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Augmented Reality for Complex Surgical Procedures

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## Abstract

In 2014, 7 million of CT and MRI scans were used pre and intraoperatively in the UK, flat 2D images whose potential is not fully used. Surgeons can use Volume rendering techniques to create a 3D model which they will display in a monitor; however, an isolation between Virtual and Real world can be observed. During an MSc Group Project, an Augmented Reality System was developed to integrate a Head Mounted Display together with optical cameras that track surgeon's position of the eyes and therefore allows to view the 3D model directly through these goggles. However, tracking inaccuracies, lack of registration process, real-time delays and difficulties to focus in the virtual object, made it impossible to bring to a surgery level.

The methodology used in this project has been to review specific sources from both Computer Science and healthcare, discover new techniques that can improve the overall AR System and develop a be-spoken AR System that include these techniques.

After testing the technology with a cadaver, results show that this research has improved the tracking accuracy by a 95%, allows users to accurately merge Real and Virtual world by providing Active Stereoscropy and provides marker-less patient tracking by using three anatomical points. Furthermore, it provides a larger range of tracking than previous researches thanks to Advanced Real Time optical cameras and proves the importance of Active Stereoscropy for user's depth perception.

Although improvements regarding rotation and scale are still needed; all in all, this research brings Augmented Reality from 4 to 6 Technology Readiness Level.

Keywords:

Head Mounted Display, optical tracking, medical visualisation, image-guided surgery, registration

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## List of Abbreviations

3D: Three-Dimensional

ACM: Association for Computing Machinery

AR: Augmented Reality

ART: Advanced Real Time

ATC: Advanced Real Time Controller

CGI: Computer Generated Image

CPU: Central Processing Unit

CT: Computer Tomography

CS: Coordinate System

DHCP: Dynamic Host Configuration Protocol

DLL: Dynamic Link Library

DOF: Degree Of Freedom

FOV: Field Of View

GPU: Graphics Processing Unit

HDMI: High-Definition Multimedia Interface

HMD: Head Mounted Display

IEEE: Institute of Electrical and Electronics Engineers

IGSTK: Image-Guided Surgery Toolkit

IMU: Internal Measurement Unity

IPD: Inter Pupillary Distance

MRI: Magnetic Resonance Imaging

OpenGL: Open Graphics Library

RJ45: Registered Jack 45 telecommunication network interface

SXGA: Super Extended Graphics Array

VR: Virtual Reality

VRPN: Virtual Reality Peripheral Network

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# 1 Introduction

Surgical operations involve dealing with complex anatomical structures that depend on each individual's specific anatomy. To successfully complete these interventions, surgeons and assistants will use technologies such as CT and MRI to help them understand these differences among patients. Because humans think in a spatial manner, volume rendering techniques are nowadays commonly used to create 3D models rather than using flat, 2D images such as CT, MRI scans originally are. Surgeons will use these 3D models pre and intraoperatively by displaying them in a monitor. However, a lack of accuracy and an increase of risks can be identified in this current process. In order to bring this 3D model and overlay it directly on the patient's body, a study on Augmented Reality (AR) was performed in a Cranfield University's MSc Group Project and a prototype was developed. In this project improvements have been made to increase this prototype's Technology Readiness Level and therefore approximate it to be applied inside real surgeries. In the following sections AR will be defined, and the requirements found in the literature to successfully implement it, will be described.

## 1.1 Definition of Augmented Reality

The concept of Augmented Reality means overlaying Computer Generated Images in the real world. While Virtual Reality immerses the user in a synthetic environment, AR allows the user to see the real world together with virtual objects that enhance his/her perception of what surrounds him/her. AR adds value to reality rather than replacing it (Azuma, 1997).

Three main characteristics, described in *Figure 1*, have to be accomplished for a technology to augment reality.

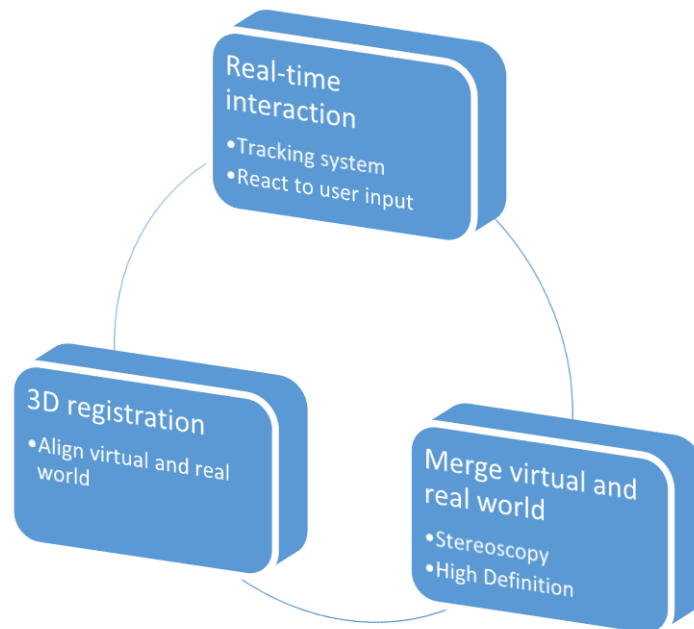


FIGURE 1- AR CHARACTERISTICS

While the aim of this project is to apply Augmented Reality to surgeries, specific papers applied to general purposes (not only surgery) have been identified. Learning from other fields where AR is already applied, we can apply those methods to develop a mature system that can be used in such a complex environment as surgeries is.

## 1.2 Classification per industries

### 1.2.1 Arts

Results show that when experiment participants were guided by an AR system, there was a better painting appreciation comparing to audio and non-guided participants (Kuo-En Chang, 2014)

### 1.2.2 Education

The use of AR used in a collaborative manner is greatly correlated with engagement and motivation by students and therefore improves academic outcomes (David Fonseca, 2013) , (Huang, 2013) and (María Blanca Ibáñez, 2014).

### 1.2.3 Manufacturing

Assistance for train maintenance tasks, maintenance instructions of an electrical transformer for operators that gave a contextual access to technical manuals. Low poly 3D models animations, video see through, it is marker based (Figure 2) (Jean-Yves Didier, 2005).

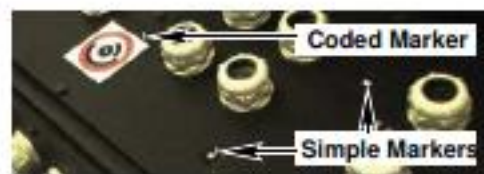


FIGURE 2 MARKER BASED REGISTRATION (JEAN-YVES DIDIER, 2005)

### 1.2.4 Gaming

Using a camera attached to an HMD together with an Internal Measurement Unit, allows the user to fire simulated bullets and look through the HMD to virtual 3D objects that interact with the gamer focusing its tracking efforts in providing an accurate 6DOF (Zhu, Branzoi, & Sizintsev, 2015).

### 1.2.5 Automotive industry

Demonstration of an AR System that tracks the position of the car using a combination between image recognition, an accelerometer and GPS signal, (Rao, Tropper, Gr, & Hammori, 2014).

In Table 1, a summary of the most important factors that constrain each of the industries is displayed.

TABLE 1 AR IN DIFFERENT INDUSTRIES

	Portability	3D models density	Registration complexity	Animations	Tracking technology	TRL
ARTS	High	Medium	Medium	Yes	Marker-less	6
Education	Medium	Low	Low	Yes	Vuforia SDK	5
Healthcare	Low	High	High	No	Marker-based	5
Manufacturing	Medium	Medium	Medium	Yes	Marker-based	5
Gaming	High	Medium	Low	Yes	Marker-less, IMU	8
Automotive industry	High	Medium	Medium	Yes	Marker-less, accelerometer, GPS	7

### 1.3 AR in the surgical field

During the group project that was followed by this individual thesis, after an extensive review of all the Augmented Reality applications that exist for surgeries, a research gap was found consisting on providing an accurate Augmented Reality consisting on a high definition Head Mounted Display that solves the ergonomic issues and optical tracking by ARTTRACKPACK5 that solves the accuracy issues. None of the previous papers delivered what was found in the Group Project.

However, this system required some critical developments that won't make it possible to bring into theatre, namely:

- Registration process: positioning, rotating and scaling the 3D model requires several inputs and the use of FlyStick buttons (a tracked device used to provide user input).
- Passive stereoscopy: this stereopsis approach won't allow the user merge naturally virtual and real world (Get into more detail in Section 4.4).
- Tracking inaccuracies bigger than 10 cm when the user changes perspective.

If these key features are solved, the Technology Readiness Level of this System will result in a big jump.

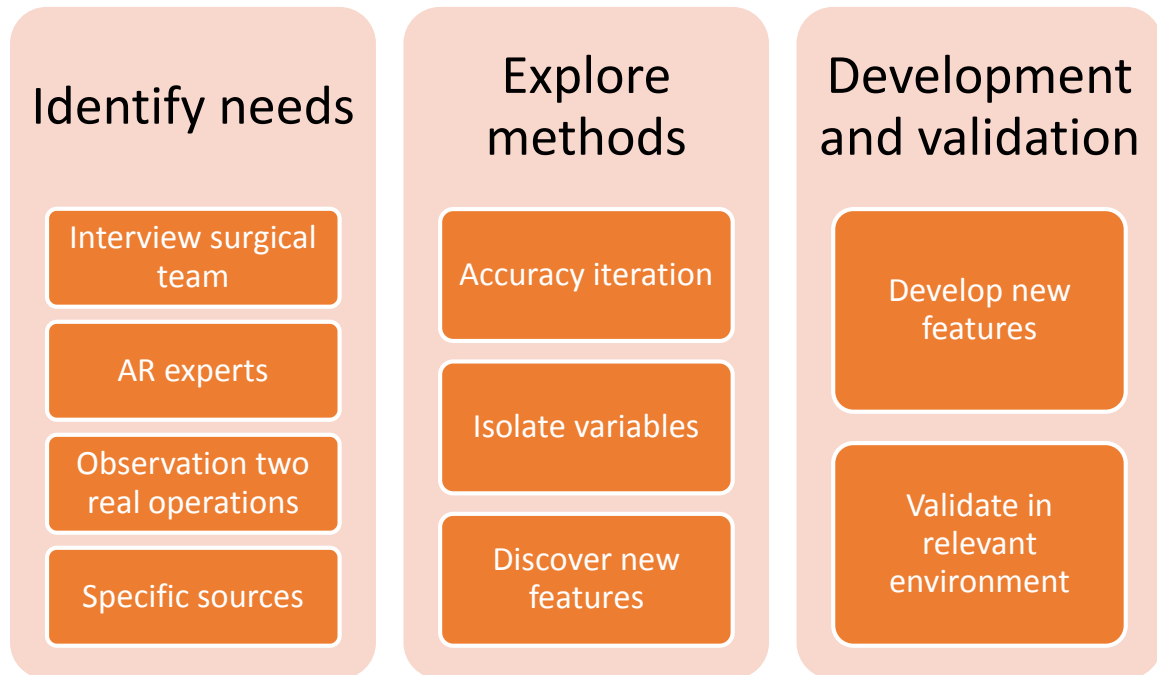
On the other hand, while finishing the Group Project, *Development of a surgical navigation system based on augmented reality using an optical see-through head-mounted display, 2015* was published resulting in a similar approach to the one adopted in the Group Project.

However, still some gaps are found when compared to this article:

- The tracking range that Polaris Vicra provides is very low and the surgeon will easily get out of the sight of view.
- There is no mention to the importance of Active stereoscopy and conclude that for the user to naturally merge virtual and real objects, the focal length is the only parameter to consider.
- The accuracy of Polaris systems is 0.25mm compared to ARTTRACKPACK5's 0.01mm
- Software used doesn't support ART nor Unity3D.

## 2 Methodology

TABLE 2 METHODOLOGY



From each stage, information gathered was used to keep researching on the next or previous stages. As an example, the surgical team and the observation of real operations resulted in coming up with new features such as the immersion effect and the pair-point registration, which in order to be developed, had to be supported by specific sources and feedback from MiddleVR.

### 2.1 Identify needs

#### 1. Interviews with pioneering surgical team in the use of 3D technology.

This research was limited since the beginning by the fact that the award-winning Maxillofacial consultant who was helping us during this project is the only surgeon in the UK that routinely uses 3D technology (Thomson Reuters, 2014).

However, he is also the industrial supervisor for this project and therefore having his expertise involved has been key for this project. His feedback throughout all the AR System iterations were crucial to get the final results.

Consultant anaesthetist, close collaboration with Maxillofacial surgeon and high interest in AR for surgeries and anaesthetic procedures.

**Questionnaires** were developed for them to give feedback on the AR System features in a formal way.

**Voice recordings** were also performed to analyse requirements.

## 2. Feedback and validation from AR industry experts

MiddleVR, one of technology suppliers was contacted on various emails to get their opinion on variables that could be affecting the AR System performance.

AR event in London attended in the final stage, contact with colleagues to gain feedback and validation on the technology used.

## 3. Observation of two real operations

Attending to two operations (nose repairing and palate tumour removal) to gather useful data and conditions that could constrain the AR System. The objective was to gain useful data from the real environment.

## 4. Computer science and healthcare specific sources

Industry reliable sources where consulted: Association for Computing Machinery and IEEE, game developing sources, Medicine journals, among others were consulted to understand Augmented Reality fundamentals and to analyse and identify which parameters can condition the AR System functionalities. Research on more than 60 relevant sources.

## 2.2 Exploration of methods

### Test Iteration

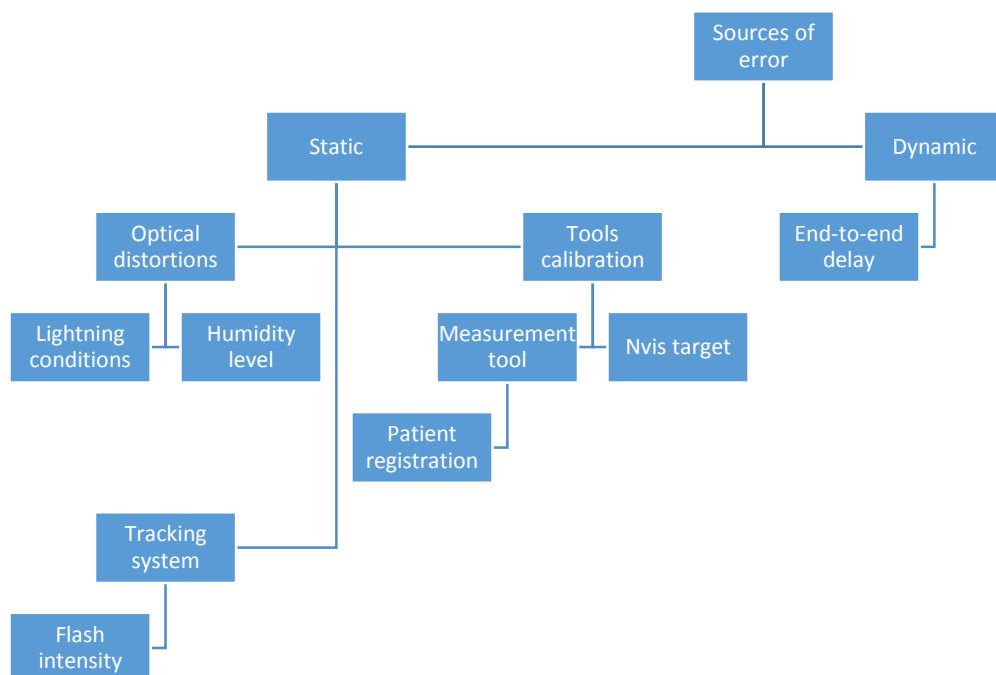


FIGURE 3 ACCURACY EVALUATION FOLLOWING "SOURCES OF ERROR" (AZUMA, 1997)

In the previous stage variables that influence the System performance were identified; these are:

- ✓ Tools calibration: Measurement tool (which influences the patient registration) and Nvis target (which ends up in a wrong tracking of user's position).
- ✓ Optical distortions: High lightning conditions, humidity level needs to be below 50%

- ✓ Time delay related with:
  - Operating system
  - DTrack2
  - MiddleVR
  - VRPN
  - Unity3D
  - Low CPU performance
  - Low GPU performance
- ✓ Isolate each variable to see how big the effect is. Eliminate all the parameters but one.
- ✓ Eventually discovered that the biggest difference in tracking performance was coming from properly calibrating user's eyes position.
- ✓ Calibration of the Measurement Tool was also influencing and with both variables influence reduced to the minimum, an improvement of 95% tracking accuracy was implemented (Appendix 9.13).

### 2.3 Development and validation

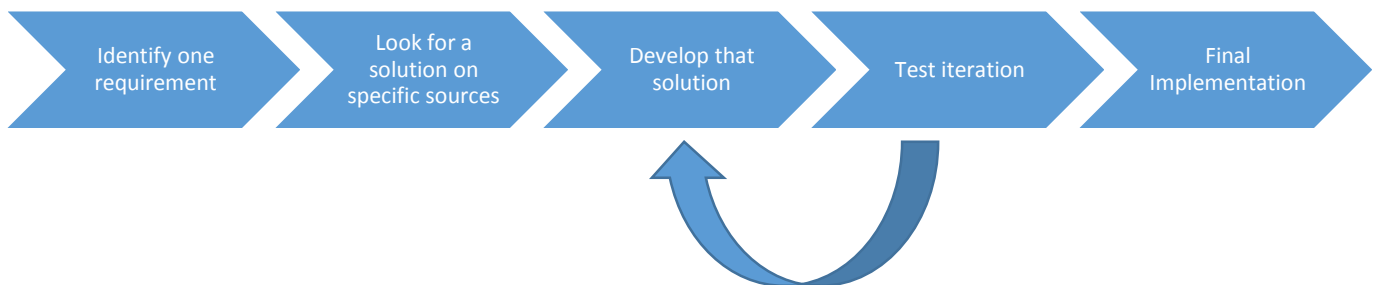
Each of the final solutions implemented in this project is backed by relevant sources, the above table represents where the data was gathered from in order to develop the final solution. Table 3 represents the variety of sources, but how reliable they are.

Regarding validation, it was clear from the very beginning that the objective of this thesis was to validate this Technology in a relevant environment, if the conditions were met.

In the beginning of the project the Technology AS-IS was tried in a simulation lab with a mannequin. Although the results were not very promising, due to problems with setting up the System, lots of useful data regarding the environment was gathered and helped to eventually develop the final solution. For a broader view on what the process was like: Figure 4.

**TABLE 3 WHERE WAS THE DATA GATHERED FROM**

	Not including marker-based registration.	Pair-point anatomical registration	Active Stereoscopy	Optical distortions	Reduce time delay	Calibration of tools
Surgery sources	X	X		X		
Computer science sources		X			X	X
AR experts			X		X	X



**FIGURE 4 METHODOLOGY, BROADER VIEW**

### 3 Comparison of technologies

#### HMD

The Head Mounted Display selected for this project is the Nvisor ST50. Which proves its reliability since it complies with Zhang’s Ideal HMD as seen in Table 4; therefore, it was selected as the Head Mounted Display to be used throughout this project.

**TABLE 4 COMPARISON OF HMDs PARAMETERS ACCORDING TO *DESIGN OF HEAD MOUNTED DISPLAYS, 2007*. ADAPTED FROM VARIOUS SOURCES.**

	FOV	Eye relief	Exit Pupil	Luminance	Image Quality	Adjustable IPD
Google Glass	14.7 degrees	15 mm	Monocular	-	640x360p	Monocular
Epson Moverio BT100	23 degrees	15 mm	-	-	960 x 540p	No
Silicon ST1080	45 degrees	yes	-	150 cd/m <sup>2</sup>	1920 x 1080	60-70 mm
Hololens	30 degrees	yes	-	-	720-1080p	Yes
nVisor st60	60 degrees	26 mm	12 mm	103 cd/m <sup>2</sup>	1280x1024p	55-73 mm
nVisor st50	50 degrees	23 mm	10 mm	79 cd/m <sup>2</sup>	1280x1024p	53-73 mm
Ideal HMD (Zhang, 2007)	100 degrees	23 mm	10-12 mm	17 cd/m <sup>2</sup>	720-1024p	50-75 mm



## Tracking

Commercial tracking technologies such as Polhemus (electromagnetic tracking) and Intersense (magnetic, accelerometer and gyroscope) were considered and the key factors are shown in Table 5. However, in order for this AR System to be applied into surgeries; accuracy is the main requirement. That is why it was decided to develop this system using optical marker-based tracking, a reliable technology, already successfully applied in Augmented Reality (Ribo, 2001), and which gives an accuracy of 0.1/0.45 mm and 6DOF.

