aurora.

After extracting the position coordinates, these values are passed to a separate script for calibration purposes.

3.5 Calibration

Calibration is essential for aligning the virtual models with the physical components to achieve accurate real-time visualization in the VR environment.

Calibration occurs in two stages: first, the sensor position is converted to Unity's coordinate system, and then the sensor is used to capture the position of the heart model, enabling correct placement of the virtual model in Unity.

3.5.1 Sensor Calibration

To calibrate the NDI sensor tip with the virtual sensor, four points are collected in both the virtual and physical environments.

A small sphere, 1 cm in diameter, was attached to the virtual representation of the VR controller, allowing the user to select four distinct points in the virtual world (Figure 9). The sphere is positioned five centimeters from the virtual controller, making it easily accessible and clearly visible to the user. Unlike fixed points, these virtual points can be adjusted to suit the environment. Fixed positioning could lead to physical obstructions, such as walls or tables, that might restrict the user's reach.

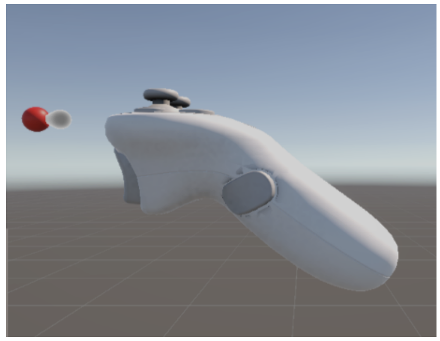

Figure 9: VR controller with sphere

Once the user moves the physical sensor tip to be aligned with the sphere and clicks the trigger button on the controller, the position of the sphere and sensor at that moment in time is recorded. This process is repeated to collect four distinct points, enabling the calibration algorithm to begin. Figure 10 illustrates the steps followed by the user in the calibration scene.

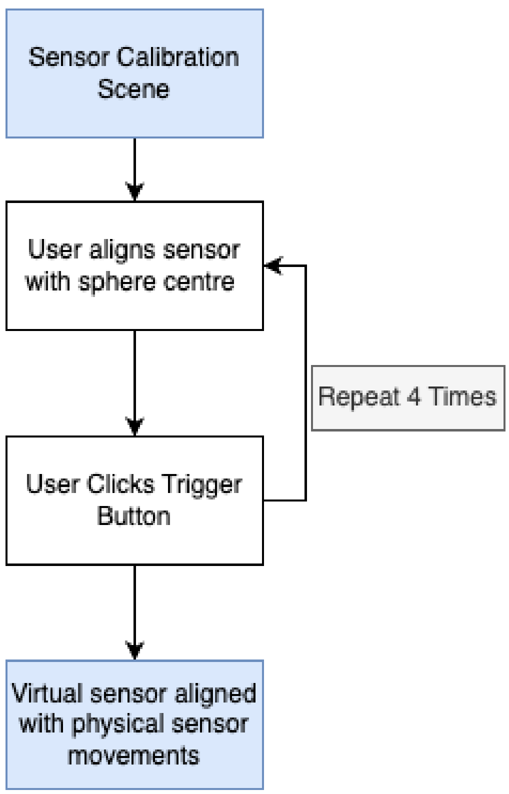

Figure 10: Sensor calibration process

The calibration algorithm used is the Kabsch algorithm, a method that aligns two sets of points in 3D space [Heidenreich, 2023]. This method is commonly used in robotics and computer vision, is well-documented, and is especially effective for aligning a limited number of points.

3.5.2 Calibration Algorithm Steps

1. **Calculate Centroids**: Calculate centroids of virtual points and physical points separately. The centroid is the mean of a set of points, calculated using the following formula

$$C = \left(\frac{x_1 + x_2 + x_3 + x_4}{4}, \frac{y_1 + y_2 + y_3 + y_4}{4}, \frac{z_1 + z_2 + z_3 + z_4}{4} \right)$$

2. **Compute Translation Vector**: Subtract the centroid of the physical points by the centroid of the virtual points to obtain a translation vector

3. **Calculate Rotation Matrix**: Use the Kabsch algorithm to compute the rotation matrix that aligns the two sets of points.

