Maria Emine Nylund

HoloUmoja

Augmented Reality training application for obstetric Doppler ultrasound

Master's thesis in Master of Science in Informatics
Supervisor: Gabriel Hanssen Kiss
Co-supervisor: Ekaterina Prasolova-Førland

January 2022

Master's thesis

NTNU
Kunnskap for en bedre verden

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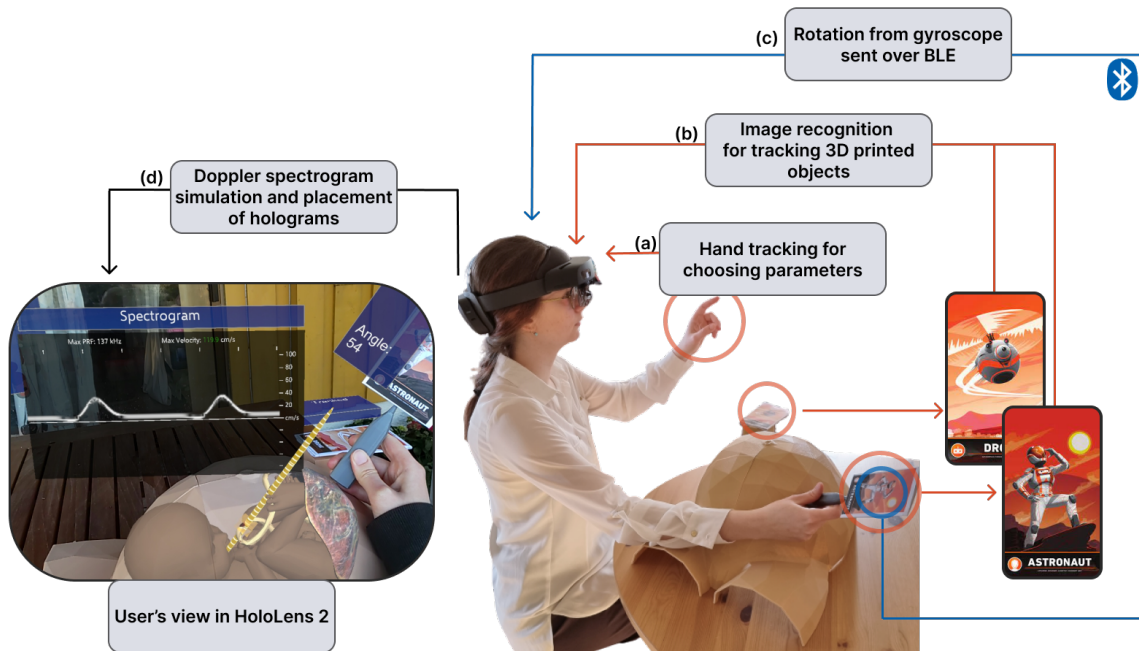Science and Technology

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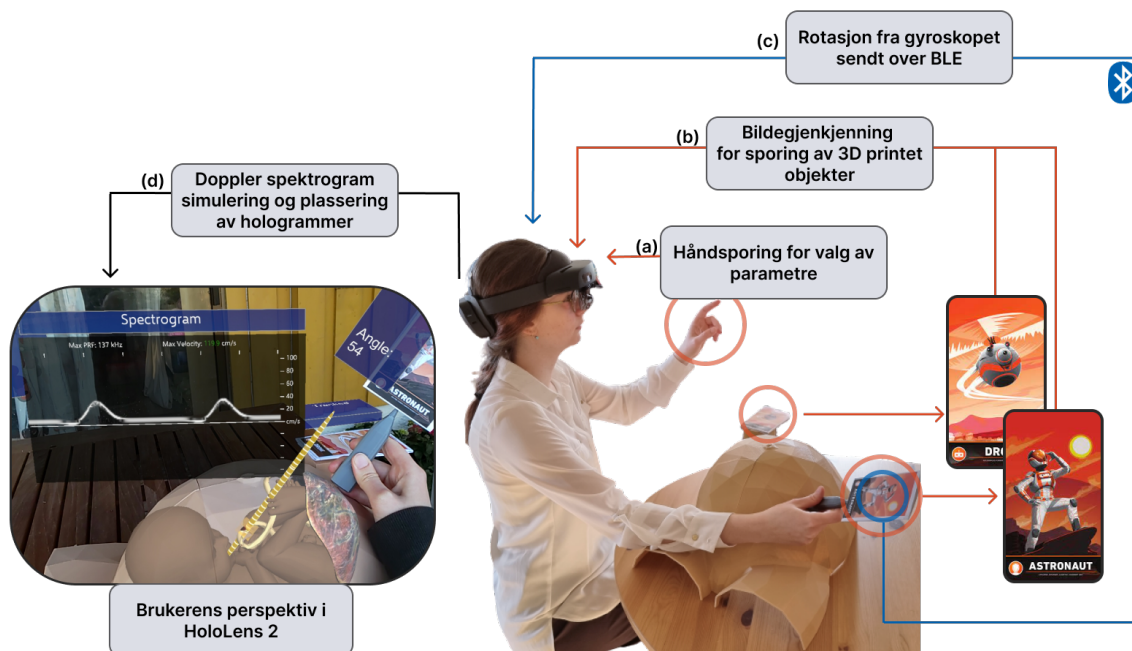
Last but not least I am extremely grateful to my friends and family for their endless support and help. I would not have been where I am today without you.