**TABLE 5 TRACKING FEATURES PER TECHNOLOGY ADAPTED FROM A SURVEY OF TRACKING TECHNOLOGY FOR VIRTUAL ENVIRONMENTS.**

	Accuracy	DOF	Refresh rate	Range
Optical	0.1/0.45 mm	6 DOF	60 Hz	High
Ultrasound	0.5/6 mm	3 DOF	25 Hz	Mid
Gyroscope+acc.	-	1/3 DOF	50 Hz	High
Magnetic	2.5 mm	6 DOF	144 Hz	Mid

For optical tracking two manufacturers were considered

- NDI Polaris Optical Tracking Systems
- Advanced Real-time Tracking

Table 6 shows the most important variables taken into account when choosing the tracking system.

**TABLE 6 COMPARISON OF OPTICAL TRACKING MANUFACTURERS**

	NDI Polaris Spectra (2015)	4 ARTTRACKPACK5 (2015)
Accuracy	0.25 mm	0.01 mm
Mobility	High	Attached to ceiling
VRPN Integration	Yes	Yes
Refresh rate	60 Hz	60 Hz
Trackable space	1.5x1.3x1.4 m (Figure 5)	3x2x3 m (Figure 21)
Software utility	NDI ToolBox/API	DTrack2/API

Table 6 shows that the main advantage of ART's cameras is that the accuracy is 2500% bigger than the one of NDI system. Again, the accuracy for this kind of procedure must be highly considered and it suggests the choice of ART. Furthermore, the trackable space offered by Polaris Spectra won't be enough to track the head of the surgeon since the height of the tracking is only 1.3 meters, as can be seen in Figure 5, while the height using 4 ARTTRACKPACK5 is of 2 meters, enough to track both the

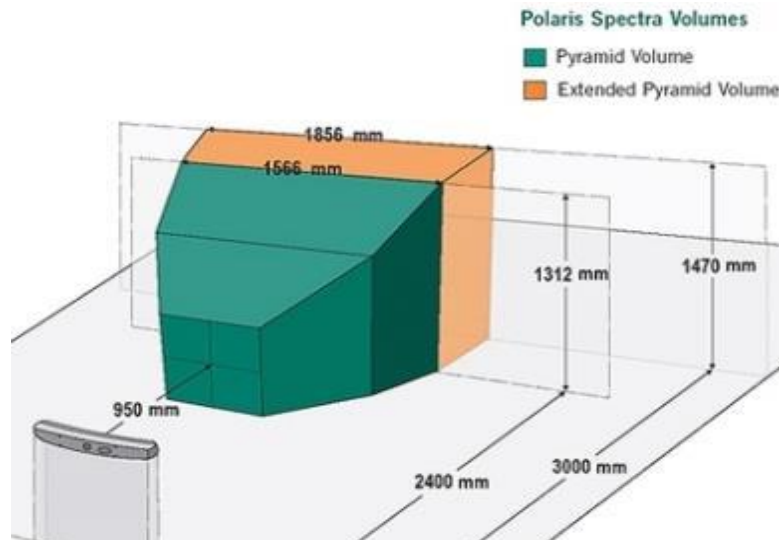


FIGURE 5 POLARIS' TRACKABLE SPACE. SOURCE: (NORTHERN DIGITAL INC, 2015)

patient and the surgeon at the same time and can be enhanced to higher scale if more cameras are added (Figure 21).

The advantage of the Polaris Spectra is its mobility that would allow it to be easily shared among different operating theatres. However, although it features a bump alarm, any shock with the system can reduce the tracking performance and would mean setting up the calibration again. Results from the hospital analysis (Appendix 9.7) showed that this can easily happen since, for a simple operation, around 10 people are walking around the surgeon in a layout loaded with different machines that reduce the possibilities of movements for surgeon and assistants.

## Tracking and display in a mobile device



FIGURE 6 AR DISPLAY ON A TABLET

During the group project it was also proved that due to graphical requirements and CPU performance, mobile devices together with image recognition (powered by Metaio) were not good enough for the needs of this project. Certainly, as can be seen in Figure 6, the definition of the 3D model had to be compromised due to the big decimation applied.

## 4 AR Software to help surgeons visualise patient's data

### 4.1 Technology

#### 4.1.1 Tracking

- [ARTTRACKPACK5 system operation](#)

ART's system works with pattern recognition to calculate the 2D markers position with high accuracy, the next step will be to calculate the 6DOF thanks to the Infrared reflections from the cameras to the markers (Jannick P. Rolland, 2001) and automatically manages, calculates and delivers the coordinates as well as the orientation thanks to its ART Controller (ATC). Since this is done by the ATC, the software implementation can be done quicker than if the coordinates had to also be calculated by the AR System itself. In order to do so, DTrack2 needs to be installed in the host computer that will connect with and run through an RJ45 (Ethernet) cable. This will be the same PC that will run the AR System's executable file.

The step by step process of setting up the layout, installing the system and calibrating the room and targets is explained later in the section about System deployment, when the system was actually set up in the operating theatre.

#### 4.1.2 Connecting the tracking technology with the rendering engine

Figure 7 Shows the AR System architecture, with 4 layers of software being used:

0. Blender is an open source 3D modelling software used to make some editions to the patient's 3D model (Hess, 2007), which is originally created by importing CT/MRI scans to Amira and following the process described in Appendix 9.7.
1. DTrack2 is a software provided by ART that connects with ATC, gathers tracker's coordinates and sends the data to the Personal Computer, in this case the one pointed in Appendix 9.7. DTrack2 is also used to calibrate each one of the tools used in this AR System. When the AR System is executed DTrack2 needs to be started at first to establish the connection with ATC and the IR Cameras.
2. Virtual-Reality Peripheral Network, a system that creates an interface between 35 different trackers (ART, VICON, Microsoft Kinect...) and VR software. Enabling motion tracking, head-tracking and any kind of user input and standardises the access to those trackers, making it easier and quicker to develop VR/AR apps. It also provides support for 32 more devices (Xbox game controller, DirectInput, Windows Keyboard...) VR software using different tracking inputs (Russell M. Taylor II, 2001). In order to make VRPN work, server needs to be configured according to ATC's output values (Kuntz, 2010) being an example of how the configuration file must be edited, the *vrpn.cfg* file used in the operating theatre test (Appendix 9.6) as well as the example in the *server\_src* directory (GitHub VRPN, 2015)Unity3D is the rendering engine chosen for this project.
3. Unity3D is a game engine with a powerful graphics processor that allows to interact with 3D scenes, made out of 3D objects, depending on user's input (Creighton, 2010). Furthermore, it allows to create videogames for various platforms (Unity Technologies, 2015). For this AR System, the 3D object will be the 3D model of the patient with all its different tissues (skin, skull, tumour, margin and vessels) in a black background (red, green and blue levels all set up at 0) that will make the HMD not show any light but the one corresponding to the 3D model.
4. To Bring VRPN into Unity3D, MiddleVR is used. Is a middleware that wraps VRPN, since it is written in C++, and allows to use it in Unity3D's C# framework by adding a Dynamic Link Library (DLL) into the project. A DLL brings functionalities to a program and helps to modularise and reuse the code as well as promote efficient memory usage (Microsoft, 2015). The *VRPN.dll*, in this case, will contain all the functionalities that VRPN provides, directly into Unity3D. By declaring MiddleVR's library inside the AR System's code, VRPN tracker's can be declared and managed to track the patient and the surgeon as in the following sections will be thoroughly explained.

For a more detailed description please refer to AR System Architecture (Appendix 9.1)

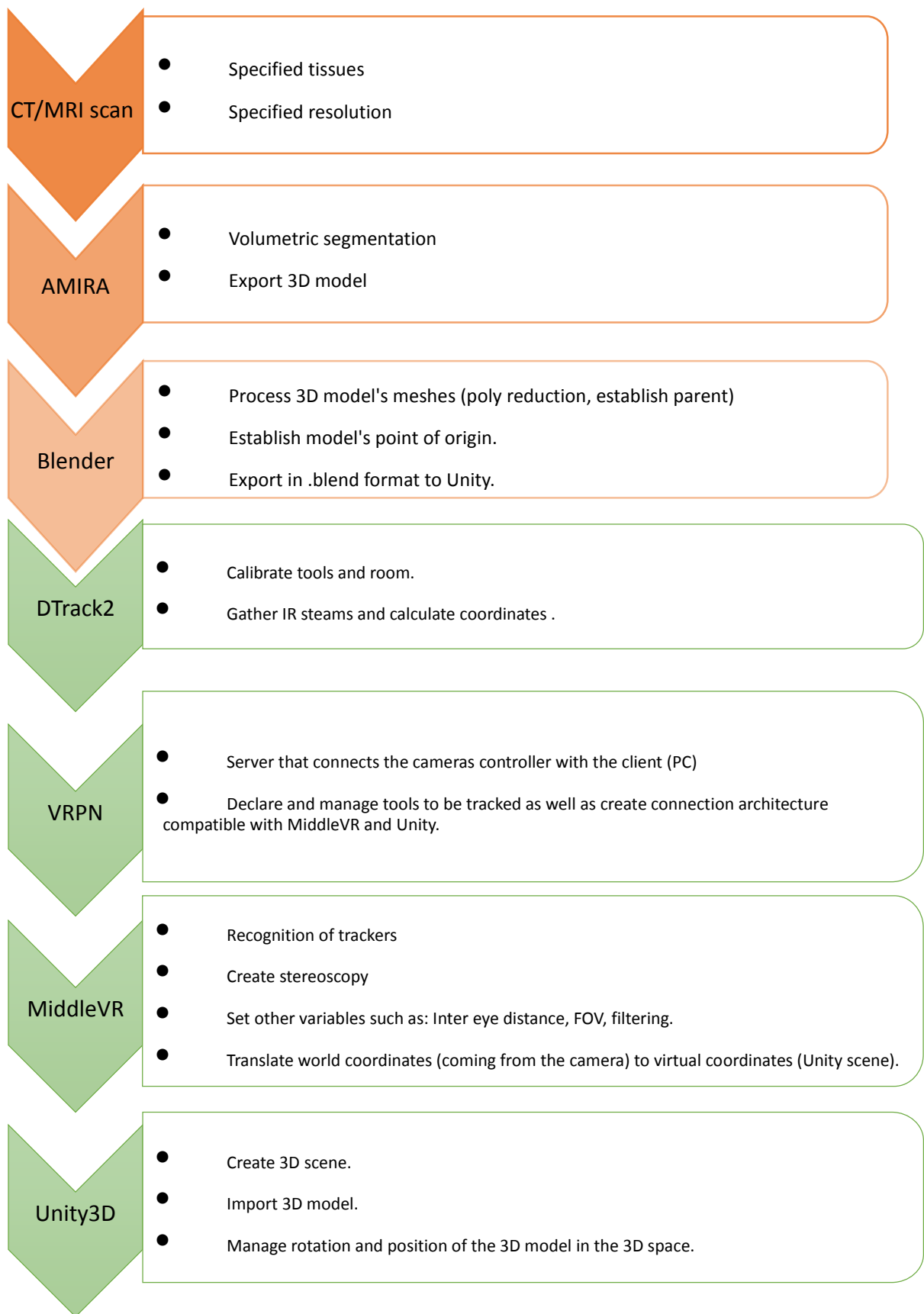


FIGURE 7 AR SYSTEM ARCHITECTURE

## 4.2 Patient registration

The process of taking CGI coordinate system (CS) and aligning it with the real world CS is called registration (G. Eggers, 2006). Not only this but also combining two different images to provide a better outcome such as combining CT and PET scans to obtain more complete data about the patient (Barbara Zitová, 2003). This results on an improvement of diagnosis as well as therapy (Pelizzari, 1998). In order to do so, a linear coordinate transform needs to be applied to convert from CGI to patient's coordinate system (PCS), with a rotation matrix (B) and linear translation ( $\vec{y}$ ) (G. Eggers, 2006):

$$\varphi(\vec{Q}_i) = B * \vec{Q}_i + \vec{y} = \vec{P}_i$$

The purpose of adapting the registration procedure to the AR system is to define the rotation and transformation between the virtual image and the patient's body.

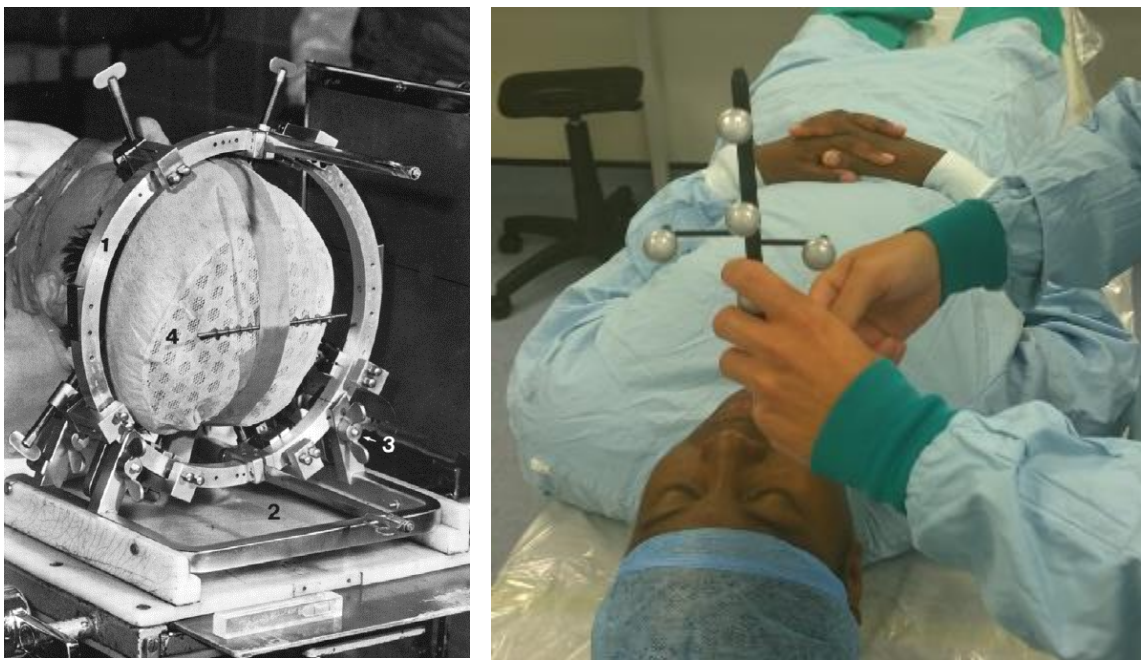


FIGURE 8 FRAME-BASED VS FRAME-LESS PCS

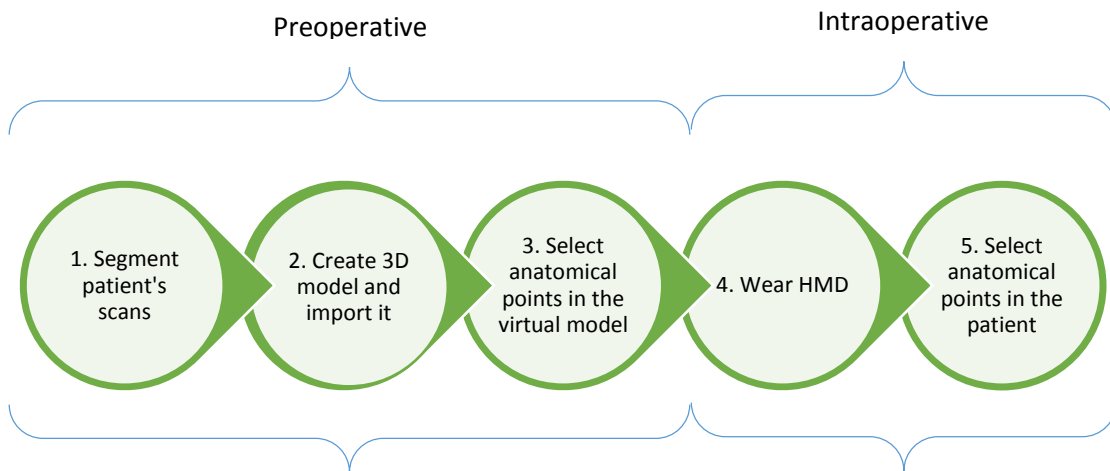
The first step of this process is to give the patient a coordinate system; this can be achieved by using devices attached to patient's body (frame-based) or by using smaller, single markers (frameless) whose position will be pointed by a tracked device (Figure 8).



**FIGURE 9 MARKER-BASED REGISTRATION (BIAO LI, 2014),**

Rather than a marker-based approach, where the position of the markers have to all the time be in line of sight preventing the surgeon to access necessary patient areas (Figure 9); the method included in this AR System is frame-less PCS and based on Marker-less pair-point registration (Figure 8, right).

For this registration method to be implemented, surgeon's input is required as shown in Figure 10.



**FIGURE 10 PATIENT REGISTRATION PROCESS**

1. The segmentation process is performed using Amira 3D software, which takes CT, MRI and other imaging modalities to visualise, manipulate and understand patient's specific data.
2. Import the 3D model into Blender and change the point of origin to the desired location as explained in Appendix 9.11.
3. Import 3D model to Unity, drag and drop A, B, C spheres in the selected anatomical points. Change view from x, y, z axes in order to accurately place the spheres in the desired positions. This step is critical for accuracy purposes. Surgeon needs to choose three points that will be easily identifiable when registering them in the patient's body (Figure 11).

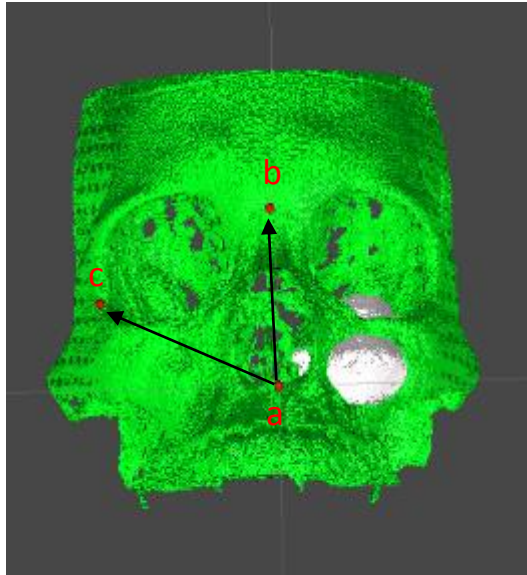


FIGURE 11 ANATOMICAL POINTS (VIEW FROM UNITY3D)

4. Using the Measurement Tool (Figure 12), the coordinates of each anatomical point can be gathered as seen in the script shown in Table 7 and a translation of 3D model's position is performed.



FIGURE 12 MEASUREMENT TOOL

TABLE 7 TRANSLATE POSITION OF THE PATIENT'S 3D MODEL SCRIPT

```

mt= MiddleVR.VRDeviceMgr.GetTracker("atc-301422026.Tracker0");
public void setA()
{
    aMatrix [0] = mt.GetX ();
    aMatrix [1] = mt.GetZ ();
    aMatrix [2] = mt.GetY ();
    transform.position = new Vector3 (aMatrix[0],aMatrix[1],aMatrix[2]);
    MiddleVRTools.Log ("Coordinates");
    MiddleVRTools.Log (""+aMatrix [0]);
    MiddleVRTools.Log (""+aMatrix [1]);
    MiddleVRTools.Log (""+aMatrix [2]); }

```



However, to calculate the rotation is more complex due to Unity3D's limitations, pair-point's registration method cannot be applied in a traditional way, 3D model's point of origin cannot be edited in real time; i.e. depending on user's input create the point of origin with the specified rotation.

Therefore, the approach required considers two three-dimensional vectors  $\vec{ab}$  and  $\vec{ac}$  which have a magnitude and orientation specified by patient's anatomy and surgeon's choice:

$$(a_1, a_2, a_3) \in R^3$$

The point where these two vectors intersect in the x, y and z axes of the Cartesian coordinate system is called the origin. And the distance of these two vectors is specified by the formula:

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

This origin is also the point "a" and the point of origin of the 3D model. Therefore, the approach is to translate the point of origin of the patient's 3D scan till vectors  $\vec{ab}$  and  $\vec{ac}$  are aligned and its distances are preserved.

In order to do so, a first transformation is made to the patient's 3D scan to have each of the three anatomical points in a known position ("First iteration" inside Appendix 9.8). For that, position in virtual world of each of the points needs to be known. For simplicity, 3D model will always be in the 0,0,0 position. However, points b and c will be where the surgeon chose them to be, and to gather that information we need a few lines of code to access the 3D spheres attributes (Table 8).

TABLE 8 GATHER VIRTUAL ANATOMICAL POINTS DATA

```
//Get spheres' coordinates
public float []A= new float[3];
//Declaring position of anatomical points
A=VectorConverter(a.transform.localPosition.x,a.transform.localPosition.y,a.transfo
rm.localPosition.z);
//To be able to access the vector
public float [] vectorConverter(float x, float y,float z){
float[] array = new float[3];
array [0] = x;
array [1] = y;
array [2] = z;
return array;
}
```

After this first iteration, the user can choose the three anatomical points selected in the virtual world and register their position in the real world, in the patient. A second iteration will be applied and rotations in each of the axes will be calculated in the algorithm implemented in "Second iteration" inside Appendix 9.8.