4. **Create Transformation Matrix**: Combine the translation vector and rotation matrix to form the transformation matrix.

The output of the algorithm is a transformation matrix, which translates points that the sensor sends to update the GameObject representing the catheter.

To enhance stability, the position of the virtual sensor is updated using **Vector3.Lerp**, which acts as a low-pass filter to smooth out abrupt position changes. This method gradually transitions the sensor from one location to another, reducing jerky movements and creating a more fluid experience.

3.5.3 Heart Model Registration

The next stage is to align the virtual heart model with the physical one, allowing users to visualize the catheter's movement in an accurately positioned virtual heart that corresponds to the real-world setup. The heart model is fixed in size and shape without any deformities, enabling rigid registration to be performed. This means we can align the model by only adjusting its position and orientation, without altering its dimensions.

Two alignment methods were considered. The first method involved manually placing the virtual model on top of the physical one by grabbing and manipulating it using a controller. The second method used a calibration process similar to that of the sensor alignment.

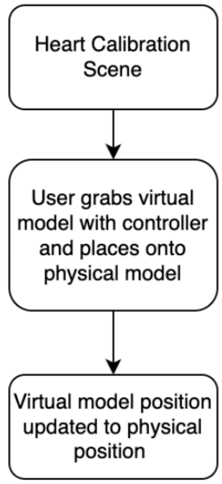

Figure 11: Manual registration

The manual registration technique is described in Figure 11.

A limitation of this method is that an initial accurate guess is needed for the position of the model, so that it is placed in the field of view of the person wearing the headset. Additionally, the model's rotation has to be preset and cannot be adjusted during the registration process. Depth perception in the VR environment also poses a challenge, as it can be difficult for users to judge the exact alignment of virtual and physical objects, potentially leading to errors in positioning.

In the point-based registration method, four fixed points were recorded by placing the NDI sensor on specific points of the heart model and pressing a button on the controller once the sensor was in position. Then, using the Kabsch algorithm, the translation and rotation between these sets of points is calculated, and the position of the virtual model is altered so that it is overlayed onto the physical model. This technique accounts for differences in the rotation of the virtual and physical model.

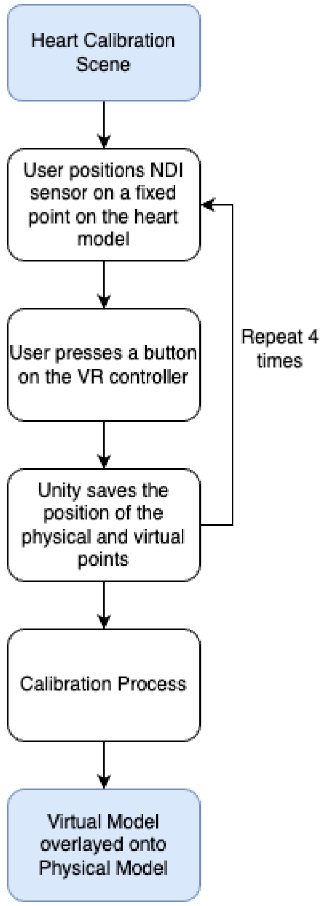

Figure 12: Point-based registration

Both methods require the virtual model to be scaled accurately prior to registration.

3.6 Game Scene

After calibration, the game scene serves as the main interaction environment where users can view the virtual heart model and catheter.

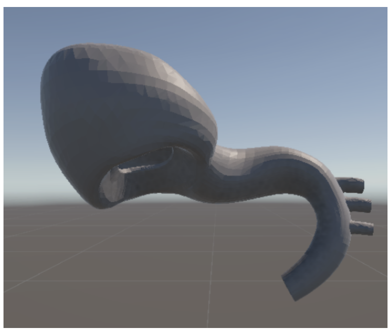

Figure 13: Left ventricle

In this scene, the position of the catheter GameObject is continuously updated in real time. The TCP client receives sensor coordinates from the physical catheter, which are then transformed using the calibration matrix to align with Unity's coordinate system. This ensures that the virtual catheter movement accurately mirrors the physical sensor's motion.