Abstract

User's view in HoloLens 2

(a) Hand tracking for choosing parameters
(b) Image recognition for tracking 3D printed objects
(c) Rotation from gyroscope sent over BLE
(d) Doppler spectrogram simulation and placement of holograms

Pulsed-Wave (PW) Doppler ultrasound is a well-established and widely used technique to monitor pregnancies and time-delivery. Its use is becoming more widespread, as the ultrasound machines are becoming hand-held and more countries are entering the developing stage where education and health opportunities emerge. In addition to the ultrasound hardware, it takes several years to become ultrasound proficient and requires resources such as the presence of a professional, ultrasound equipment, and a volunteering patient. In this study, we proposed the use of an augmented reality (AR) application to facilitate the understanding of parameters used in PW-Doppler ultrasound when acquiring a spectrogram of the umbilical cord and to develop the skills required for this task. Doppler spectrograms are simulated by parsing a synthetic sinus curve through a Fourier transform, while the user has the possibility of adjusting various parameters (pulse repetition frequency (PRF), sampling depth, and beam-to-flow angle). The AR application was implemented in C# using Unity Engine for HoloLens 2 headset combined with a 3D printed abdomen and ultrasound probe, tracked using Vuforia Engine Library. The rotational tracking was improved by combining the image tracking data with rotational changes from the gyroscope on an Arduino Nano 33 BLE. The technical feasibility of such an application, as well as the merging of AR elements and physical 3D printed objects, were tested in two phases. The results of the HoloUmoja application were collected through observations during user-testing, SPINE questionnaire, and feedback from experts. The application as seen in the figure above has shown simulation and visualisation methods of the procedure and provided possible interactions. Based on the expert feedback, the application has the potential to be a useful teaching tool for obstetric Doppler ultrasound.

Sammendrag

(c) Rotasjon fra gyroskopet sendt over BLE

(b) Bildegjenkjenning for sporing av 3D printet objekter

(d) Doppler spektrogram simulering og plassering av hologrammer

(a) Håndsporing for valg av parametre

Brukerens perspektiv i HoloLens 2

Pulset (PW) Doppler ultralyd er en veletablert og bredt brukt teknikk for å undersøke graviditeter og termindato. Bruken av den blir mer utbredt ettersom ultralydmaskiner blir håndholdte og flere land går inn i utviklingsstadiet hvor flere utdannings- og helsemuligheter oppstår. I tillegg til ultralyd-maskiner tar det flere år å bli dyktig i å gjennomføre ultralydundersøkelser, og det krever ressurser som en utdannet ultralydekspert, utstyr og en frivillig pasient. I denne studien foreslo vi bruk av en utvidet virkelighet (AR) applikasjon for å bidra med forståelsen av parametre som brukes i PW-Doppler ultralyd for å få et spektrogram av navlestrengen og for å utvikle ferdigheter som kreves for denne prosedyren. Doppler spektrogrammer simuleres ved å sende en syntetisk sinuskurve gjen-nom en Fourier-transformasjon, mens brukeren har muligheten til å justere ulike parametre (pul-srepetisjonsfrekvens (PRF), prøvetakingsdybde og stråle-til-strømningsvinkel). AR applikasjonen ble implementert i C# ved hjelp av Unity Engine for HoloLens 2 headset kombinert med en 3D printet mage og ultralydsonde, sporet ved bruk av Vuforia Engine Library. Rotasjonssporingen ble forbedret ved å kombinere bilde-basert sporing med rotasjonsendringer fra gyroskopet på en Arduino Nano 33 BLE. Den tekniske gjennomførbarheten av en slik applikasjon, samt sammenslåing av AR elementer og fysiske 3D printede objekter, var testet i to faser. Resultatene av HoloUmoja-applikasjonen ble samlet inn gjennom observasjoner under brukertesting, SPINE spørreskjema og tilbakemelding fra eksperter. Applikasjonen, som er visualisert i figuren over, har vist simulerings- og visualiseringsme-toder for prosedyren og mulige interaksjoner. Basert på ekspert-tilbakemeldinger har applikasjonen potensialet til å være et nyttig undervisningsverktøy for obstetrisk Doppler ultralyd.