Once these rotations are applied, Quaternion.Euler() function by Unity3D will be used. Which applies a rotation of z degrees in the z axis, x degrees in the x axis and y degrees in the y axis. Please note that the order of applying the rotations is critical and in Unity3D follows this order (first z then x and

lastly y). Quaternions are Unity3D's internal structures to represent all rotations, and in this function will allow the input of a rotation in Euler angles.

It is also very important to note at this stage that two rotations are required as stated in the previous lines (one to set the rotation somewhere known in the x, y, z axes and the second one taking into account user's input). These two rotations are consecutive and the second one has to be performed around the new existent vector after the first rotation has been applied.

There's actually one function that allows to do this and it is rotating by the product of two rotations as in Table 9.

TABLE 9 SEQUENTIAL ROTATIONS

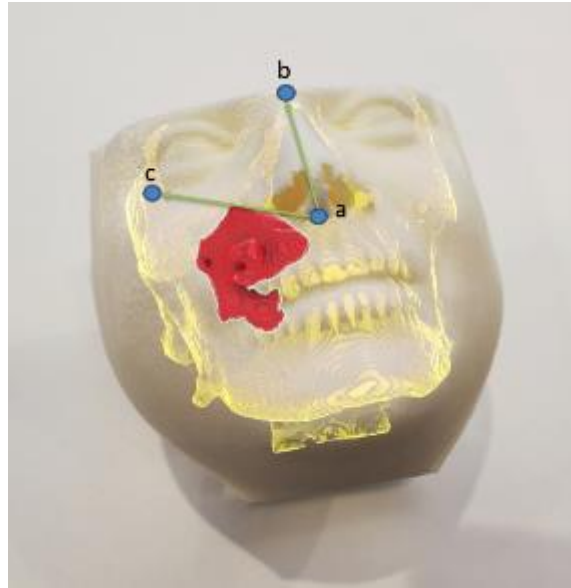
```
public void firstRotation() {  
    transform.rotation = Quaternion.Euler(rx, ry, rz);  
}  
public void secondRotation()  
{  
    transform.rotation *= Quaternion.Euler(rx2, ry2, rz2);  
}  
transform.localScale = new Vector3 (0.001F, 0.001F, 0.001F);
```

Finally, the last transformation required will be the scaling. As tests performed in Appendix 9.12 (Size of 3D objects in Unity3D) resulted, the transformation required to apply to the 3D model consists in reducing the size by a 1000 times (Table 10).

Please note there's no need to declare patient's 3D scan from the code since the script is directly associated with this specific 3D object and the transform functions are only applied to it.

TABLE 10 TRANSFORM 3D SCAN'S SCALE

```
transform.localScale = new Vector3 (0.001F, 0.001F, 0.001F);
```



**FIGURE 13 ANATOMICAL POINTS VIEW ON THE PATIENT**

Eventually, after applying these three transforms (position, rotation, scale) what the surgeon will see through the HMD will be the image seen in Figure 13; the real world and the virtual world accurately overlaid no matter which perspective he/she is looking from. To handle this changes in the perspective, head tracking is provided as explained in the following section.

### 4.3 Surgeon tracking

Surgeon needs to look at the patient and, at the same time, the information overlaid over him/her. This information, the 3D scan, must be dynamic: transform its position, rotation and scale depending on surgeon's viewpoint.

There are, therefore, two main requirements: track surgeon's eyes and apply the above mentioned transformations.

In order to track user's perspective, the Nvis Target Figure 14, consisting of 8 spherical markers, must be securely attached to the HMD in a manner that assures no movements after calibration is performed as stated in section Room and tools calibration. Calibration is the process of teaching a target's geometry (in this case the Nvis Target) to the tracking system. This calibration is critical so that user's real perception is accurately tracked and there is no offset between the real and virtual world (Azuma, 1997). Being the tracker attached to user's head, will provide AR System user's coordinates at 60 frames per second.



FIGURE 14 NVIS TARGET

The second requisite is that Unity3D handles the transform of the 3D object depending on that change on user's coordinates. Unity3D provides Cameras, devices that display the world to the player (or user) and which can be customised or manipulated depending on user's input. For our case, the user's input that will manipulate the Camera is the coordinates of Nvis tracker. MiddleVR includes a script, VRPNTracker.cs, gathers those coordinates and changes Unity3D's camera (the window to the virtual world). By declaring the Nvis target in MiddleVR as in Figure 39 HMD tracker setup, VRPNTracker.cs can access its values and manipulate the Camera scene.

TABLE 11 TRANSFORM CAMERA

```
pos = DeviceToUnity.InverseTransformPoint(pos);
quat = Quaternion.Inverse(DeviceToUnity.localRotation) * quat;
UpdateTransform(pos, quat);
protected virtual void UpdateTransform(Vector3 pos, Quaternion quat)
{
    if (ApplyTracking == Transform_Type.Both || ApplyTracking ==
Transform_Type.Position)
        transform.localPosition = pos;
    if (ApplyTracking == Transform_Type.Both || ApplyTracking ==
Transform_Type.Orientation)
        transform.localRotation = quat;
}
```

#### 4.4 Immersion effect

One of the requirements for Augmented Reality to exist is to make the user perceive like the virtual object is physically present in the real world. Humans have binocular vision, with eyes located at different positions in the head which result in two different images projected in the retina (Warren Robinett, 1991) as can be seen in Figure 15. The closer one looks into an object, the bigger the difference between those two images projected is. This is called stereopsis and it is key to facilitate the convergence between the real and virtual world (Milgram, 1996).

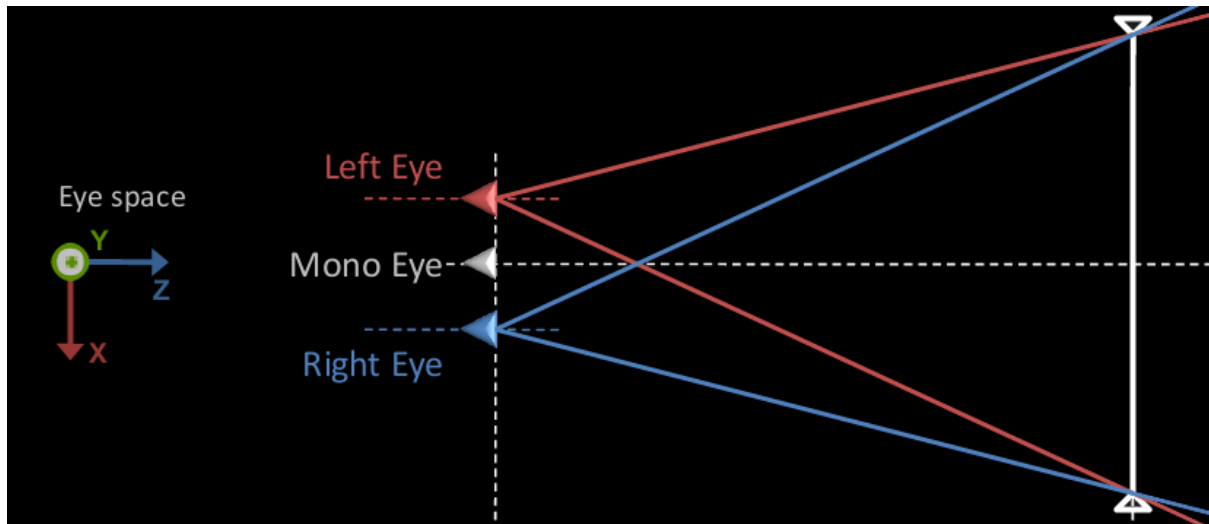


FIGURE 15 STEREO PROJECTION (SAMUEL GATEAU, 2011)

In a first system iteration, a method for implementing passive stereopsis was provided in the AR System. Both images of the patient's 3D model were presented with slightly difference.

In order to provide stereoscopy, user's particular Inter Pupillary Distance (IPD) needs to be measured. The distance between each centre of the pupil varies depending on age, gender and race, being a separation of 63 mm the mean IPD for adults. However, It can range from 50 to 75 mm (Dogson, 2004), which suggests that for some users this system won't apply since HMD's values range from 53 to 73 mm (NVIS, 2015). Usually, systems will consider only the average IPD; however, this assumption is incorrect and even small errors in the measurement can lead to big errors (Akira Utsumi, 1994)

This requirement can be easily applied on the software side (Borke, 2008) by creating two camera objects in Unity3D (Unity Documentation, 2015), and giving a horizontal offset to each camera equal to user's IPD. Then, each camera is assigned to each of the viewports where the ST50 is connected.

As can be seen in Figure 16, each screen in NVIS ST50 is treated like a different display via its dual HDMI interface and can be, therefore, selected as a different viewport from in the AR System.

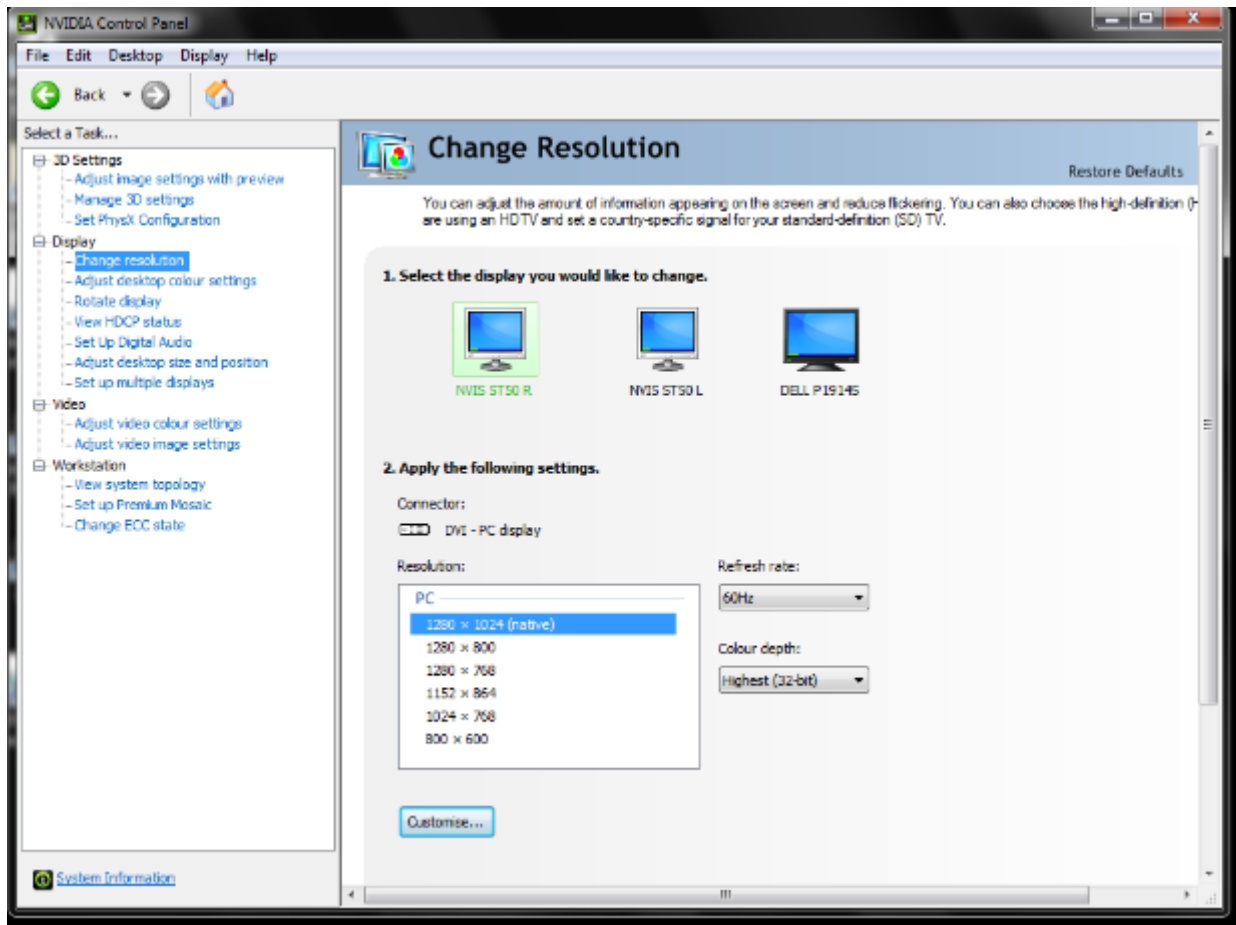


FIGURE 16 NVIDIA CONTROL PANEL FOR WINDOWS 7

In order to compare both stereopsis approaches, active stereoscopy was implemented. With the same stereopsis principles, the difference between passive and active stereoscopy is that the latter

#### HOW ALTERNATE-FRAME SEQUENCING WORKS

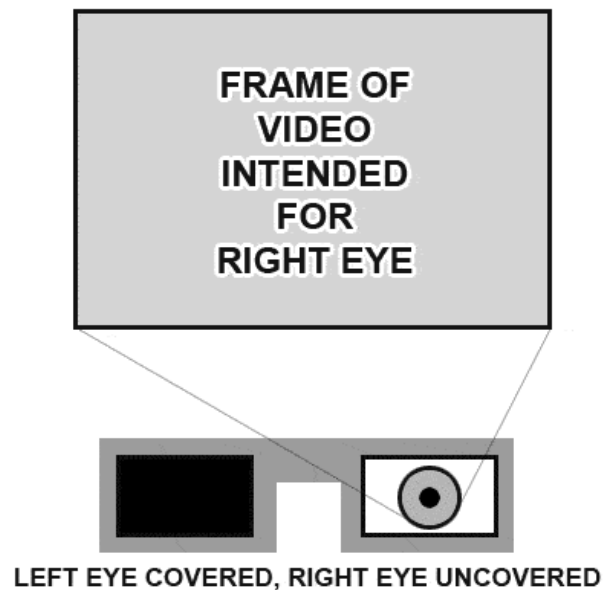


FIGURE 17 ACTIVE STEREOSCOPY

applies OpenGL's quad buffer:

- 1) Set the geometry for the view from left eye
- 2) Set the left eye rendering buffers
- 3) Render the left eye CGI
- 4) Clear Z-buffer
- 5) Set the geometry for the view from right eye
- 6) Set the right eye rendering buffers
- 7) Render the right eye CGI
- 8) Swap buffers

It shuts down Nvis ST50's left screen and render the 3D model in the right screen (Figure 17) then does the opposite at a rate of 60 frames per second, which makes the image appear smoothly in the eyes of the user and allowing to better represent 3D view.

Active stereoscopy has been tested in this project thanks with Nvidia Quadro K5000 4GB GPU Memory, which supports OpenGL Quad Buffered Stereo (NVIDIA Corporation, 2015). Nevertheless, there are other graphics card that support this feature: ATI Fire GL, Oxygen GVX 1 or ELSA Gloria XL.

Active stereoscopy has proved to be useful compared to passive stereoscopy in Robot Teleoperation and simulated driving (Jessie Y. C. Chen, 2010): results from this research showed that, when using shutter glasses, users would complete the tasks significantly faster and would have a better perception of the simulated world. Contrary to what other researches concluded (Kay M. Stanney, 1998), data gathered didn't prove any sickness due to the use of Active stereoscopy.

However, other researches concluded that Active stereoscopy would have negative effects in Combat Identification Tasks (Joseph R. Keebler, 2014).

Stereopsis was applied for the first time into surgeries using optical tracking to register the position of the patient and display real-time ultrasound scans on a 3D stereoscopic monitor (Xin Kang, 2014)

However, it was applied to Minimally Invasive Surgery, using 2D ultrasound scans (not capable of detailing bony structures and flat) and using a monitor rather than a HMD.

According to surveys to 6 subjects, this project shows that Active stereoscopy makes a huge improvement. As Table 12 shows, 86% of the users consider that there is a better merge of the virtual objects with the real world and that they don't when using a HMD with 3D patient data segmented out of CT and MRI scans. Furthermore, as seen in Table 13, 86% didn't feel dizziness after using active stereoscopy and 66% of them preferred a level of luminance of 15 foot-lambert (International Light Technologies, 2015).

**TABLE 12 ACTIVE VS PASSIVE FOR 86% OF PARTICIPANTS (APPENDICES 9.14 AND 9.15)**

	Active	Passive
Better Immersion effect		
Feels "more real"		
Allows to focus on both reality and 3D model		

**TABLE 13 ACTIVE STEREOSCOPY (APPENDICES 9.14 AND 9.15)**

	Level of agreement	
Brightness' level I prefer is	15fL (MID): <b>66%</b>	23fL (HIGH) : <b>33%</b>
Feeling dizziness after using Active Stereopsis	Strongly disagree: <b>86%</b>	Disagree : <b>14%</b>



#### 4.5 Graphics processing optimisation

Active stereoscopy requires a considerable amount of computer processing and the computer will get stuck when running the executable file. Therefore, an optimisation method needs to be applied to the graphics in order to reduce CPU consumption.

As explained in Appendix 9.11, and following method applied in Methodology to Create Optimized 3D Models Using Blender for Android Devices (Bhawar, 2013), each mesh component of the patient 3D scan was decimated to comply with Unity3D's maximum number of polygons (density of meshes) as seen in Table 14. The result in the image can be seen in Figure 18.

**TABLE 14 NUMBER OF POLYGONS PER MESH WHEN IMPORTING TO UNITY3D**

MeshPart	Mesh density(Polygon)	Maximum in Unity3D	Transformation applied	Percentage of decimation
Maxillo	1976876	65534	0.033150284	97%
Margin	118192	65534	0.554470692	45%
Tumour	81915	65534	0.800024416	20%
Skin	816594	65534	0.080252855	92%
Skull	985810	65534	0.066477313	93%

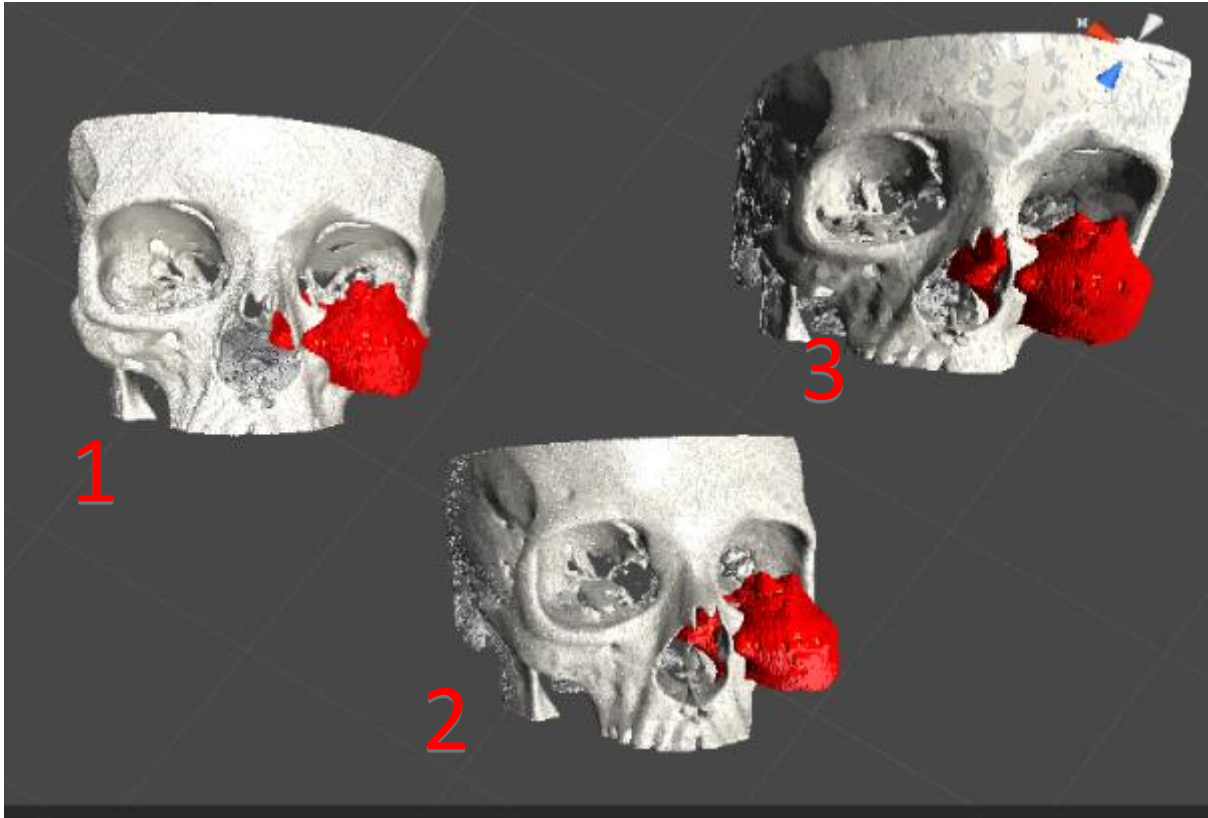


FIGURE 18 DECIMATION PERCENTAGES 1: 0%; 2: 50%; 3: 97%

Nonetheless, the above mentioned method was not enough as to achieve the maximum number of Frames Per Second in the AR System.



FIGURE 20 QUALITY SETTINGS REDUCTION. FANTASTIC (LEFT) TO FASTEST (RIGHT).