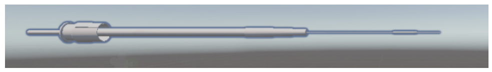

Figure 14: Catheter

Similarly, the virtual heart model's position is set based on the stored calibration data, ensuring proper alignment with the physical setup. For testing purposes, an open source model of the left ventricle and catheter is used [Jadhav, 2019, Sudar, 2023] .

Users can navigate the virtual catheter through the heart model, simulating procedural steps and offering hands-on practice in guiding the catheter within an anatomically accurate structure.

For ease of navigation, a simple UI menu was created using a basic template, with a SceneManager script to facilitate switching between scenes.

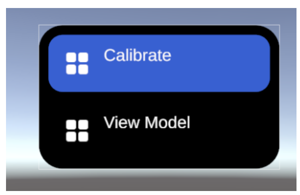

Figure 15: Menu

4 Results

The metrics for evaluating this project included the accuracy of the calibration between the physical and virtual, as well as the qualitative analysis of the user experience and interactivity of the scene.

Calibration accuracy was assessed by measuring the positional discrepancy between known points on the physical and virtual models after completing the calibration process.

4.1 Sensor Calibration

The distance between a fixed virtual point and a corresponding physical point was recorded across five trials conducted by the same individual. Table 2 presents the error in millimeters for each trial, along with the calculated average error.

In comparison to several studies in the literature that achieved registration accuracy of less than 2 mm, our system demonstrated an average accuracy of 6.8mm. While this level of accuracy is adequate for basic interaction within the simulation, it falls short of the precision required for medical applications.

This discrepancy may be due to the calibration process, which relies heavily on user input and experience. Factors like hand tremors and individual precision likely contributed to variability, as less

Point	Error (mm)
1	7
2	5
3	9
4	8
5	5
Average	6.8

Table 2: Error measurements for each point and their average.

experienced users encountered greater fluctuations in accuracy, with some measurements reaching an error of nearly 30 mm. With practice, users were able to reduce the error rate.

Another factor affecting accuracy is the inherent error in the Aurora NDI system, which can be as much as 2.0 mm.

Another issue observed during calibration was a slight lag between the sensor's physical movement and its virtual representation, with delays of up to 5-10 ms causing the virtual model to momentarily fall behind before synchronizing with the physical sensor's position.

4.2 Heart Model Registration

The accuracy of the heart model calibration was assessed by measuring the distance between three known points on the physical and virtual heart models. Two calibration methods were tested: manual alignment and point-based alignment. Table 3 summarizes the average error for each method.

Method	Average Error (mm)
Manual	20.20
Point Based	13.25

Table 3: Average error for each method.

The point-based method demonstrated a lower average error of 13.25 mm compared to 20.20 mm for manual alignment, suggesting that point-based calibration provides more precise alignment for the virtual heart model.

The accuracy of manual alignment was influenced by the user's precision and their ability to perceive depth and alignment of a 3D object while wearing a headset.

For point-based calibration, accuracy relied significantly on the initial precision of the sensor calibration; any inaccuracy in the sensor setup compounded the overall error in the heart model alignment.

4.3 User Experience

Although a large-scale user study was not conducted, personal testing revealed that the scene was generally responsive and immersive. The virtual catheter and heart model allowed for an engaging interaction within the simulation. However, the slight lag between the physical sensor movement and its virtual representation sometimes disrupted the immersive experience. This delay, though brief, created a subtle disconnect that affected the overall realism of the simulation.

This project demonstrates a promising concept simulation for the TAVI procedure in a mixed reality environment, providing an immersive training tool that could help users gain experience in a realistic virtual setting. This simulation illustrates the potential for mixed reality to enhance medical training, enabling interactive practice of procedural steps.