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Acronyms

BLE   Bluetooth Low Energy.

CW   continuous wave.

DLL   Dynamic-link library.

EWK   Extent of World Knowledge.

FPS   frames per second.

FS   full scale.

HCI   Human Computer Interaction.

IMU   inertial measurement unit.

IR   infrared.

LMICs   low-middle income countries.

MRTK   Mixed Reality Tool Kit.

ODR   output data rate.

PRF   pulse repetition frequency.

PW   pulsed wave.

RBC   red blood cells.

RCTL   Real-time Contour Tracking Library.

SPINE   spatial interaction evaluation.

UML   Unified Modeling Language.

Chapter 1

Introduction

1.1 Motivation

Pulsed wave (PW) Doppler ultrasound is a well-established and widely used technique to monitor pregnancies and time-delivery. Its use is becoming more widespread as the ultrasound machines are becoming hand-held and more countries are entering the developing stage where education and health opportunities emerge. The procedure is highly operator dependent to successfully get the correct results [1] because it has to be done in real-time. Specifically in obstetric ultrasound both the patient and fetus might move during an examination, the technician has to constantly re-position the ultrasound probe to get correct measurements. In addition, several parameters have to be set correctly by the operator, such as beam-to-flow angle, sampling depth, pulse repetition frequency (PRF), and more. To become ultrasound proficient, one has to dedicate several years to practice and have access to costly resources such as ultrasound equipment, the presence of a professional for guidance and a volunteering patient or simulation station, e.g. ScanTrainer [2]. Learning ultrasound becomes an even bigger issue where there is limited access to the aforementioned resources, making it difficult to scale the number of experts.

In this project, we follow the inspiration from the "UMOJA - Ultrasound for midwives in rural areas" [3] project. It started in 2014 with the goal of making a simple ultrasound machine with Doppler for midwives in low-middle income countries (LMICs). The issue they recognised was how bad the ultrasound machines created for developed countries functioned in LMICs. They were too sensitive, a small hardware error could cause a full stop in usage. In addition, the machines were too complicated to be used by medical professionals that do not have proper technical training.

AR has already shown promising results in education and simulation of the medical procedures, seeing as it has been applied to surgery [4]–[6], eye examination [7] and ultrasound [8]–[10]. In addition, Barteit, Lanfermann, Bärnighausen, *et al.* [11] have done a systematic review of head-mounted devices for teaching medical content in low-resource settings. Their results suggested the applicability and potential effectiveness of using AR/VR headsets for training medical content in LMICs. Seeing the need for an effective training tool, the positive results from using AR and inspiration from previous works, in this project, we explored ways to create an AR application for simulation of the Doppler ultrasound procedure.

1.2   Research questions

During this thesis, we decided to concentrate on the simulation, visualisation, interaction and guidance in AR with 3D printed objects and sensors.

RQ1:   How can one **simulate** and **visualise** in AR the procedure of measuring the blood flow in the umbilical cord using Doppler ultrasound?

RQ2:   How should the **interaction** be implemented in AR to accommodate midwife students?

   RQ2.1: To what degree can midwife students use the prototype without external **guidance**?

RQ3:   How can user experience be improved with the use of **3D printed objects** and **sensors**?

1.3   Stakeholders

The stakeholders in this project are the supervisors, the customers and the users. The supervisors have influenced the application and its outcome. The customers, which are midwife educators, have provided feedback at the end of each phase of the project. At the very end of the project, the application was tested on the possible users.