Therefore, it was decided to reduce the quality settings, since the higher the lower the Frames Per Second level of rendering. In this way, latency was reduced to the minimum possible from Unity3D's part (Figure 19).

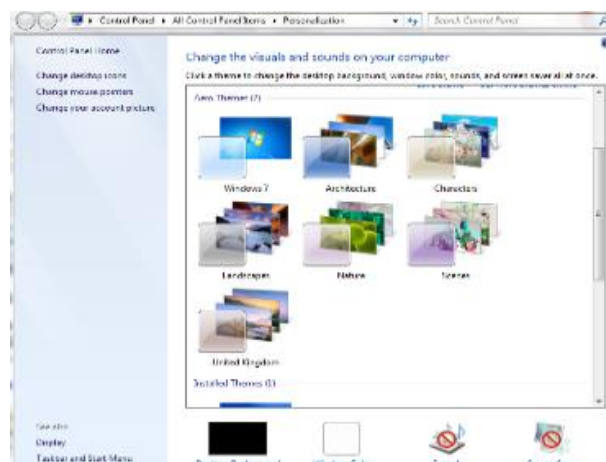


FIGURE 19 DISABLE AERO BACKGROUND IN WINDOWS 7

Last but not least, the Aero interface provided by Windows 7 (Appendix 9.10) reduces also GPU performance (adding a delay of one FPS) and it was disabled. Figure 20 shows how to disable the aero screen. However, and as later will be described in the Future work section, there exist other sources of time latencies that will need a further development to reduce them.

## 4.6 System deployment

### 4.6.1 Hardware setup

#### 4.6.1.1 Mounting the cameras

Four Advanced Real Time cameras were mounted in a cadaver lab at St George's Hospital. The cameras were placed on four tripods with crank to adjust height and orientation as desired to target the head of the user at its best. The layout displayed in Figure 21 allows to cover an area of three meters in the x axis, two meters in the y axis and three meters in z axis (considering a left-handed Cartesian coordinate system). Results coming from the analysis performed during two operations in the operating theatre (Appendix 9.7), showed that the typical range of movement for a surgeon will be around this area. Therefore, this arrangement of the cameras will cover a typical surgical intervention. If further range is desired for bigger operating theatres; more cameras can be included in the system, increasing the scale of the trackable space.



FIGURE 21 ROOM LAYOUT IN CADAVER LAB AT ST. GEORGE'S HOSPITAL

Furthermore, with this layout, cameras' emitted radiation is considered and security distance suggested by ART in Figure 22 is maintained at all times.

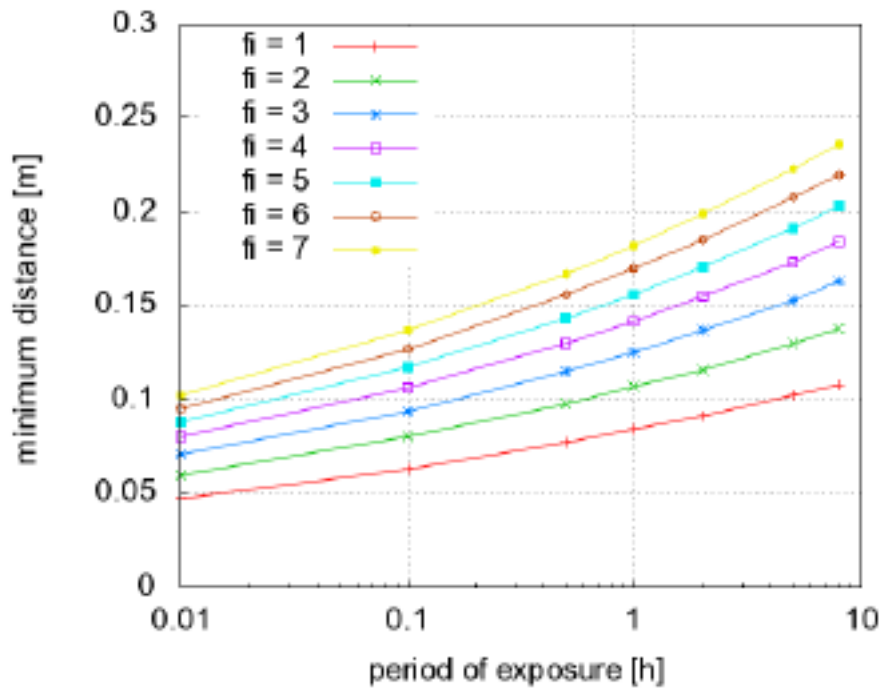


FIGURE 22 MINIMUM DISTANCE DEPENDING ON FLASH INTENSITY. (DTRACK2 USER MANUAL, 2013)

For demonstrating the technology, the cameras were mounted in tripods. However, they can also be mounted in a wall or a ceiling. ART's cameras are sensitive to movements; once the room and body calibration have been performed, collisions must be avoided to have the best tracking performance. That is why in a final operating theatre solution, and considering the conditions that surround the surgeon described in section Operating theatre analysis, the optical cameras will be mounted in a ceiling as described in Figure 23.

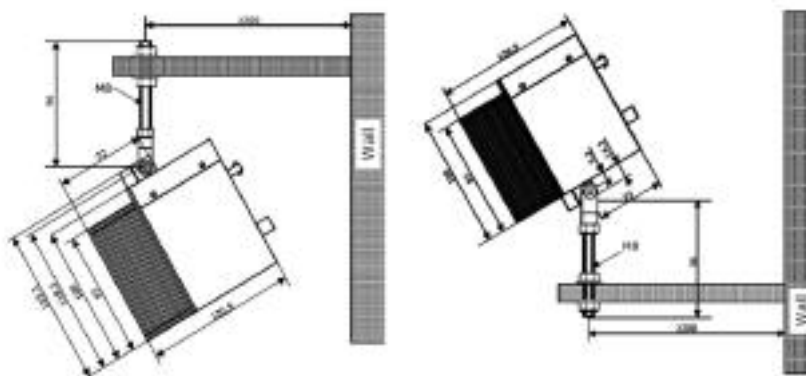


FIGURE 23 MOUNTING CAMERA TO A WALL OR CEILING. (DTRACK2 USER MANUAL, 2013)

#### 4.6.1.2 Cameras connection

1. Connect the cameras with the 10 meters-long RJ45 patch cables, a standard plug that connects the camera to the ART Controller (ATC) and forms, in this way, a Local Area Network (ART, 2015)
2. Install DTrack2 in the host PC.
3. The ATC will be handled by the host PC via ART's frontend software DTrack2. This controller is set up to support DHCP which dynamically requests the IP address and network parameters of the controller and reduces the need for further configurations. Nevertheless, ATC also allows to configure it if a DHCP server is not available.
4. Select the desired controller from the Controller Selection window in DTrack2.
5. Controller's name needs to be copied and input in VRPN's configuration file. By using an editor such as Notepad++ we can access it and write the ATC full name in the Advanced Real Time field provided by VRPN.
6. Once this is done, tracker's coordinates sent by the four cameras can be accessed from Unity3D.

#### 4.6.2 Room and tools calibration

1. Calibration>Room. Select wand available, marker distances that will setup the coordinate system and press calibrate.
2. Rotate the wand around the room trying to reach upper, mid and lower heights. DTrack2 displays percentage of calibration per camera, the higher the value, the better the tracking performance.
3. Change the room coordinate system to make it coincide with Unity's left-handed coordinate system.
4. Body administration>calibrate standard trackers>calibration due to room.
5. Calibration>Body adjustment Mount the SX60 target in the HMD and while facing the front (-Z axis): Due to Room (origin in marker closer to user's eyes).
6. As in Figure 24, measure distance from marker to actual eyes position, and IPD setup that offset in the AR system.
7. Same process for Measurement Tool, making 0,0,0 rotation in the Cartesian coordinates when tip is facing down.



FIGURE 24 CALIBRATING USER'S EYES POSITION

#### 4.6.3 AR software

- I. Import 3D model into Unity's scene.
- II. Attach A, B, C spheres into specified anatomical points in the 3D model.
- III. Skin associated meshes removed due to customisation of the needs for the purpose of the test.
- IV. Rest of instructions followed as referred in Appendix 9.1
- V. Import also 3D model for anaesthesia intubation by Consultant.
- VI. Build the executable file and run it.
- VII. "Space" to register each of the three anatomical points.
- VIII. "Backspace" to adjust rotation
- IX. "T" to track the surgeon

Please note: This software has been tested with the workstation pointed in Appendix 9.10

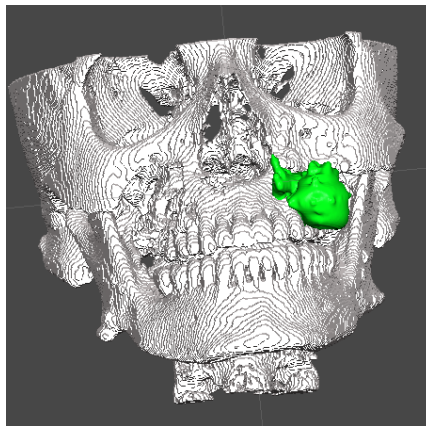
## 5 Validation

### 5.1 Cadaver maxillofacial surgery simulation

After deploying the AR System the day before, a simulated validation was performed using a cadaver as the subject for trial. In the following lines the steps followed by the surgeon while using the AR System at all times (Optical cameras running, wearing Head Mounted Display, running the software).

The simulation with the cadaver is run under these conditions:

- Female 70 years old.
- Tumour in the right side of the face.
- Requires a margin that includes removal of soft and hard tissues.
- AR System will be used throughout the whole session.
- Coordinate systems are opposite in the z axis (Figure 26).
- 3D scan with a simulated tumour (Figure 25)



**FIGURE 25 3D SCAN USED FOR DEMONSTRATION**





FIGURE 28 TOOLS USED

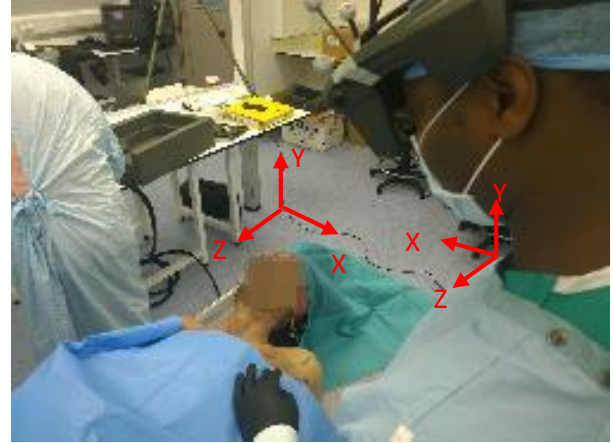


FIGURE 27 SURGEON AND PATIENT COORDINATE SYSTEM



FIGURE 26 EXPOSING THE TUMOUR AREA WITH A BISTOURY

Surgeon starts by making an incision around the nose with a bistoury (Tools, Figure 27), exposing the area under the tumour region to be able to start accessing to it requiring a margin of soft tissue around it. Surgeon explains that he can reference the distance from the tumour and is capable to give the virtual tumour a good safety margin, the extra area of soft and hard tissue that the surgeon will take out to make sure that all the cancer cells are removed (Breastcancer.org, 2014).



**FIGURE 31 TUMOUR MARGIN**



**FIGURE 30 FINAL RESULT**



**Figure 29 Removed Zygoma**

For this case the surgeon works with a margin that requires the removal of the zygomatic bone (Figure 31). At some point in the process, the surgeon mentally blocks the focus on the virtual world and just focuses on the reality. He doesn't need to turn the goggles off, managed to ignore the model when it is not required and continues operation as normal(Figure 29). Looks at the AR and the reality simultaneously because can reference to the position of the bone. After 20 minutes of operation, surgeon successfully removes margin while experiencing the guidance of the AR System (Figure 30).

## 5.2 Cadaver anaesthesia intubation simulation

Endotracheal intubation was performed using the AR system Figure 32. This is a medical process in which a tube is positioned into the patient's trachea through the mouth or nose, to conduct the anaesthetics drugs (Reardon RF, 2013). Since the intubation is usually done blind, it has risks



FIGURE 32 INTUBATION PROCESS

associated and complications have been reported in some cases (Takenaka, 1999) and (Cormarck, 1981). There exists a potential use of this AR system for this complex procedure and so it was confirmed in the validation stage.

For this purpose, the AR System was customised and a 3D scan was imported for this procedure (Figure 34) the consultant anaesthetist tried the AR system using the Bougie elastic tube: Looking at the model through the goggles. Where she sees the epiglottis (Figure 33), a thin leaf-shaped cartilage at the root of the tongue which folds back over the entrance to the larynx (National Library

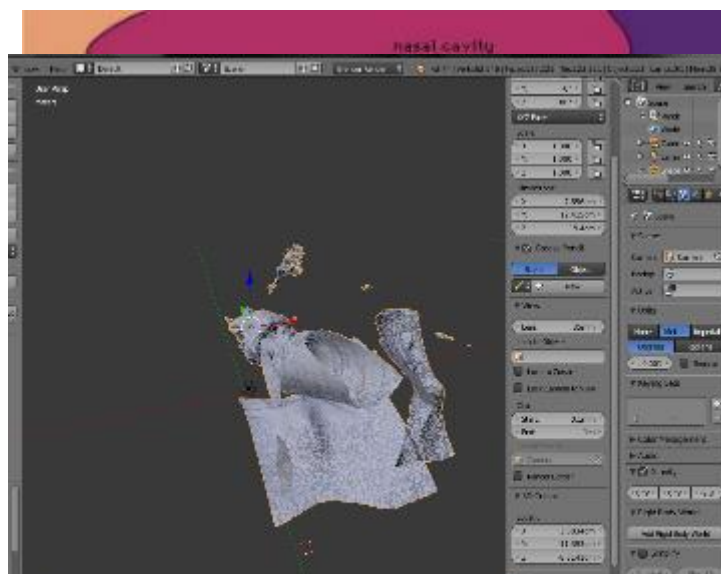


FIGURE 34 3D MODEL USED FOR INTUBATION PROCEDURE

of Medicine) in the model, she's passing the Bougie relying on the 3D model, being able to focus on both the real and virtual world. She didn't feel dizziness or discomfort and didn't feel that it could be distracting but, on the contrary, she felt it was useful and will give a good reference to help reduce complications in anaesthesia intubation, no need to do blind anaesthesia any more.

### 5.3 Real patient registration



FIGURE 37 PAIR-POINT ANATOMICAL REGISTRATION

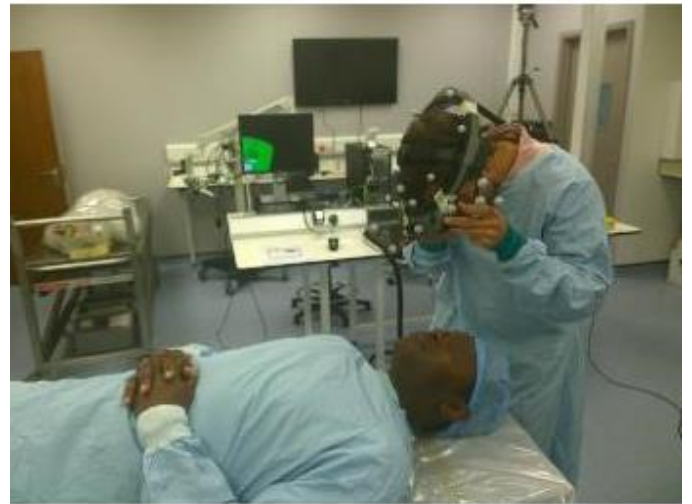


FIGURE 36 LOOK FROM 180 DEGREES ROTATION IN Y AXIS AND 90



FIGURE 35 LOOKING FROM 90 DEGREES ROTATION IN Z AND Y AXIS

In the previous sections, the whole AR system was tested, how it feels to wear the HMD through the process, if the user is able to feel the depth perception and combine both the virtual with the real world and its usefulness, these qualitative results will be detailed in the Discussion section.

In this section the focus is on gathering quantitative results comparing the transformations applied in the virtual 3D model in the rotation, scale and position with the real subject. For that, a CT scan was taken of him. This scan was later segmented following the process from Amira software described in Appendix 9.7 and later imported into Unity3D after applying the changes required from Blender. User registered the anatomical points of the test subject (Figure 37) User looked both at the real and virtual world from different points of view, upside down view (Figure 36) and looking from one of the sides (Figure 35) and jotted down the different information which will be detailed in the next section.

## 6 Discussion











### 6.1 Results

#### 6.1.1 Qualitative

According to our users, this AR System successfully merges virtual and real world and is, although its accuracy limitations (shown in Table 16), already a good reference to look into patient's particular anatomy. Users reported that it feels like real-life thanks to the inclusion of the active stereoscopy together with the improvement of real-time tracking and, even though decimation of 3D model's density had to be applied, the good resolution of the 3D model (Table 15).

However, users also reported ,on the other hand, that having the whole 3D model as represented in Figure 25 and Figure 34, can be distractive when the consultants want to focus their view on a single area. Therefore, it is suggested to slice the 3D model in different meshes that will dynamically change depending on the surgery process. It was also identified the need of having different colours and to develop a quicker calibration method.

TABLE 15 QUALITATIVE RESULTS ACCORDING TO USERS (APPENDICES 9.14 AND 9.15 AND TRIAL VIDEOS)

	Constant reference to deeper anatomy
	It feels like looking through the tissues directly to the tumour
	Very good depth perception
	Good resolution of the 3D model
	Able to combine both the real and virtual world
	No dizziness was felt by the user at any time due to the good focus he/she can apply thanks to customising the view to his IPD.
	No ergonomic issues reported by users despite HMD's 1kg weight.
	Too much information coming at the same time, need to remove parts of the skull in the 3D model, depending on the step of the operation.
	Need to think on different colours to represent tumours and soft tissues. Too much contrast against the background can be distractive
	Need to develop a quicker and more reliable calibration method for user's eyes

### 6.1.2 Quantitative

On one hand, and after comparing tracking stability with the initial test iteration performed in the Group Project, it has been improved by a 95%, from 10 cm instability to only 1 cm; the sources of error have been identified and will allow to, in a not-too-long future, reduce even more the tracking error that still can be found in the AR System.

Furthermore, the anatomical registration proves that it is the good way to go. Since it is marker-less, the spherical markers do not need to be continuously in the IR cameras field of view, it allows surgeons to work as usual without having to be concerned on not affecting the markers. Besides, the inaccuracies (Table 18) are manageable.

On the other hand, lightning and humidity levels where checked and, indeed, did not affect the tracking performance. Also, the distance requirements due to radiation exposure coming from the IR cameras was met at all-time naturally and the FPS was improved.

Nevertheless, measurements showed a key factor that can affect the system very much. 3D model's size is smaller than it should, around 40% smaller, rotation is not accurate enough and demands user input to correct it, and there is no possibility of utilising speech recognition in a surgical environment due to the wearing of masks and people talking around the HMD's internal microphone (Table 16).

Scripts used to gather this data can be found in Table 17 and Table 19.

In Future Work section, will be analysed what is needed to overcome the negative results shown in this section.

**TABLE 16 QUANTITATIVE RESULTS**











	Reduced tracking instability by a 95% as can be seen in Appendix 9.13
	Registration process has manageable inaccuracies that can be reduced with an accurate calibration of tools (Table 18).
	Lightning conditions don't affect tracking performance
	Humidity 50%, no condensing. Good operative conditions for optical cameras
	Minimum distance due to radiation to optical cameras of 20 cm met at all times, naturally, no need to warn the users.
	Reduced latency with higher FPS
	Size of the 3D model is 40% smaller. Reasons: either Unity3D's coordinate system or FOV. Further discussion in Future work section.
	Rotation is not accurate and required a correction of 3 degrees in X axis, 6 in Y axis and 2 degrees in Z axis (Table 21). Further discussion in Future work section.
	Need to develop a quicker and more reliable calibration method for user's eyes
	No possibility of functioning with speech recognition 50/60 db during operation. Besides, surgeon wears mas, more difficult to understand.



TABLE 17 SCRIPT CALCULATING ANATOMICAL DISTANCES

```

//Declaring position of anatomical points
A=vectorConverter(a.transform.localPosition.x,a.transform.localPosition.y,
a.transform.localPosition.z);
//calculating distances
rAB=distance (B,A);
//Distance function calculator
public float distance(float[]x, float[]y){
    float distance=0f;
    float calculator=0f;
    for(int i=0; i< 3; i++){
        calculator+= (float)Math.Pow(x[i]-y[i],2);
    }
    distance=(float)Math.Sqrt(calculator);
    return distance;
}

```

TABLE 18 COMPARISON OF MEASUREMENTS COMING FROM TABLE 13

Anatomical Landmarks	3D model	User Input	Linear difference
AB distance	92.736185	96.35	3.613815045
AC distance	58.309519	56.92	-1.389518948
BC distance	66.332496	71.43	5.097504193

TABLE 19 ROTATION CORRECTION

```

public void correctRotation()
{
    rx = mt.GetPitch ();
    ry = mt.GetYaw ();
    rz = -1*mt.GetRoll ();

    transform.rotation = Quaternion.Euler (0, 180, 180);
    transform.rotation *= Quaternion.Euler (rx, ry, rz);
}

```

## 6.2 Contribution to healthcare

This system can be applied to two different areas in the healthcare sector: it has been validated both for a maxillofacial surgery and for anaesthetic procedures which can be required consecutively in the same operating theatre as the analysis suggested (Appendix 9.7).