The current calibration accuracy, though adequate for basic interaction, constrains the simulation's effectiveness for medical applications, which require a much higher level of precision. Further refinement is essential to improve both calibration and alignment accuracy, enhancing the system's reliability and making it more suitable for medical training applications.

5 Discussion

This project aimed to create a mixed reality simulation of the TAVI procedure to provide users with an immersive and interactive training environment. As a proof of concept, this simulation illustrates the potential of mixed reality in TAVI training, though it is not yet suitable for precise medical training applications due to calibration limitations and reliance on user input. These factors underscore the need for further refinement before it can be implemented in formal training environments.

The average calibration error of 6.8mm for the sensor and between 13.25-20.20mm for the heart model, while suitable for basic interactions, highlights a need for higher precision for medical applications. This aligns with other studies using VR headsets with manual input, though studies employing surface-based registration methods achieved a target registration error of under 2 mm.

A key consideration is the inherent error in the Aurora NDI system, which ranges from 1.4–2 mm [Northern Digital Inc, 2024], setting a limit on the achievable precision for our system.

Additionally, there is a strong reliance on user input, making the final calibration accuracy dependent on the user's experience and precision. Observations showed that less experienced users produced higher calibration errors, suggesting that additional training could help improve accuracy.

The dependence on manual input also means that any hand tremors while holding the sensor or controller can impact sensor readings. Furthermore, the proximity of electromagnetic objects, such as the controller, near the sensor introduced additional errors, presenting a persistent challenge during registration.

To minimize calibration errors from hand tremors and electromagnetic interference, it would be helpful to average sensor readings over multiple frames rather than relying on a single data point. Precise handling of both the NDI system and the controller is essential, making careful device positioning critical to reducing errors. Consequently, placing calibration points on a stable physical surface, rather than having users hold the controller and sensor in mid-air, may help prevent hand shakiness and enhance alignment stability.

A notable issue encountered was the transmission lag between the physical catheter and its virtual counterpart. This latency stems mainly from the disparity in frame rates between the NDI system, which runs at a fixed 40Hz, and Unity, which operates at 72Hz. Additionally, the data transfer over TCP and subsequent parsing within Unity introduces further delays, slowing the system's responsiveness.

This lag, along with susceptibility to electromagnetic interference, can significantly impact user trust in the simulation, particularly for high-stakes, time-sensitive procedures like TAVI. Real-time responsiveness is crucial for such medical applications, where even minor delays or inaccuracies in positioning could hinder training effectiveness or lead to missteps in real scenarios. The perceptual disconnect caused by this lag may compromise the immersive experience, potentially limiting the system's utility in refining procedural skills.

To address these delays, several optimizations were already implemented, including interpolation with Vector3.Lerp to smooth transitions between frames, using Coroutines in Unity for multithreading, and optimizing data parsing on both the NDI server and Unity client.

Nonetheless, further improvements could reduce latency even more. For example, sending multiple frames of tool position data in a single request could reduce the frequency of network communications. Reducing Unity's frame processing load by lowering graphics quality and disabling unnecessary packages and features would free resources for handling incoming data more quickly. Additionally, creating a dedicated Unity API to handle communication with the NDI system over the COM port would streamline the data transfer process and reduce some of the latency introduced by TCP.

5.1 User Experience

To assess the user-friendliness of our calibration technique, it is essential to gather user feedback, which we did not conduct during this study. We observed that inexperienced users required additional time to adjust to the system, highlighting the importance of usability. However, further feedback from a larger pool of users is necessary to obtain meaningful results, as our current dataset is too limited. Collecting qualitative feedback through surveys and interviews will provide valuable insights into the user experience and help identify specific areas for improvement.

5.2 Future Work

The current calibration accuracy restricts the suitability of this simulation for advanced procedural training where fine motor control is essential. Furthermore, latency issues could disrupt the trainee's sense of spatial awareness, potentially hindering learning in scenarios that require rapid, precise actions.

To address this and improve calibration accuracy, we could implement techniques that do not rely on user input. One of these is the detection of ArUco markers using computer vision techniques; however, the Meta Quest headset does not allow access to the camera feed through the passthrough layer, making this approach impractical. Instead, detection could be accomplished with an external camera feed or an optical tracking system.