- Supervisors: Gabriel Kiss, Ekaterina Prasolova-Førland
- Customers: Eva Tegnander, Eva Johanne Leknes Jensen
- Users: Midwife students at NTNU

1.4   Thesis outline

Chapters 2 & 3 presents the relevant background theory used in this thesis. It starts with explaining AR and its history, following two widely known design principles. Then it explains ways to describe rotation and position especially in regards to sensors before going into detail about ultrasound and shortly explaining the function and structure of an umbilical cord. Lastly, it describes related work for ultrasound training divided into two parts where the first one presents research done without the use of AR and the second using AR.

Chapter 4 & 5 goes through the processes of research, awareness, evaluation and the decisions in the form of requirements and technology that were made in this thesis. Then it goes through the phases of implementation of the proof-of-concept application.

Chapter 6 & 7 describes the final version of the HoloUmoja application and the results from user testing and expert feedback. The videos of the application can be found in section 6.2. Then it discusses the results in light of the user tests, requirements, research questions and related work.

Chapter 8 summarises the thesis and proposes focus areas for future work.

Appendix includes a published abstract (section A.1) that was submitted to NFUD (Norwegian union for ultrasound-diagnostics [1]) 2022 Symposium where the project won "Best Free Presentation" [2] prize of 10k NOK. In addition, it contains code snippets, diagrams, full transcriptions of user test materials and a build guide for the HoloUmoja application.

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[1] Norsk forening for ultralyd–diagnostikk
[2] "Best Frie Foredrag"

Chapter 2

Background

In this chapter, we describe the necessary theory that went into creating the application. Firstly since the project is in the field of AR, we describe what AR is and the relevant research in the area, with a focus on the visualisation and interaction referring to RQ1, RQ2 and RQ2.1. Secondly, we explain the technical details of tracking, rotation and sensors that can be used, supporting RQ3. Finally, we introduce the theory of ultrasound, specifically Doppler and shortly the important medical aspects of an umbilical cord (both anatomy and blood flow related aspects) to explain the simulation of the application in RQ1.

2.1   Augmented Reality (AR)

Already back in the 19th century, the famous author of "Wizard of Oz", L. Frank Baum described an idea for glasses that overlay data - holograms onto the real world. It was introduced on page 94 of the short story "The Master Key":

> Therefore, that you may judge all your fellow creatures truly, and know upon whom to depend, I give you the Character Marker. It consists of this pair of spectacles. While you wear them every one you meet will be marked upon the forehead with a letter indicating his or her character.

It took some time before such goggles became a reality as we can see in the timeline Figure 2.1, where the first experimentation was conducted in the 60s. Already in the beginning, AR was developed to be used as a training tool for military pilots. Although the first commercial applications did not come until 2005, right now we are at the beginning of spatial computing taking off with the first widely available AR headsets. Their price tag still makes companies their primary market rather than private consumers. For private consumers, AR is available for many to use on their smart phones where we have seen a huge success in recent years because of the mobile game Pokémon GO [12].

Early Experimentation	Basic Research (Tracking, display technology)	Tools & applications (Interaction, Ux, theory)	First commercial applications (Games, Medical, Industrial)	Smart Glasses on the rise (BT-200, Glass)	Spatial Computing takes off (Hololens / Magic Leap)
1960s – 80s	1980s – 90s	1995 – 2005	2005 –	2011 – 2015	2016 –

Figure 2.1: The history of modern Augmented Reality. Source: Open AR book [13]

Now let us look at how AR actually works and what the difference is between AR and (what AR is often confused with) virtual reality (VR). It is often explained following Milgram, Takemura, Utsumi, *et al.* [14] by creating a line, see Figure 2.2, that goes from a real environment as we normally see it to a completely virtual environment where everything we see is computer-generated. VR exists at the right end of the axis while AR is between the left end and centre of the axis. This is because in AR the user can still see their real environment with additional computer-generated graphics overlaid.
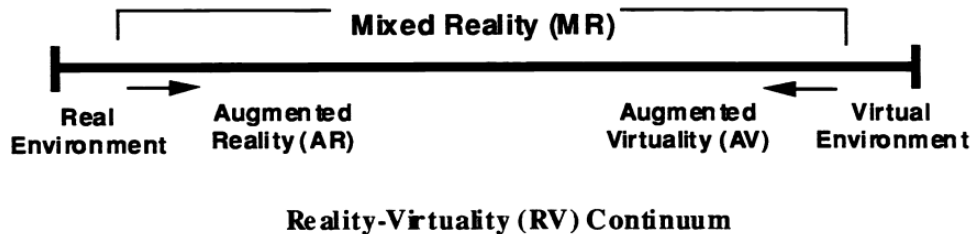
Figure 2.2: Simplified view of RV continuum. Source: [14]