This study suggests the potential appliance of Augmented Reality to not only Minimally Invasive Surgeries but also to more complex procedures such as Maxillofacial surgery as well as for anaesthetic procedures (which are both necessary in a same operating theatre and therefore would require moving the optical tracker).

*“A New Method of Surgical Navigation for Orthognathic Surgery: Optical Tracking Guided Free-Hand Repositioning of the Maxillomandibular Complex”* (Biao Li, 2014), a guiding system using a monitor rather than a HMD, concluded that preoperative preparation time was reduced by 100 minutes per operation and that the outcomes showed a 100% satisfaction from patients.

While further real operations analysis and testing on a real patient is required with an Augmented Reality System for surgeries, it wouldn't be too audacious to expect even a higher reduction in the whole operating cycle by reducing the time intraoperatively as well as immensely improving the outcomes of surgeries compared to the above mentioned research.

All in all, this technology has the potential of saving £420M every year to the NHS if we take into account the reduction of both negligence litigation expenditure (£300M in 2014) and surgeon's hours of work.

## 6.3 Contribution to Augmented Reality

### **Optical tracking**

Although previous papers worked with Advanced Real-time Tracking Optical Cameras (Splechtina, Fuhrmann, & Wegenkittl, 2002), (Santos, Graf, Fleisch, & Stork, 2003) and (Zaitsev, Dold, & Sakas, 2006), none of them was using them together with Nvis ST50, the most reliable HMD available in the market together with its newer model ST60. Furthermore, all of them were published prior to 2006, before TRACKPACK5 by ART was introduced to the market, a more accurate and more reliable optical camera than its previous models.

Introduction of a different optical tracker TRACKPACK5 by ART, there has been no research on the use of these optical cameras. than the one introduced by Xiaojun Chen et al conclude that they should use Polaris Spectra which has a larger dimension of 613 mm x104 mm x86 mm rather than Polaris Vicra with 273 mm x69 mmx 69 mm, this project suggests that the surgeon will need even a bigger range of movements than the one presented by the quoted article. The distance between the surgeon and the patient will usually be larger (0.6- 1 meters [Operating theatre analysis]) and therefore the range of tracking should be bigger to provide flexibility to user's movements. User should not have to worry about getting out of the frame of reference. Since IGSTK doesn't provide a tracking interface to this hardware (IGSTK: The Book, 2009), this research also suggests the use of Unity3D together with MiddleVR. Furthermore, ART's cameras will provide a bigger accuracy than Polaris system.

Last but not least, this research also proves that there's no need for the markers to be continuously in place with the inconveniences it can cause to operate and therefore there's no need to drill in the patient and attach any screws. Furthermore, Radix Lens won't be required since, according to our data, the humidity levels comply with ART operating requirements.

### **Successfully combining real and virtual world**

Maxillofacial surgery, which involves bone, muscle and skin operation, requires high definition anatomically accurate 3D models, something achievable applying Amira's segmentation algorithms. Which, in exchange, requires a better GPU used in this research: Quadro K5000 (4 GB) rather than Quadro FX4800 (1.5 GB) used in Chen et al. And last but not least, not only a change of the focal length is important as Chen et al suggest but this paper suggests the importance of using Active stereoscopy against Passive stereoscopy to provide an immersion effect, to be able to focus both the virtual objects with the real world.

### **Increase of Technology Readiness Level**

All in all, this research is the continuation of a previous group project in which the fundamental characteristics and functions were achieved and some of those components were validated in laboratory (TRL 3/4).

This group project concluded with some further work that needed to be developed in order to increase its TRL (Table 20).

TABLE 20 TRL INCREASE

Requirements	Results
Improve tracking accuracy	Improved by a 95%
Reliable registration process	Triangulation of anatomical points
Guarantee depth perception	Active stereopsis to the detriment of Passive
Dispense of Flystick and change to accurate tool	Measurement Tool implemented

All these enhancements have made possible to demonstrate this AR System in the hospital using a cadaver, which can be considered as a relevant environment, and therefore the TRL has jumped from 3 to TRL 6 (Figure 38) and therefore take Augmented Reality closer to be applied in complex surgeries.

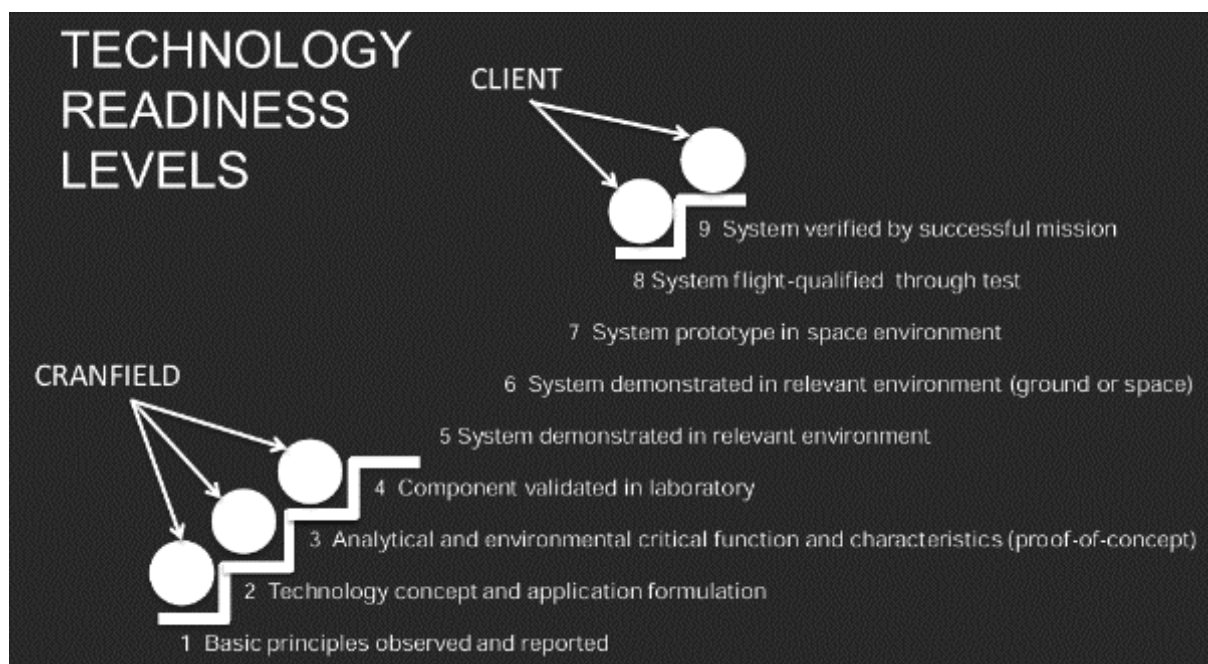


FIGURE 38 TECHNOLOGY READINESS LEVEL. SOURCE: CRANFIELD START UP WEEKEND

## 7 Conclusion and future work

During this project, variables that affect to the AR System performance have been identified and minimised with the tools available.

- By accurately calibrating each of the tools used, using the Measurement Tool and providing a reliable registration, the AR System allows the flexibility that final users where asking, user is allowed to select the anatomical points that are most easily identifiable in patient's body and register them in the real world. This patient registration process provides a translation in 3D model's size, rotation and position autonomously. Moreover, this is supported by minimum inaccuracies.

**Future work:** Although translation in the position is very accurate, rotation and size translation need further development.

- **Rotation:** Research on Unity3D's internal handling Quaternions to analyse how are they managed and if they comply with the algorithm being applied in Appendix 9.8.
  - **Scale of the 3D model:** Analysis of variables that could be affecting this malfunction: Field Of View and Unity3D's coordinate system.
- Inaccuracies of tracking have been minimised as much as possible with tools available. In that way, tracking performance has been enhanced by a 95% setting an accurate calibration of the eyes with the method described in section Room and tools calibration

**Future work:** Further minimise inaccuracies that still exist due to three reasons:

- **Time latency:** the frames are not displayed with the real time perspective. This is, at a specific time "t" the System displays the perspective of "t-1". Computing this time "t" was not inside the scope of this project due to its complexity. Yet, there's some information in our hand like, as shown in Appendix 9.9, DTrack2's time latency which is around 17 ms. This is something that could be negligible, the problem is that AR System is composed of 4 layers of software and each one of them adds its own latency. In order to solve this issue, there's a need to use DTrack2's SDK to connect Unity3D directly to the ATC.
- **ART's rotation description:** according to ART's technical appendix, rotation angles can show strange behaviour at certain orientations. In particular, for orientations close to +90 degrees, the other two angles can experience large odd-looking changes. Indeed, after reducing the influence of eyes calibration, still strange behaviours can be observed when applying certain rotations from the HMD. As can be seen in Appendix 9.13, is in the orientations closer to 90 degrees where more misalignment can be noticed.
- **Eyes calibration method:** a new method to calibrate user's eyes could be applied by creating a target with only one spherical marker and creating a 3D object inside Unity3D which will be attached to this spherical marker. If user eyes are not properly calibrated, he/she will see that the 3D object is misaligned. AR System will allow to set an offset in the axis of the Nvis target till the user sees both spheres overlaid when looking from any of the perspectives.

- Immersion effect has made a huge impact on how the user is capable to merge both virtual and real world.

**Future work:** Upgrade graphics card so that no graphics optimisation need to be applied.

- The system has successfully been deployed in a relevant environment, a cadaver lab with machinery and tools that will usually be used during a real operation. Indeed, it has been proved in this thesis that this System can be installed and used and therefore it has jumped into a higher TRL.

**Future work:** Keep increasing the TRL by deploying the system in the real environment (a real operating theatre) with a real patient.

I am confident that this ambitious and promising project will be continued, and that these further developments can be done and bring this Technology to the next level and eventually in a not-too-long future bring it into UK's operating theatres.

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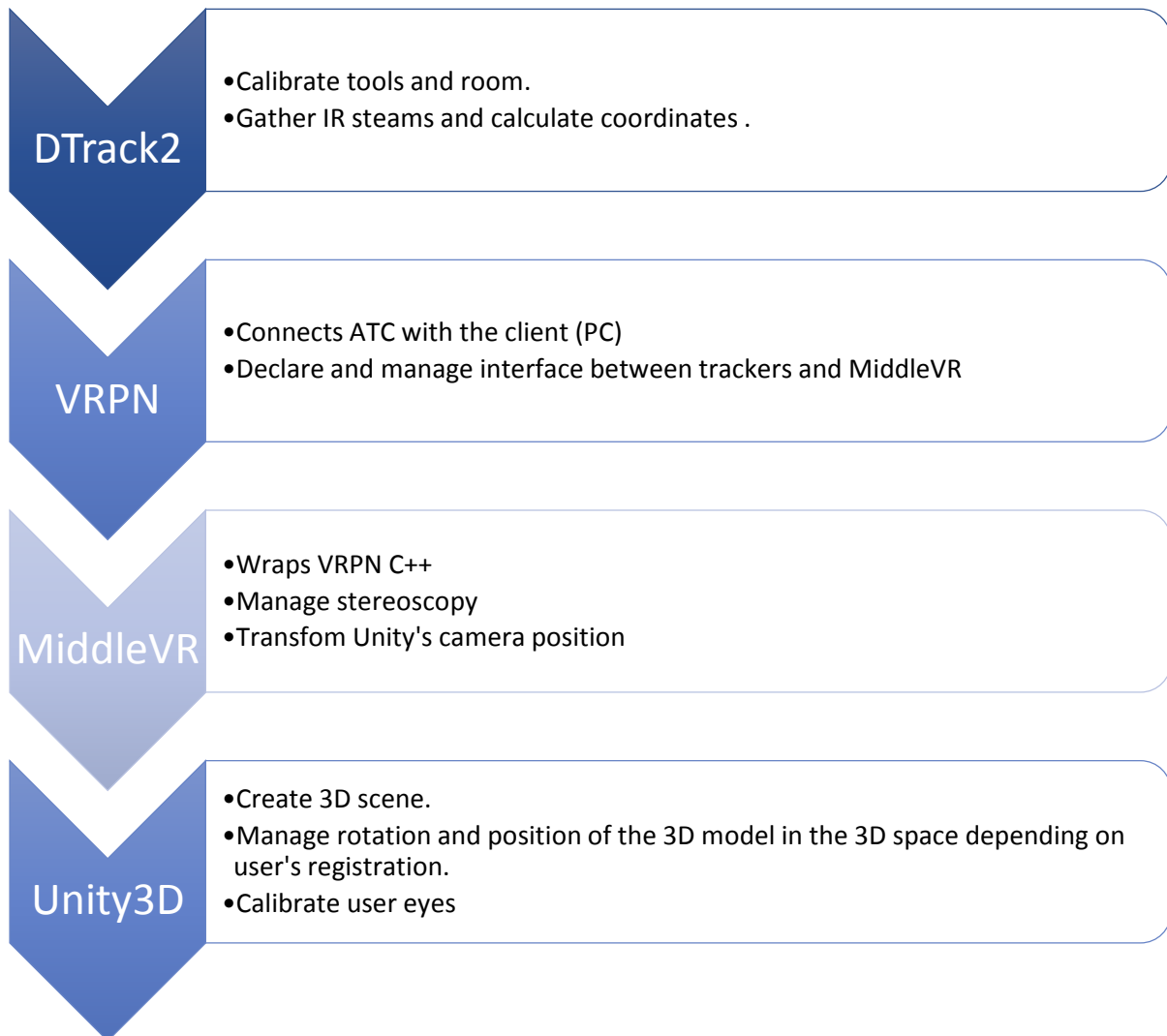
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## 9 Appendices

### 9.1 AR System Architecture

#### Augmented Reality System Architecture

##### Software



DTrack2 is used to control the tracking cameras as a frontend and backend software. The frontend is installed in the user's PC and the backend in the cameras' controller to perform all the calculations needed. Working in pair with DTrack2, VRPN is a server that establishes the connection protocol with TRACKPACK controller and sends the data to the client, MiddleVR, which is a middleware that allows to create the configuration of which devices to track: the FlyStick with its entire buttons and the HMD tracked tree target. The middleware is also responsible of translating the world coordinates (coming from the camera) to virtual coordinates (Unity scene).

A scene is created in Unity with the imported 3D model, a camera (that will be the HMD's perspective) and the different programmed scripts.

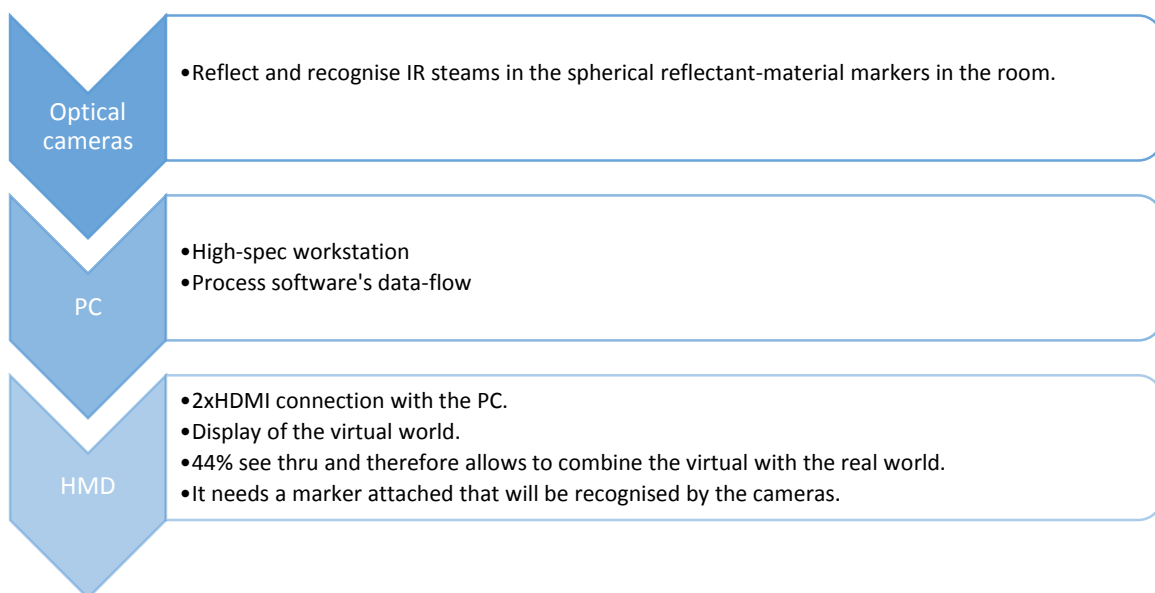
The scripts inside Unity will be programmed with the different actions for the model: registration, rotation, scale and speech recognition. Unity is directly connected to MiddleVR by importing its library and methods.

### Hardware

Eight TRACKPACK cameras are positioned around the workspace. Infrared flashes are sent out and the reflections are recorded in order to create a grayscale image that will identify the bodies targeted, its changes of position and orientation.

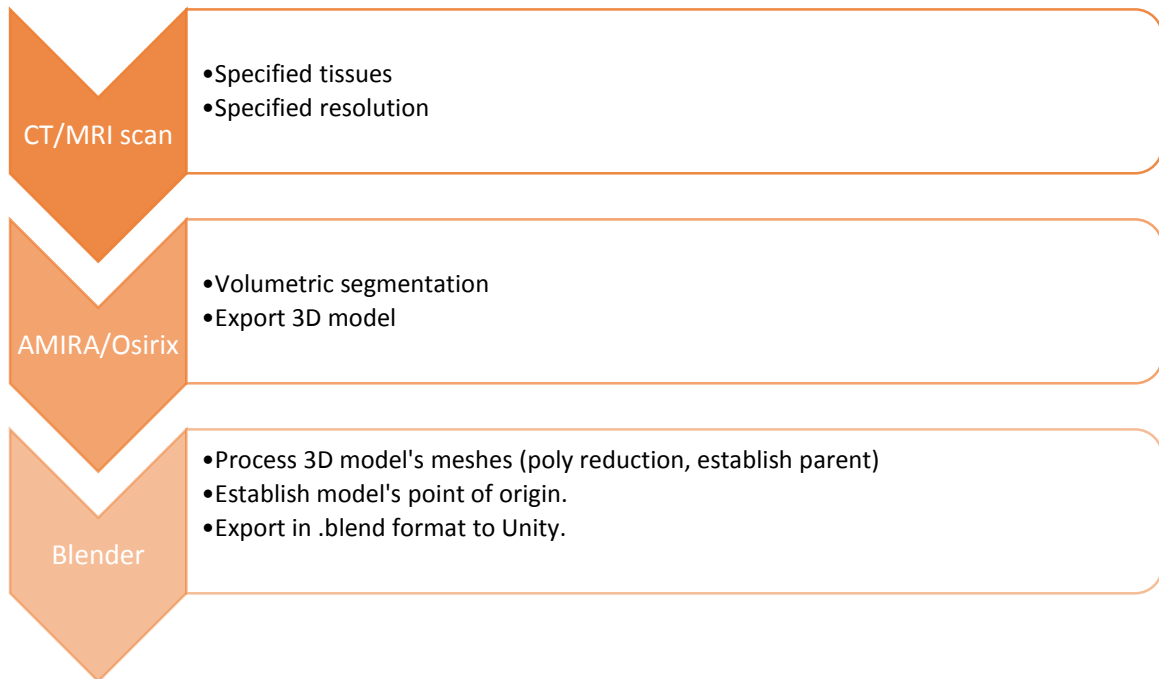
When the software is launched, the PC processes the image and sends it to the HMD. DTrack2 calculates the coordinates of the Surgeon and the Patient received from the ART system and sends that information to the PC. Using the registered coordinates of the Patient, the computer will overlay the 3D image and, in real time, will change the representation of the 3D model depending on the coordinates of the Surgeon. The employed head-mounted display is nVisor ST50, 44% see-through glasses that permit to see both the reality and virtual at the same time. In this way the reality is directly seen by the user, not through a camera. It provides an outstanding definition of the display. Its dual HDMI input allows that a stereoscopic vision can be provided.

Placed on top of the HMD, the tree target provided by ART contains 5 spherical markers that allow to be tracked with six degree of freedom.