Alternatively, we could consider a surface-based algorithm like Iterative Closest Point (ICP), where we gather point cloud data of both the virtual and physical heart models and align them with the algorithm. The issue with this is that it is very computationally intensive, and the VR headsets have limited processing power. In contrast, the Kabsch algorithm offers distinct advantages as it requires fewer data points for processing and operates more quickly. Although it may not provide the highest accuracy with noisy data, its efficiency made it a suitable choice for our application.

Using surface tracking algorithms integrated within the Unity XR API could enhance the realism of the virtual environment by enabling the system to recognize walls, tables, and other surfaces. This would allow virtual objects to interact with the physical environment in a realistic way, applying appropriate physics to enhance user experience and immersion.

For testing purposes, we used open-source models for the left ventricle and catheter. However, incorporating real scans of the actual objects would provide a more precise and authentic training experience.

Incorporating haptic feedback and real patient imaging data could significantly enhance the realism of the simulation, bridging the gap between basic interaction and immersive medical training. These advancements would help to create a realistic understanding of catheter manipulation in complex anatomy.

Adding more UI elements, such as on-screen text with instructions, would provide valuable guidance for users navigating the calibration process, making it more intuitive and user-friendly. Additionally, developing step-by-step prompts for the TAVI procedure itself would offer structured guidance, helping users move through each stage of the procedure with confidence. These enhancements would significantly improve the overall usability and accessibility of the software, supporting a smoother and more instructive user experience.

This simulation offers a virtual alternative to traditional cadaveric or animal models, potentially lowering training costs and reducing the need for physical resources. By using an XR rig compatible with any headset that supports mixed reality, this setup ensures adaptability across different devices, allowing for future flexibility as more affordable headsets become available. Currently, the Meta Quest headset provides an effective, high-quality mixed reality experience; however, its relatively high cost may limit accessibility. With the XR rig's adaptable design, the simulation can be implemented on a range of mixed reality devices, supporting scalability and the adoption of lower-cost hardware solutions in the future. If improvements to the user experience and calibration are made, the simulation would make procedural training more accessible, particularly in educational settings or regions where resource constraints are a factor.

6 Conclusion

The increasing prevalence of heart diseases, especially aortic stenosis, poses a significant public health concern, driving the need for effective, minimally invasive treatments like Transcatheter Aortic Valve Implantation (TAVI). TAVI offers an effective solution that improves the quality of life for patients who cannot undergo traditional open-heart surgery. However, as a relatively new procedure, TAVI demands specialized training to ensure accurate stent placement, a critical aspect that is currently hindered by limitations in 2D imaging tools. Integrating extended reality (XR) for 3D visualization has the potential to address this issue, providing medical practitioners with a 360-degree view that enhances depth perception and spatial orientation—key factors for precise and confident stent placement.

To explore this potential, we developed a simulation of a heart model and catheter using Unity, designed for immersive viewing on a Meta Quest headset. Our setup overlays a virtual heart model on top of a physical heart structure, allowing users to navigate the simulated environment in real time. The system mirrors physical movements in the virtual space using VR controllers and an NDI Aurora electromagnetic tracking system that tracks a sensor attached to the catheter. This approach provides users with a tactile and interactive experience, enabling them to gain hands-on practice in navigating the catheter within a realistic anatomical model.

A major challenge of this project involved aligning the virtual and physical worlds accurately, a crucial step for realistic simulation. We employed calibration techniques, including point-based and manual methods, to achieve this alignment. The resulting accuracy was satisfactory for basic interaction, though further refinement is needed to meet the high precision required for medical training. Future work could focus on enhancing calibration accuracy to improve spatial alignment further, optimizing the XR environment to better emulate real-world anatomy, and incorporating more user feedback and UI elements to guide users through each step of the TAVI procedure. These advancements could significantly enhance the immersive and educational value of the simulation, paving the way for a robust training tool that closely replicates the demands of real-life interventions.

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