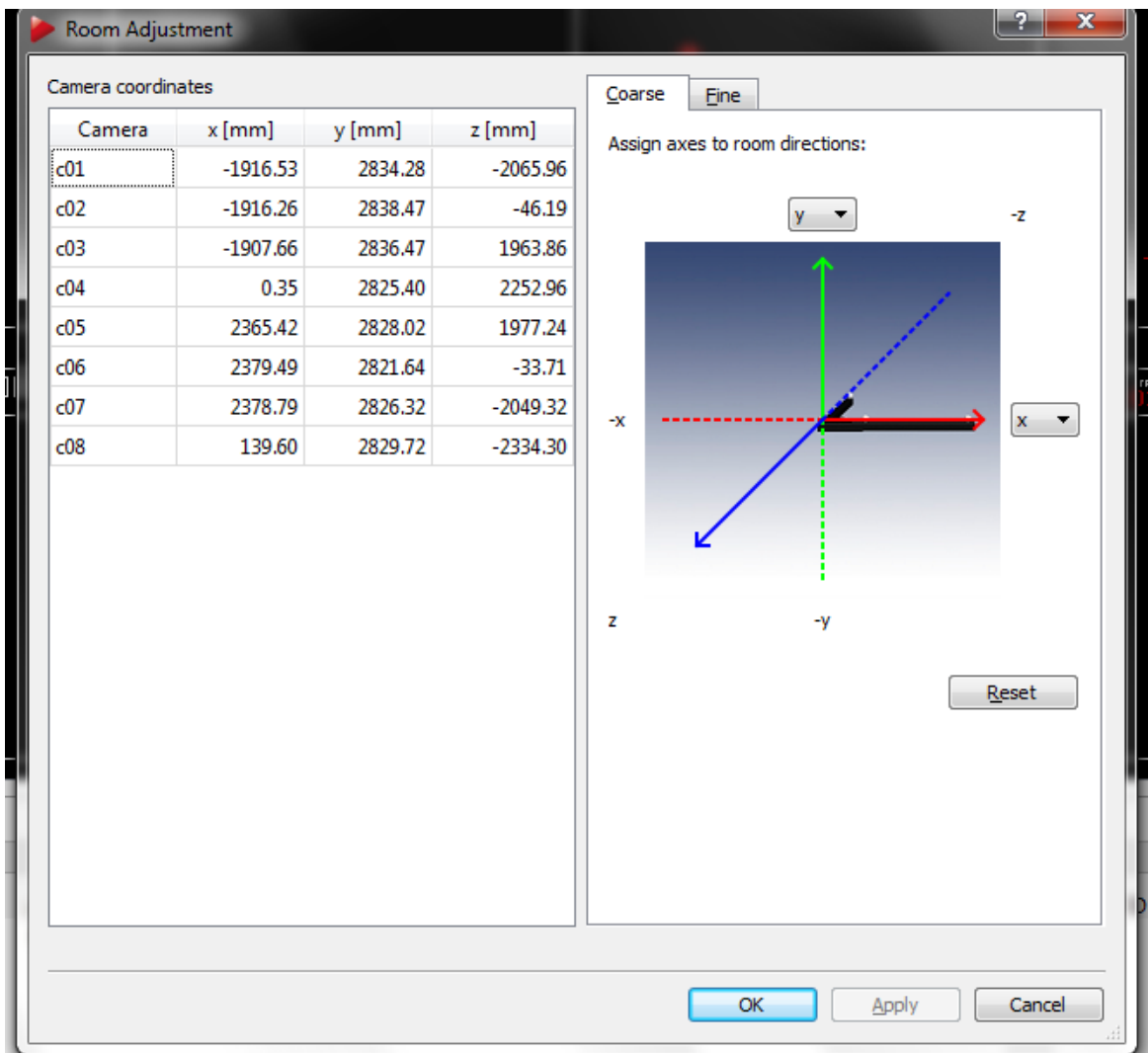
### 3D Model Creation

The process starts by creating the 3D model that will be imported to the system. The user imports patient's 2D scans (with the selected resolution and parts of the body) to the workstation. With Osirix or Amira, the surgeon builds the 3D model of the patient. Later, some changes will be applied to this 3D model in Blender and will finally import the 3D model into the software developed using Unity3D.



### 9.2 Settings from DTrack2

X/Y calibration tool facing the computer as in the lab. And with the patient's bed as if it was the table. After calibration applied: Calibration>room adjustment so that it coincides with Unity's left-handed coordinate system.



Body Administration>Number of Bodies>Write names and calibrate

After bodies calibration, Calibration>Body Adjustment. Mount the SX60 target in the HMD and while facing the front (-Z axis): Due to Room(origin in marker).

Measure distance from marker to actual eyes position, change that difference from code.

Calibration>Body Adjustment: Calibrate the Measurement Tool with the same rotation as the initial 3D model rotation.

To register the position of the patient, face the spheres opposite to the patient.

### 9.3 Settings from MiddleVR HMD

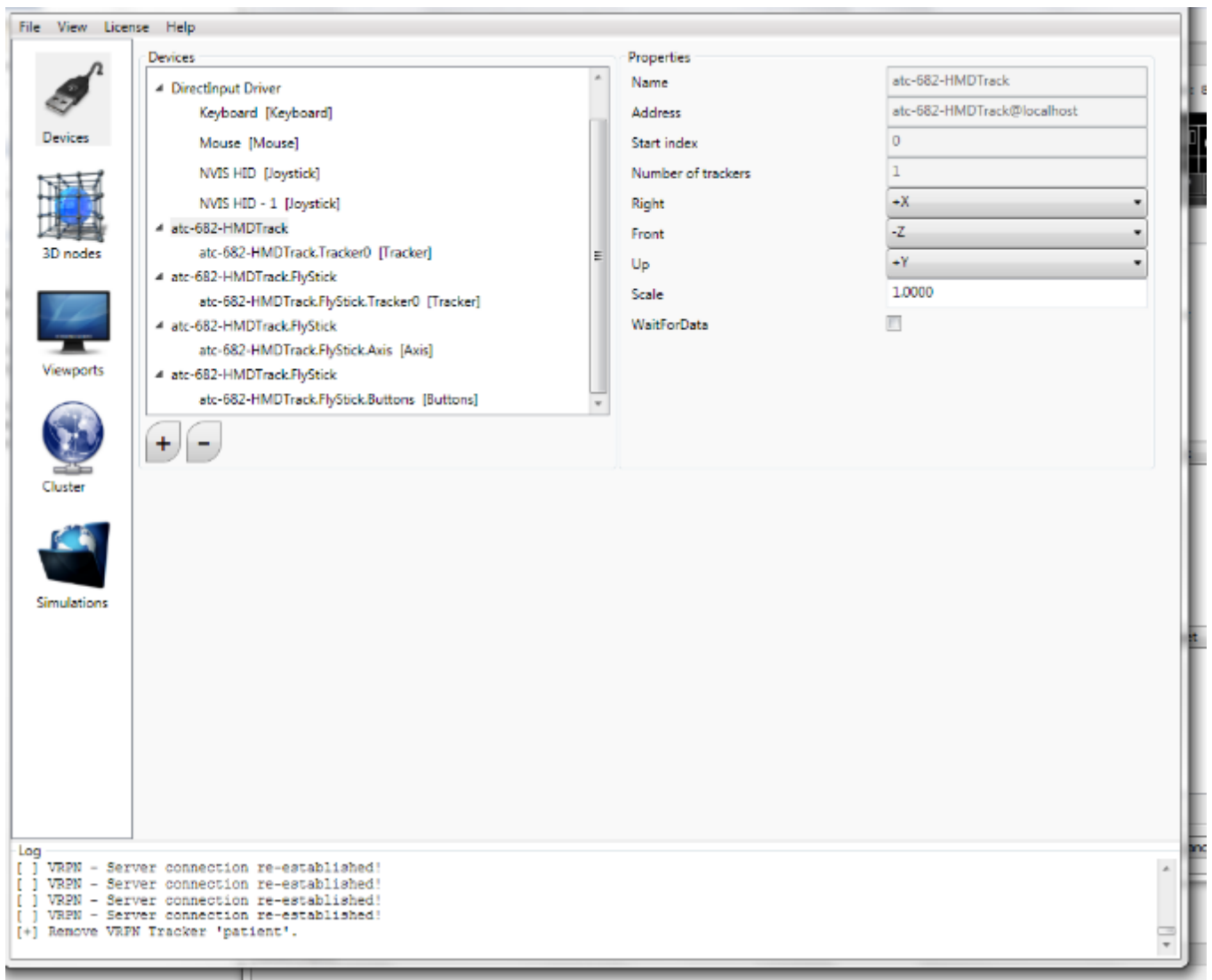


FIGURE 39 HMD TRACKER SETUP



## Flystick

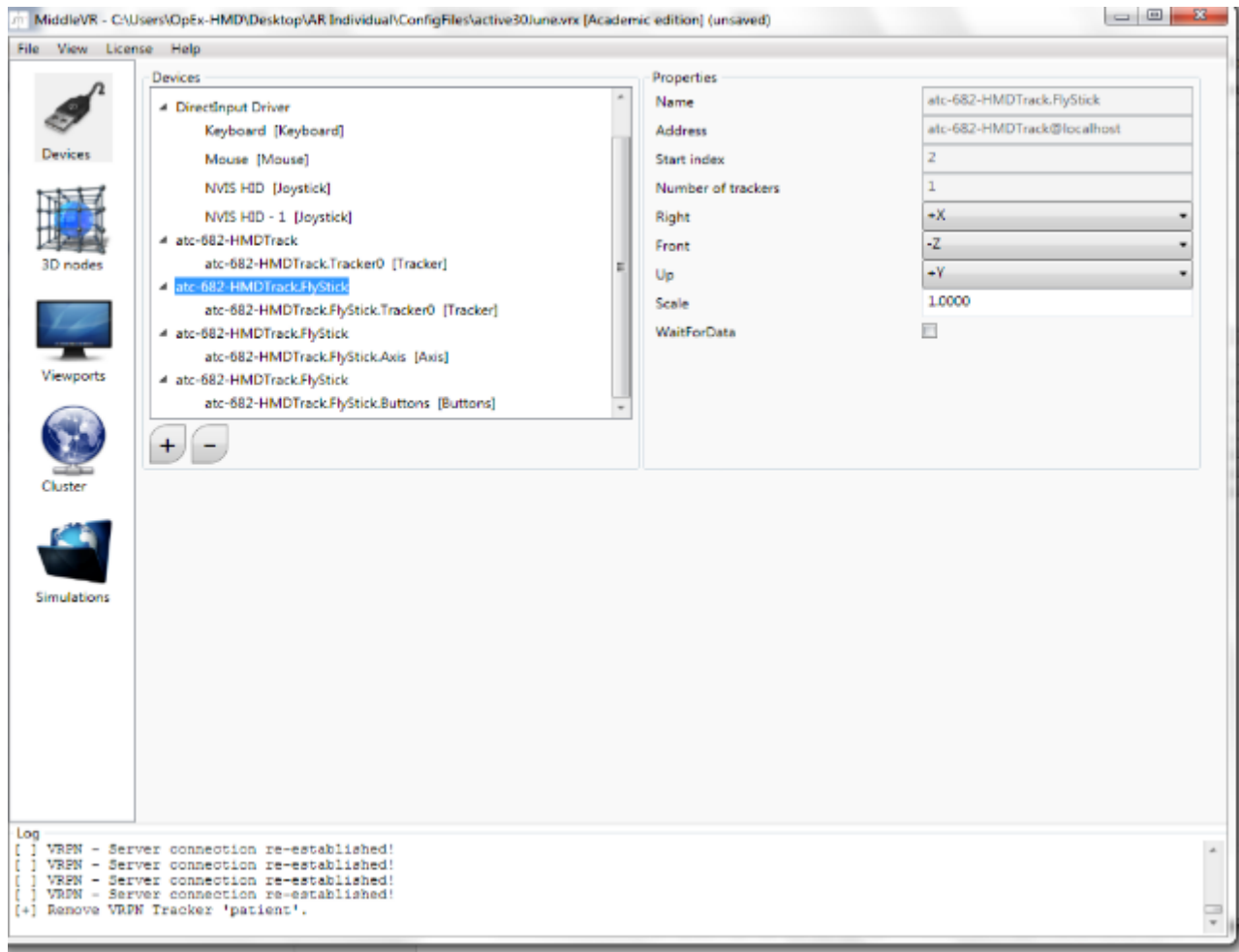


FIGURE 40 MT TRACKER SETUP

## 3D Nodes settings

Declare two cameras, FOV 32, change IPD from code.

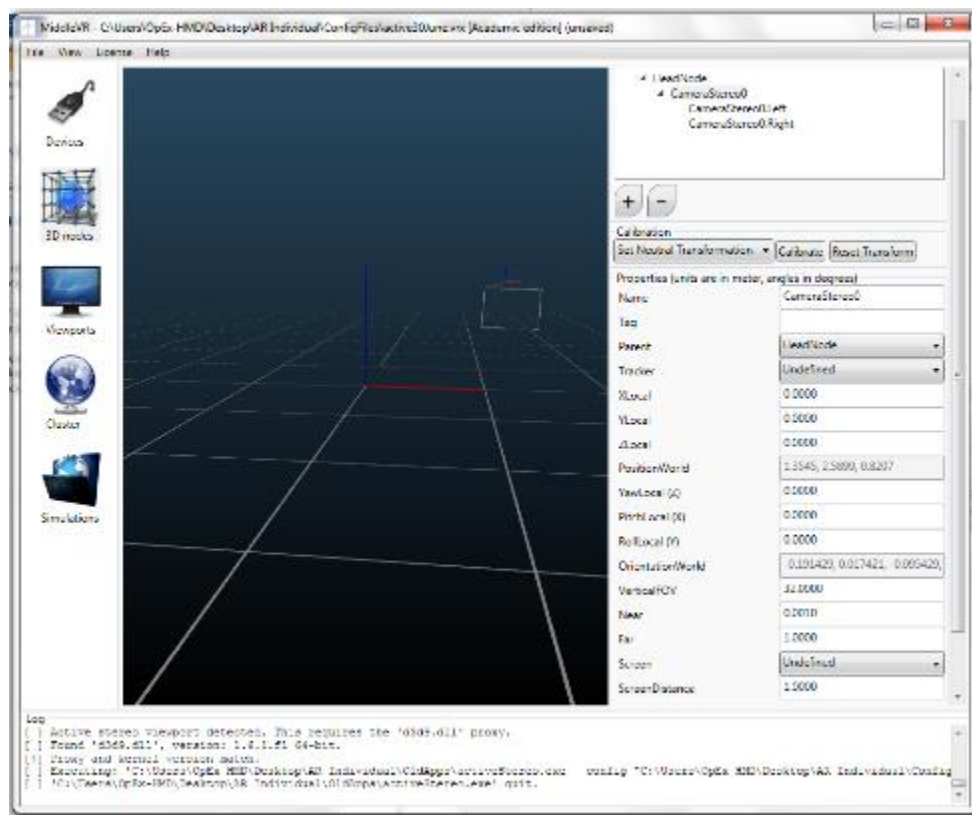


FIGURE 41 DECLARE TWO CAMERAS, FOV 32.

# Active Stereoscopy

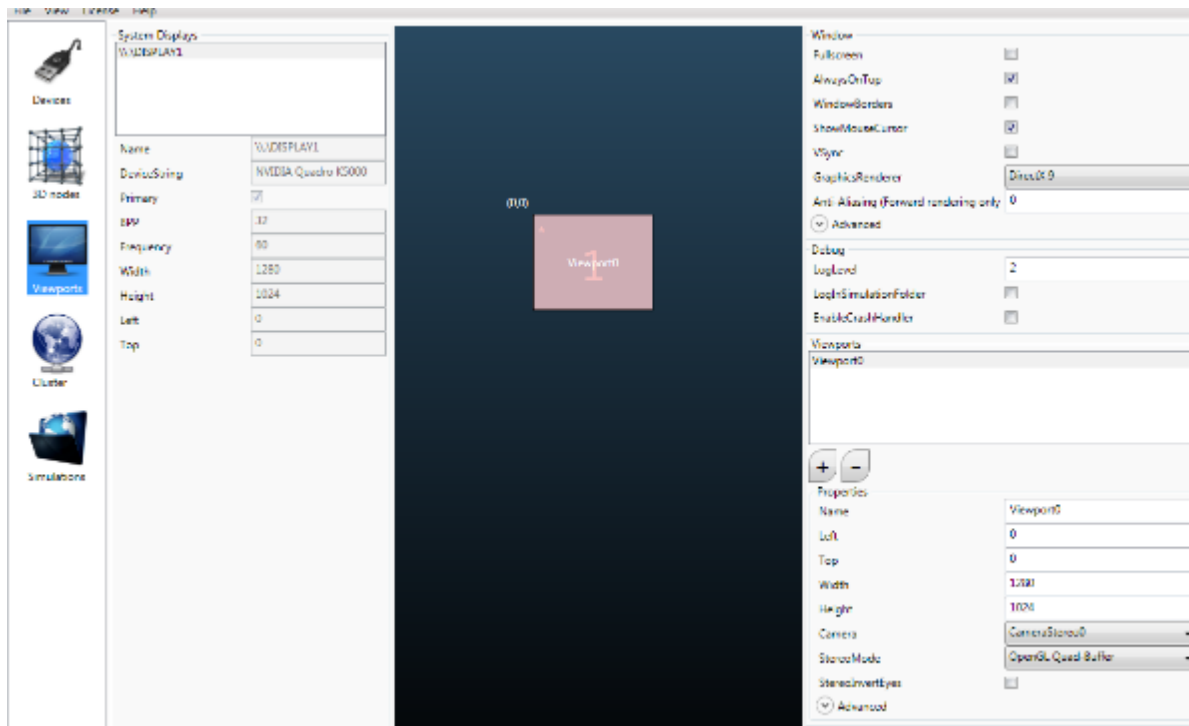


FIGURE 42 ACTIVE STEREOSCOPY SETUP

# Passive Stereoscopy

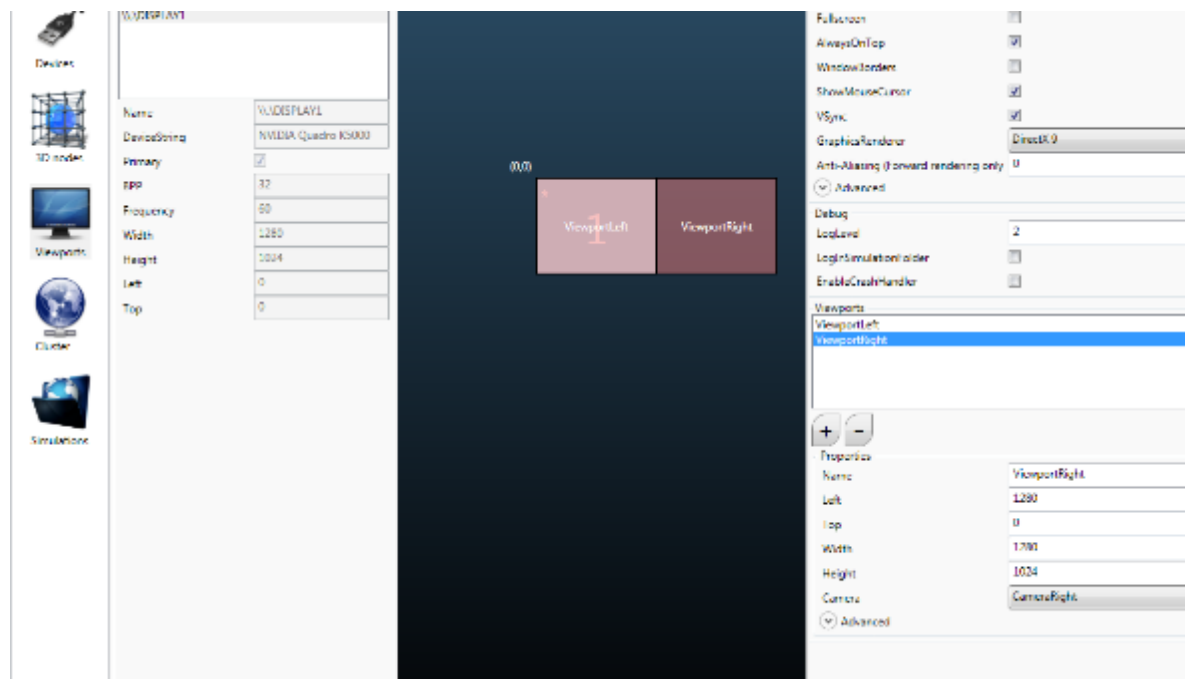


FIGURE 43 PASSIVE STEREOSCOPY SETUP

## 9.4 Checklist before operation trial

- Code to track both new targets
- Code to register when keyboard(Enter==Clicked)
- Active vs Passive stereoscopy
- Measure distance from HMD's case to actual position of the eyes.
- Review how to change the PoO of the 3D model from Blender.
- Use Cinema4D to do that and the change of size (put that it is cm)  
<http://docs.unity3d.com/Manual/HOWTO-ImportObjectCinema4D.html>
- All the interactions using the FlyStick. Rather than zoom in zoom out use change tissue.
- Code to implement Mauro's equations.
- Implement change of the calibration of the tracker for Surgeon to change the position to his actual eyes.
- Check room coordinates setup!
- Change flash intensity
- Implement different IPD for me, Sam and Surgeon.
- Prepare questionnaire about Active vs Passive, registration accuracy, tracking accuracy, time delay.
- Calibrate new HMD target
- Calibrate Measurement Tool
- Installation procedure.
- Noise level measurer, humidity level measurer, light environment measurer.
- Look at the whole flow: Volume rendering of Surgeon's CT scan.
- Change lightning conditions (Measure it with any dispositive?)
- Possibility of looking at the real operation?
  - Gather timings.
  - When does Surgeon need to look at the 3D scan.
  - Gather list of most common words
  - Bring software to check sound levels.
  - Humidity might affect tracking:
    - Humidity 5-50% non-condensing.
    - Ask Francisco if he has any humidity tester.
- Due to radiation problems, the minimum distance from the cameras to the users has to be of 20 cm if higher than an hour exposure.
- Measure range of movement around patient (is it necessary to use ART or do we need to track a smaller range?).

### I. **Import model to Unity3D**

#### **Blender**

- Import 3D model
- Change to metric units, cm scale.
- Select the 3D model.
- Change rotation to 0,0,0.
- Inside object mode: Cursor to anatomical point that will act as PoO
- Ctrl+Alt+C (Origin to 3D cursor)
- Change location to 0,0,0
- File>export obj
- Save inside Unity project>Assets

## Unity

- Change scale of 3D model to 0.001
- Create three 3D object>sphere as child of the 3D model
- Change material so colour can be selected.
- Position one of them in the same coordinates as PoO
- Place the other two in the selected anatomical points.
- Look from x,y,z perspective to be able to accurately place them in the desired anatomical point.
- Tag each one of the spheres with the selected name (being A always the PoO sphere).
- Create three 3D text objects as child of the 3DM
- Place them next to it but not overlaid on it.
- Tag them with their respective names.
- Change Quality Settings between Fastest to Fantastic in Edit>Project Settings>Quality.

## 9.5 Checklist during operation trial

### 1. REAL OPERATION-25<sup>TH</sup> AUGUST

- Gather timings, i.e. when does Surgeon need to look at the 3D scan.
  - Ll** Gather list of common words
  - Ll** Check sound level.
  - Check humidity conditions and if it condenses.
  - Plan where to put Optical cameras (at least 20 cm due to radiation exposure).
  - Possibility of features to be included in the system
- 
- 

### 2. INSTALLATION AND FIRST TRIALS-25<sup>TH</sup> AUGUST (AROUND 2 HOURS)-

- Ll** Change VRPN to track the new system
  - Ll** Check room coordinate system fits with Unity's coordinate system
  - Ll** Change code to track new VRPN variables
- 
- 

### 3. SIMULATION TEST -26<sup>TH</sup> AUGUST STARTING AROUND 9:00/10:00-13:00

- Follow process of volume rendering Surgeon's CT scan using Amira.
- Ll** Import the 3D model into Unity and create the executable file
- Ll** Try new HMD custom passive tracker.
- Compare Active vs Passive stereoscopy
- Surgeon's eyes position calibration process
- Measure registration accuracy (actual distance of the 3D model against distance pointed by user)
- Measure angular accuracy
- Measure size registration
- Measure time delay
- Measure tracking accuracy
- Measure Surgeon's range of movement around patient
- Check proper brightness level
- Take pictures and video
- Feedback

## 9.6 VRPN Configuration file

```
Advanced Realtime Tracking GmbH (http://www.ar-tracking.de) DTrack client
#
# creates as many vrpn_Tracker as there are bodies or Flysticks, starting with the bodies
# creates 2 analogs per Flystick
# creates 8 buttons per Flystick
#
# NOTE: when using DTrack's older output format for Flystick data ('6df'), the numbering
#   of Flystick buttons differs from DTrack documentation (for compatibility with
#   older vrpn releases)
#
# Arguments:
# char name_of_this_device[]
# int  udp_port              (DTrack sends data to this UDP port)
#
# Optional arguments:
# float time_to_reach_joy      (in seconds; see below)
# int  number_of_bodies, number_of_flysticks (fixed numbers of bodies and Flysticks)
# int  renumbered_ids[]       (vrpn_Tracker IDs of bodies and Flysticks)
# char "3d"                   (activates 3dof marker output if available;
#                             always last argument if "-" is not present)
# char "-."                   (activates tracing; always last argument)
#
# NOTE: time_to_reach_joy is the time needed to reach the maximum value (1.0 or -1.0) of the
#   joystick of older 'Flystick' devices when the corresponding button is pressed
#   (one of the last buttons amongst the 8); not necessary for newer 'Flystick2' devices
#   with its analog joystick
#
# NOTE: if fixed numbers of bodies and Flysticks should be used, both arguments
#   number_of_bodies and number_of_flysticks have to be set
#
# NOTE: renumbering of tracker IDs is only possible, if fixed numbers of bodies and
#   Flysticks are set; there has to be an argument present for each body/Flystick

#vrpn_Tracker_DTrack DTrack 5000
#vrpn_Tracker_DTrack DTrack 5000 -
#vrpn_Tracker_DTrack DTrack 5000 3d
#vrpn_Tracker_DTrack DTrack 5000 3d -
#vrpn_Tracker_DTrack DTrack 5000 0.5
#vrpn_Tracker_DTrack DTrack 5000 0.5 2 2
#vrpn_Tracker_DTrack DTrack 5000 0.5 2 2 2 1 0 3
#vrpn_Tracker_DTrack DTrack 5000 0.5 2 2 2 1 0 3 3d -
#vrpn_Tracker_DTrack atc-682-HMDTrack 5000 0.0 2 1 3d – (Usual setting in the lab)
#vrpn_Tracker_DTrack atc-301422004 5000 0.0 2 1 3d – (Used for first hospital trial)
vrpn_Tracker_DTrack atc-301422026 5000 0.0 3 0 3d -(Used for second hospital trial)
```

## 9.7 Operating theatre analysis

### Surgical layout:

- Most common words: Numbers, surgical vocabulary but also normal words.
- Machines surrounding the patient:
  - 2 pc
  - 3 Light sources directly facing patient's body, not the surgeon.
  - Endoscopy machine.
  - Machine to cut with anode and cathode Cavalier.
- Room: operating theatre with a 6x4 meters
- Normal general lightning conditions.
- Power sockets coming from rooftop.
- Optical cameras could be installed in the rooftop.
- HMD's wire should come from the rooftop (people walks around surgeon's limited space).

### Nose operation

- Started at 16:50
- Patient couldn't breathe correctly due to nose misalignment.
- Operation consisted on correcting that deviation.
  - Points drawn in the nose to mark the area where to pound the Howarth's spatula in order to break the bones.
  - Break the nose bones in parts till it is flexible enough to make the correction.
  - Correction of the deviation, made with surgeon's fingers.
  - Positioning Howarth's tool to compare the alignment against the nose
    - Possibility of providing this information from the glasses (drawing a parallel line to the nose in the z axis).
  - Cutting lower part of the nose to access inner cartilage and extract some pieces of it.
  - Then sew them back again with needles.
    - This is an example of a tool that could be tracked
  - Local anaesthesia is applied in various incisions (3 in this case), since it covers a little area. The amount applied ranges 5-10 ml, depending on a number of variables, the anaesthetist will chose the amount
- Six people around the bed and four more in the rest of the room (surgeon, anaesthetist, assistants, nurses...).
  - AR system should provide different information for each different role while they are looking at the patient. Only relevant data. No distraction.
- Sound level: 50/60 db (normal conversation). However due to wearing masks, I don't see the potential appliance of speech recognition.
- Consider gesture recognition by Kinect or Leap Motion.
- Movements of the surgeon around an area of 1x1 meters
  - Small range of movements with 10/15 seating, standing up movements.
  - Head rotation, flexing movements that can be affected by the weight of the HMD.
- At the end of the operation, anaesthetist and rest of assistants will write a report about the operation which take 5 to 10 minutes to complete. Surgeon doesn't need to complete any form at this stage.
- The surgeon successfully completed the operation at 17:47.



- Assistants will stay completing the process, recovering consciousness.

#### Surgical planning using Amira

- Surgeon spends the time it takes to prepare the next patient to be operated; on planning a 2 weeks ahead procedure.
- Female, 70 years old with a tumour in the cheek.
- Ask assistant to send the CT/MRI scans to surgeon's personal computer.
- Move to the coffee room close to the operating theatre where he will spend the remaining minutes till the next operation starts.
- Start Amira process at 18:25
  1. Open CT/MRI scans from Amira.
  2. Files were named in a format that makes it difficult to open directly from Amira.
  3. Open CT/MRI scans from OsiriX
    - a. Interface will display all the CT layers with the thickness and position in the x,y,z axes from different views: Axial, Sagittal, Coronal.
    - b. Export selected layers to Amira.
  4. Open selected CT/MRI scans.
  5. Add a picture of the patient as a reference to segment the tissues.
  6. Segment out the bone.
    - a. Apply threshold algorithm in the x/z plane.
    - b. Select layers that contain the bone
  7. Compactify to reduce polycount by a 39% (now is 1.3 M polygons)
  8. Create ISOSurface. A surface that represents points of a constant value (e.g. pressure, temperature, velocity, density) within a [volume](#) of space; in other words, it is a [level set](#) of a continuous function whose [domain](#) is 3D-space.
  9. Extract Isosurface, which deals with the problem of generating the surface (or, more generally, the point set) defined by the preimage of a scalar function of several variables.
  10. Remove polygons that are not necessary
  11. Balloon segmentation applied to select tumour:
    - a. Surgeon chooses pixels that are similar from Axial axis then drag to choose other pixels
    - b. Do the same for Sagittal and Coronal axis.
    - c. Look at the region selected in the 3D space.
    - d. Wrap the rest of the pixels, ending up in a surface reconstruction of the tumour.
- Finish at 18:40, next operation ready to start.

#### Palate tumour

- Starts at 18:45
- Male, 21 years old with a non-aggressive tumour in the palate
- After CT/MRI preoperative planning, it was decided to only perform soft tissue removal.
- Cutting around tumour with electrical tool that burns at the same time as cuts.
- Arrive to the roof of the mouth which is recognised by touching the inner part of the palate.
- Check vessels that will encounter during the operation.
- Check if the bone has been dented by the tumour.

- Checklist could be something useful to be included <http://www.amazon.com/The-Checklist-Manifesto-Things-Right/dp/0312430000>.
- At 19:00 Tumour is entirely extracted.
- Bone behind was not dented therefore no need to remove bone.
- In 4/6 weeks it will be healed.
- 19:05 Sewing up the tissues.
- Cream makes a reaction and put between the dental appliance and the tissue.
- The dental appliance was customised for the patient with a structure that considers the tumour has been already removed.
- 19:15 finishes the procedure.

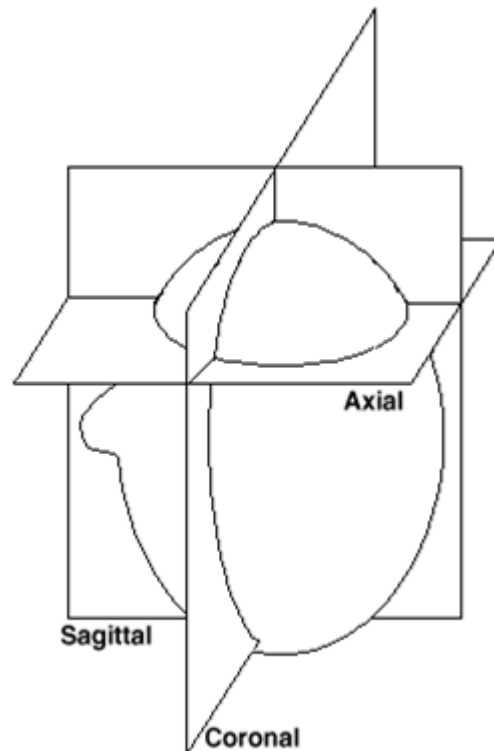


FIGURE 44 CORONAL, SAGITTAL AND AXIAL VIEW

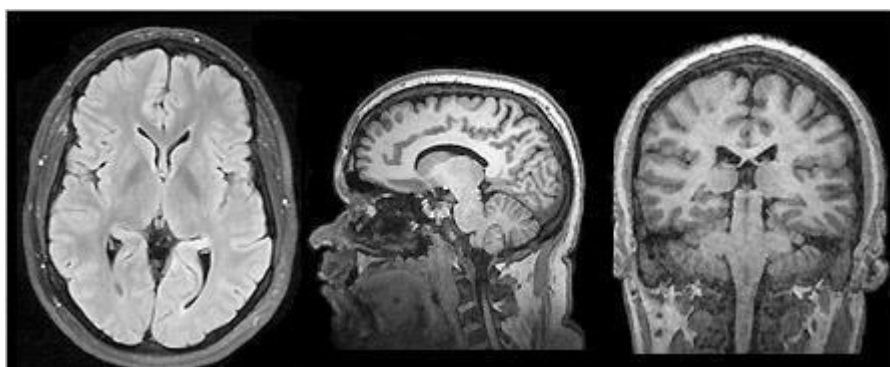


FIGURE 45 MRI SCAN. LEFT TO RIGHT: AXIAL, SAGITTAL AND CORONAL

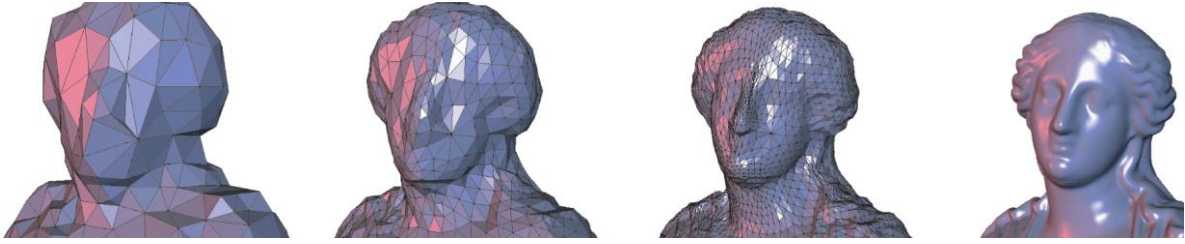


FIGURE 46 ISOIMAGE EXTRACTION

## 9.8 Rotation algorithm

### First Iteration

$$\theta = \tan^{-1}\left(\frac{-x_B}{y_B}\right)$$

Rotate around z of  $-\theta$

$$\beta = \tan^{-1}\left(\frac{z_B}{\sqrt{x_B^2 + y_B^2}}\right)$$

Rotate around x of  $-\beta$

$$\psi = \tan^{-1}\left(\frac{x_C \cdot \cos(\theta) + y_C \cdot \sin(\theta)}{z_C \cdot \cos(\theta) - y_C \cdot \sin(\theta) + x_C \cdot \sin(\theta)}\right)$$

Rotate around y of  $-\psi$

Using  $360^\circ$  arctangent functions.

### Second iteration:

Points of the model in reference space, after transformation 1:  $x_B, y_B, z_B, z_C, y_C, z_C$  Points of the patient in rotated frame of reference:  $x'''_B, y'''_B, z'''_B, z'''_C, y'''_C, z'''_C$

First calculation of these coefficients:

$$\Gamma = \frac{x'''_C - \frac{x'''_B}{y_B} \cdot y_C}{z_C}$$

$$\Lambda = \frac{z'''_C - \frac{z'''_B}{y_B} \cdot y_C}{z_C}$$

$$\Xi = \frac{y'''_B}{y_B}$$

Afterwards, calculation of:

$$\cos(\theta) = J \quad \cos(\beta) = L \quad \cos(\psi) = N \quad \sin(\theta) = K \quad \sin(\beta) = M \quad \sin(\psi) = O$$

As:

$$J = \frac{\Xi}{\Lambda} \cdot N$$

$$M = \frac{y_C \cdot \frac{y_B'''}{y_B} - y_C'''}{\Lambda z_C}$$

$$L = \frac{\Lambda z_C}{N}$$

$$K = \frac{\left( -\frac{x_B'''}{y_B} + J \cdot M \cdot O \right)}{N}$$

$$N = \sqrt{\frac{\frac{x_B'''}{y_B} \cdot \frac{\Gamma}{\Lambda} + \frac{z_B'''}{y_B}}{M \cdot \frac{\Xi}{\Lambda} \cdot \left( 1 + \frac{\Gamma^2}{\Lambda^2} \right)}}$$

$$O = \frac{\Gamma}{\Lambda} \cdot N$$

Finally find the angles as:

$$\theta = \text{atan2}(K, J)$$

$$\beta = \text{atan2}(M, L)$$

$$\psi = \text{atan2}(O, N)$$

Using 360° arctangent functions.

And implemented in the script:

TABLE 21 ROTATION ALGORITHM SCRIPT

```

public void firstDerivation(){
    float numerator;
    float divisor;
    //Rotate around Z of -θ
    rz = Mathf.Atan2(-B[0],B[1])* Mathf.Rad2Deg;

    //Rotate around X of -β
    divisor = Mathf.Pow (B [0],2) + Mathf.Pow (B [1],2);
    divisor=Mathf.Sqrt(divisor);
    rx= Mathf.Atan2(B[2],divisor)* Mathf.Rad2Deg;

    //Rotate around Y of -ψ
    numerator= C[0]*Mathf.Cos(rz)+C[1]*Mathf.Sin(rz);
    divisor = C [2] * Mathf.Cos (rx) - C [1] * Mathf.Cos (rz) * Mathf.Sin
    (rx) + C [0] * Mathf.Sin (rx) * Mathf.Sin (rz);
    ry = Mathf.Atan2(numerator,divisor)* Mathf.Rad2Deg;
}

public void secondDerivation(){
    //first part
    float numerator,divisor,coefficient0,coefficient1,coefficient2, aux;
    numerator = cMatrix [0] - ((bMatrix [0] / B [1]) * C [1]);

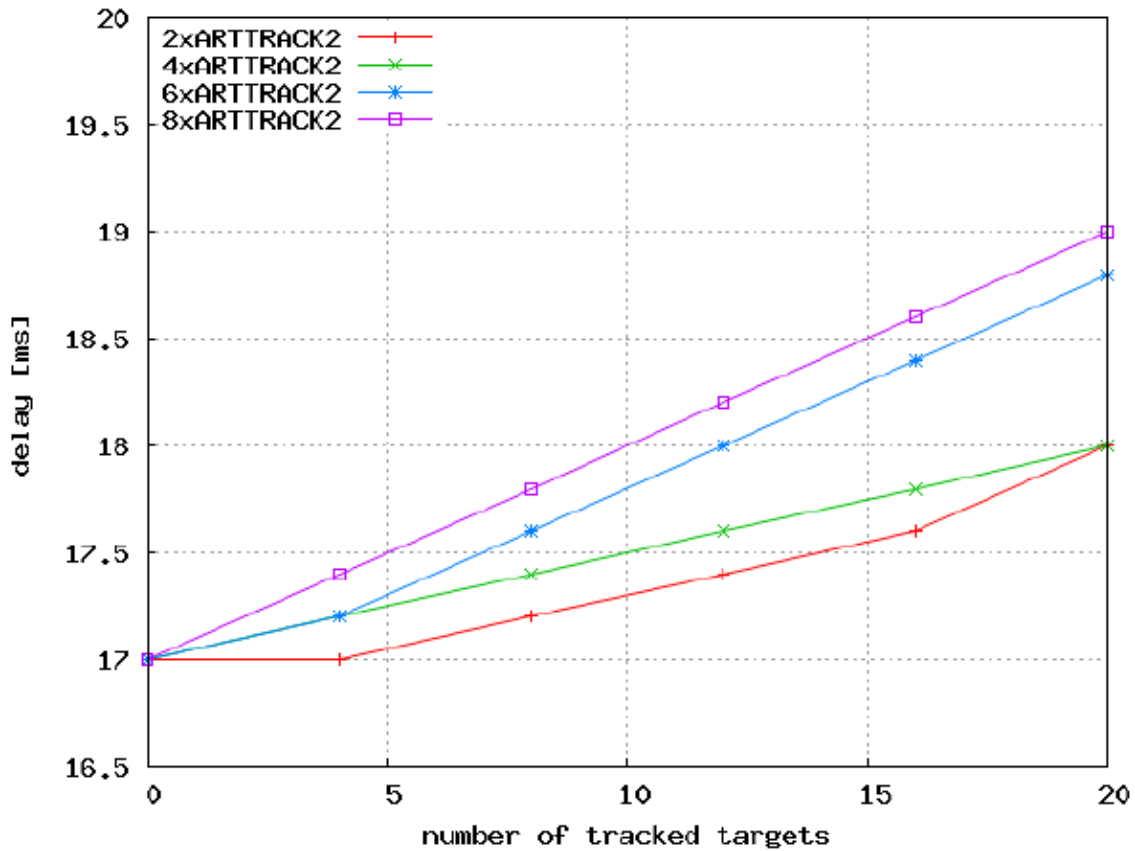
```

```

coefficient0 = numerator / C [2];
numerator = cMatrix [2] - ((bMatrix [2] / B [1]) * C [1]);
coefficient1 = numerator / C [2];
coefficient2 = bMatrix [1] / B [1];
//second part
float J,K,L,M,N,O;
M = (C [1] * bMatrix [1] / B [1]) - cMatrix [1];
numerator = bMatrix [0] / B [1] * coefficient0 / coefficient1 +
(bMatrix [2] / B [1]);
aux=Mathf.Pow (coefficient0,2)/Mathf.Pow (coefficient1,2);
divisor = M * coefficient2 / coefficient1 * (1 + aux);
N = Mathf.Sqrt (numerator / divisor);
O = coefficient0 / coefficient1 * N;
J = coefficient2 / coefficient1 * N;
L = coefficient1 / N;
numerator = (-1 * bMatrix [0] / B [1]) + J * M * O;
K = numerator / N;
//Find the rotation angles
rz2= Mathf.Atan2(K,J)* Mathf.Rad2Deg;
rx2= Mathf.Atan2(M,L)* Mathf.Rad2Deg;
ry2 = Mathf.Atan2 (O, N)* Mathf.Rad2Deg;
}

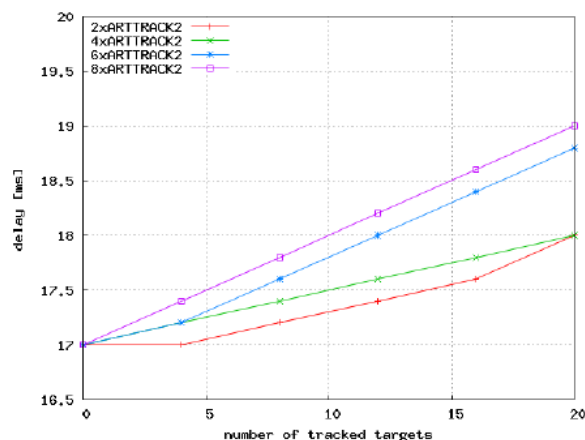
```

## 9.9 DTrack2 time latency



**Definition of the system latency:** the time delay between sending out the IR flash by the cameras and the availability of the tracking data at the Controller's Ethernet output. The latency is a function of the number of cameras, the number of targets, enabled or disabled 3DOF tracking and additional reflexes (e.g. single markers). Another dependency, which is quite important, can be found in the software version of *DTrack2* being used (here: v2.8.6). We recommend to always use the latest version in order to have the most recent features.

### ARTTRACK2



## 9.10 Hardware requirements

- **Workstation:**

- *Minimum specifications:*

- Operating System:
  - Windows XP/7, Linux kernel version 3.2+, MAC OS X 10.7+.
- Processor: @2GHz
- RAM Memory: 8GB
- Graphics Card: 1 GB memory and OpenGL/DirectX compatibility.

- *Recommended specifications:*

This software has been tested using Dell Precision T3610.

This 2013 workstation contains, among others, these components:

- Operating System: Windows 7
- Processor: Intel Xeon E5-1620 V2 @3.70 GHz
- RAM Memory: 16 GB
- Graphics Card: 4 GB NVIDIA QUADRO K5000

- **Markers:**

- Tree target composed of passive spherical markers attached to the HMD (page 17 in DTrack2 manual).
- Interaction devices (to allow input):
  - Measurement Tool provided by ART.
- Tracking system:
  - 8 ART cameras (4 cameras mean 2x1 meters).
  - ART Controller: Calculates the coordinates using the data coming from the ART cameras (page 171 in DTrack2 manual).

## 9.11 Blender process

For the first step of the user guide, it is mentioned that the surgeon needs to prepare the model in Blender before importing it in the software. The steps to change the origin and the meshes' name are explained as following:

1. Import the .wrl file of each anatomical parts and export as obj file one by one (this will make sure the model won't have holes in unity). Then import obj files.

2. Rename each mesh:



FIGURE 47 BLENDER: RENAME THE MESHES

3. Add color to each mesh
  - Select one object, select the material button and add new material.

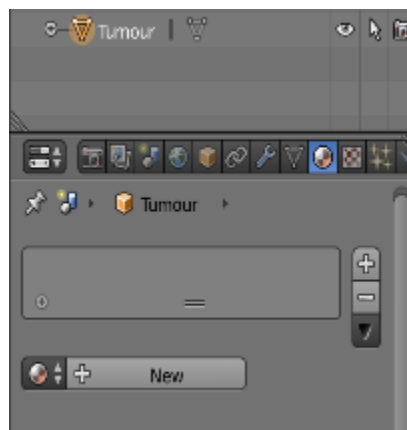


FIGURE 48 BLENDER: ADD A MATERIAL TO AN OBJECT

- Then change the material colour; you can also name the material as the same name of object.



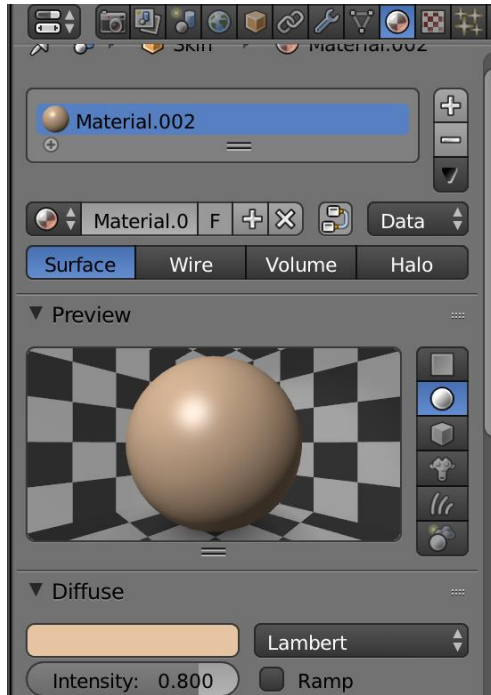


FIGURE 49 BLENDER: CHANGE MATERIAL COLOUR

- To set transparency, click the object button and click the check box of transparency under display. Then go to material, also click the transparency check box and set the alpha value.

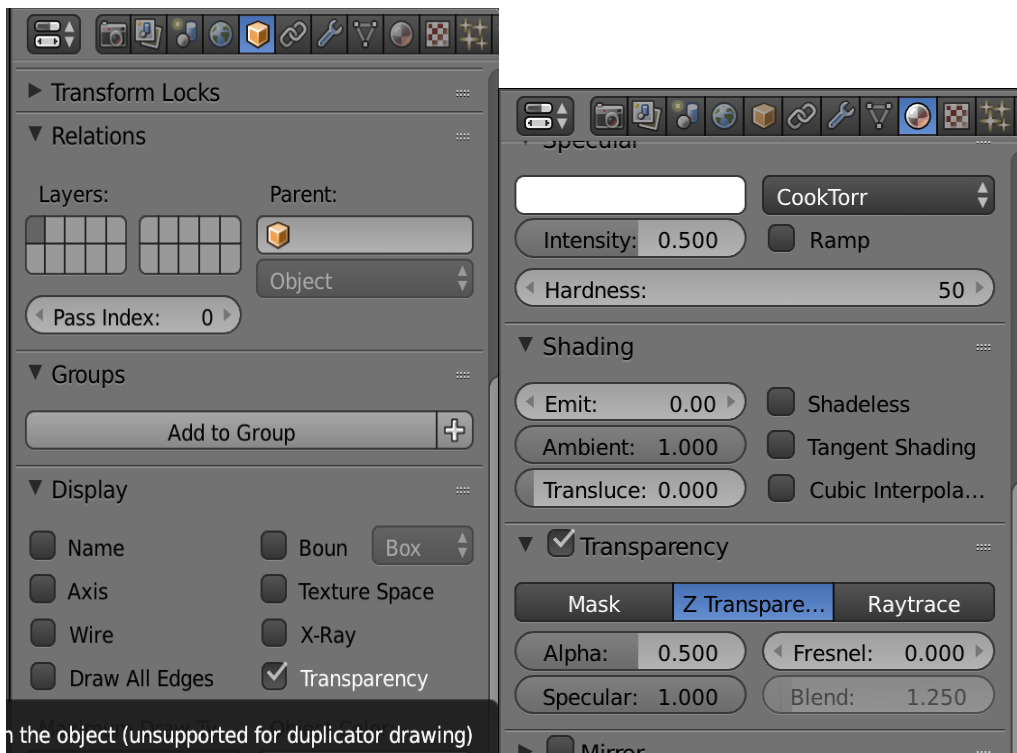


FIGURE 50 BLENDER: SET TRANSPARENCY

#### 4. Change the origin point

In this example, we want to set the origin point of the whole model as the geometry centre of skin.

- Click the triangle shape to drag to skin and drop to set parent, do the same to other parts.



FIGURE 51 - BLENDER: ADD CHILDREN TO A PARENT

- Click skin, then choose geometry to set the origin point as the geometry centre. Then set the location to (0,0,0) in properties.

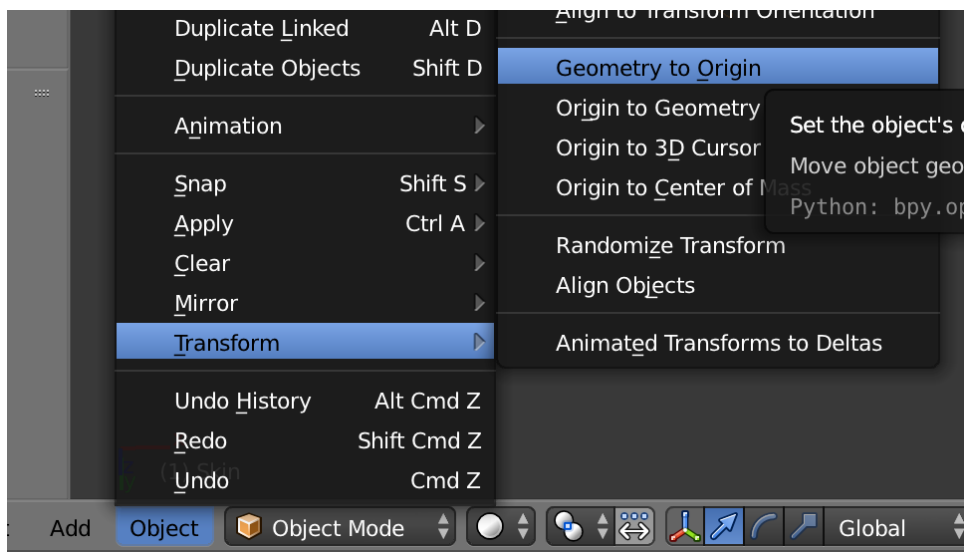


FIGURE 52 - BLENDER: CHANGE ORIGIN

To move the origin point to selected place, under edit mode, shift+s, and cursor to selected, then select the point. Then under object mode, shift+control+ alt+c, origin to 3D cursor. Then set the coordinates value in properties.

- Then move the model to the expected position, choose to clear parent and keep the transformation.

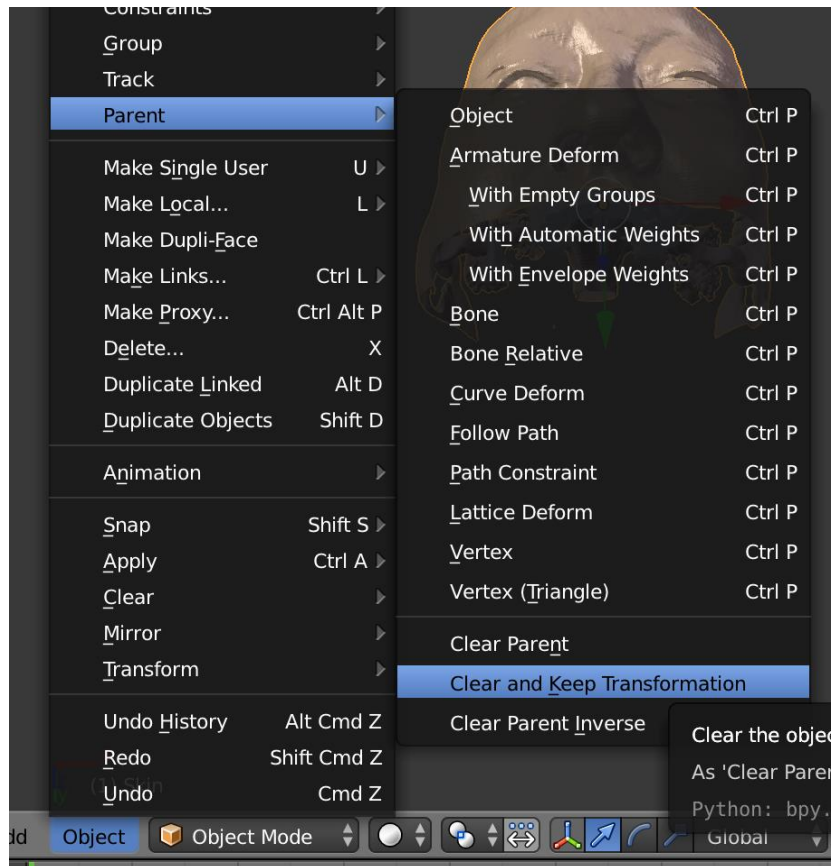


FIGURE 53 - BLENDER: SET THE NEW ORIGIN

5. Change number of polygons for each part

Add a new modifier and change the ratio value (in Unity, the object with more than 65534 triangles will be divided into small parts. If you look for higher resolution, its still ok to import larger files )

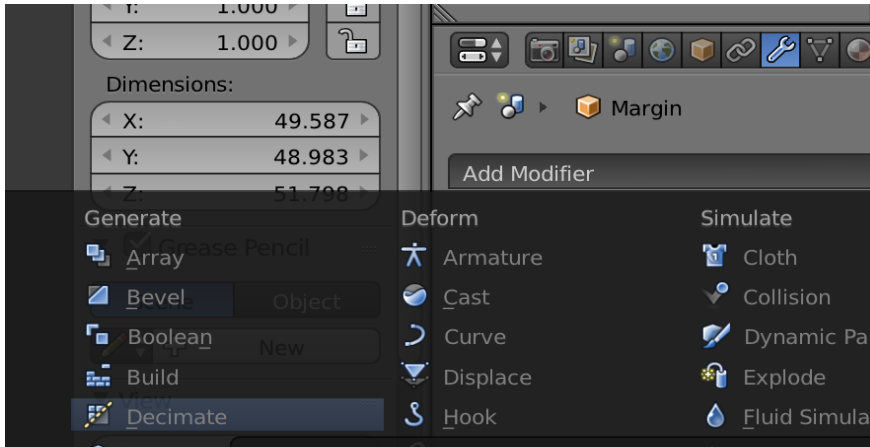


FIGURE 54 - BLENDER: CHANGE QUANTITY OF POLYGONS

6. Save the project as .blend file.

### 9.12 Size of 3D objects in Unity3D

When the 3D model of the patient is directly imported into Unity3D and the executable file is created and run, the glasses display it way bigger than its actual size. In order to check the transformation that Unity3D is applying to the scene and resulting in a bigger size than it should, a scene with only a 3D cube with scale x=1;y=1;z=1 as seen in Figure 55.

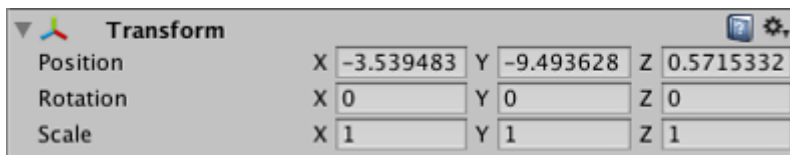


FIGURE 55 SCALE OF AN OBJECT (UNITY 3D EDITOR)

However, this cube was occupying the whole room and reducing its scale iteratively till 0.001 in each axis (which means reducing its scale by a thousand times), showed the proper measurements of the 3D object as seen in Figure 56. Therefore, from now on, it becomes proved that the patient's 3D scan's scale will need to be reduced in a thousand times for each axis.

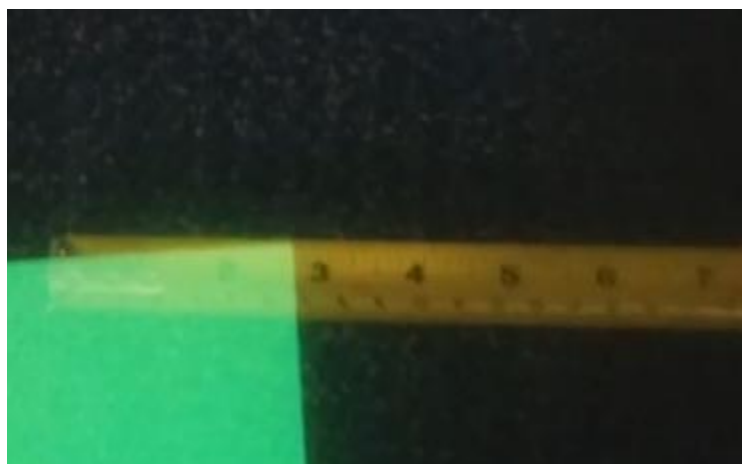


FIGURE 56 PROPER SIZE OF UNITY3D'S SCENE

### 9.13 Inaccuracies AR System

*“The accuracy of matching is really low when user changes the observing directions. When user rotates his head, the 3D model cannot stay on the patient’s head. The user must go back to previous position to make the 3D model match patient’s head. In real life practice, this could be really bad for surgeons who try to find a specific angle to operate the surgery. The surgeon cannot change the operating angle and match the 3D model at the same time. Then the 3D model will be useless or disturbing to the surgeons.”*

*“Every time when user rotates his head, the position changing captured by system is not the real position changing of the observing point.”*

*AR for complex surgeries (Group Project).*

In inaccuracies where tested and these are the results after the first and after the second AR System development.

**TABLE 23 TRACKING INACCURACIES AFTER FIRST DEVELOPMENT**

Axis of rotation	Distance	Angle	Error	Axis of error
X	50	-90	-10	y
	50	-45	-5	y
	30	-90	-10	y
	30	-45	-5	y
Y	30	-90	-6	x,
	30	-90	6	z
	30	-45	-3	x,
	30	-45	3	z
	50	-45	3	z
	60	180	14	z
	60	180	-4	x

**TABLE 22 INACCURACIES AFTER SECOND DEVELOPMENT**

Axis of rotation	Distance	Angle	Error	Axis of error
X	50	-90	1.1	y
	50	-45	-0.3	y
	30	-90	0.8	y
	30	-45	-0.4	y
Y	30	-90	-0.4	x,
	30	-90	0.3	z
	30	-45	-0.1	x,
	30	-45	0.1	z
	50	-45	0.1	z
	60	180	1.5	z
	60	180	-0.2	x

## VALIDATION QUESTIONNAIRE

### 1. GENERAL

1. Name:
2. Organisation
3. Role:
4. Years of experience

### 2. Quality

a. The registration is accurate:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

b. I find the image rendering:

1	2	3	4	5	6	7
Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional

c. The stability of the 3D image is:

1	2	3	4	5	6	7
Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional

d. The resolution of the HMD screen is:

1	2	3	4	5	6	7
Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional

e. I think the Head Mounted Display is ergonomic enough for my needs:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

### 3. Usefulness

a. The logic of the registration procedure is:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

b. In my opinion this prototype will provide added value:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

#### 4. Ease of use

a. In my opinion, it is easy to use:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

b. The overall system is user-friendly:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

c. It requires the minimum steps possible:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

d. I quickly learned how to use it:

1	2	3	4	5	6	7
---	---	---	---	---	---	---

Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree
-------------------	----------	-----------------	---------	--------------	-------	----------------

e. I easily remember how to use it:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

f. It will be easy for me to train other people:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

## 5. Satisfaction

a. Does the system answer to your needs:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

b. It works the way I expected:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

c. I would recommend it to other doctors:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

1. If there are other deficiencies or weakness please describe briefly

.....  
 .....



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2. Suggest possible improvements

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9.15 Questionnaire expert AR

**VALIDATION QUESTIONNAIRE**

**6. GENERAL**

- 5. Name:
- 6. Organisation
- 7. Role:
- 8. Years of experience

**7. 3D model display**

- a. The optimal decimation should be established around:
  - i. 97%
  - ii. 50%
  - iii. Without (leaving it as it is)

b. The scale of the 3D model has improved:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

c. Regarding stereoscopy, I prefer:

- i. Active
- ii. Passive

Explain why:

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d. I feel dizziness after using active stereoscopy:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

e. The type of brightness of HMD screen I prefer is:

- Low
- Mid
- High

f. I think the tracker for the Head Mounted Display is ergonomic enough for my needs:

1	2	3	4	5	6	7
Strongly disagree	Disagree	Mildly disagree	Neutral	Mildly agree	Agree	Strongly agree

## 8. Registration

a. The stability of the 3D image with Low-filter activated:

1	2	3	4	5	6	7
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Very poor	Poor	Fair	Good	Very good	Excellent	Exceptional
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- b. The registration step should be done:
  - i. Autonomously (with a fiducial marker).
  - ii. With manual input.
- c. How should the registration tool look like? (Form, material, weight...)

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3. If there are other deficiencies or weakness please describe briefly

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4. Suggest possible improvements

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