To define AR more specifically, we must mention the most cited work of Azuma in AR field. They define AR as any system that combines real and virtual environments, is interactive in real-time and is registered in three dimensions [15]. This definition, although widely used, adds more questions about what reality is and how a user perceives that. In this work, we will follow the definitions and standards given by "IEEE Standard for Augmented Reality Learning Experience Model" [16]. This standard has been developed especially for augmented reality learning experience models (ARLEMs). There augmented reality refers to enhancing **human perception** with additional, **computer generated sensorial input** to create a new **user experience** including, but not restricted to, enhancing human vision by combining natural with digital offers.

Milgram *et al.* presents more dimensions used to classify AR displays, in our case Extent of World Knowledge (EWK) dimension is useful to look at as well. It presents how much the AR systems know about the surrounding world, look at Figure 2.3.
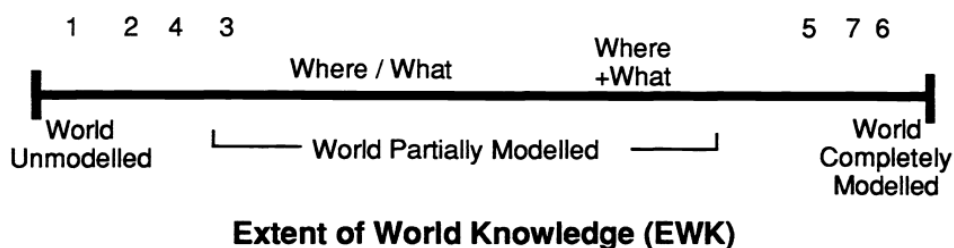
Figure 2.3: Extent of World Knowledge (EWK) dimension. Source: [14]

In order to improve the EWK dimension and create a relationship between an object in the natural space and in the computer-generated space, one might use detectables. Using the definition from the IEEE standard [16]:

> **Detectables** are entities that link to fiducial markers, target feature models, or other sensor state properties providing input to computer vision and other sensor processing sys-

tems. They have a unique identity and link to data enabling their tracking with the help
of the sensor processing system referenced.

For example, if we want an AR system to know where a table is and what it means we can either teach
it to recognise tables; we tell it to expect a signal from a sensor or a certain image to appear in the
view to indicate that this is a table, or we can add a sensor to said object that knows where it is in the
space or relative to the sensor processing system.

2.1.1 Tangible AR

When an application implements physical objects into an interaction, it is called tangible AR. This
adds the complexity of new interactions and further connects the real and computer-generated space,
thus improving the EWK dimension (2.3). It provides the user with tactile feedback and in some cases
also affordance (more about Norman's principles in subsection 2.2.1). In the case of possible inter-
actions or gestures with a physical object are not understood right away, the application might need
to provide the user with further guidance. White *et al.* [17] have compared different *visual hints* for
tangible gestures: text explaining the motion; diagram of the motion; or ghosting, meaning placing
transparent copies of the physical object in the different positions needed to complete the motion.
The latter two can be animated or static. Their pilot study with seven participants showed that the
combinations of ghosting with text or animation proved to be the most preferred because each on its
own had some drawbacks. Textual hints could be ambiguously caused by language or culture, whilst
diagrams were difficult to map correctly from 2D to 3D space. Ghosting on the other hand proved
successful at showing the gesture, but the movement could be distracting and the speed of the move-
ment could be confusing. On the bright side, a pilot study showed that there were 'significant learning
effects, once a user knows the gesture, they can apply that knowledge to other hints about the same
gesture' [17].

2.2 Human-Computer Interaction (HCI)

Moving from 2D interactions on the screen to 3D in AR leads to innovation of the interactions and user
interface. But that does not mean we cannot use widely used HCI design principles. In this section,
we will shortly summarise Norman's [18] and Gestalt [19] principles, which we have used throughout
this project.

2.2.1 Norman's design principles

Norman in his book *The design of everyday things: Revised and expanded edition* [18] presented a set
of principles that would help designers:

- **Visibility** is about reminding users about the available functions instead of making them re-
  member them. For the system to be understandable, its functions should be visible and avail-
  able. Norman compares the design of a phone to a car and explains that even though the car is
  more complex, its functions are more visible to the user, so it is easier to learn.

- **Mapping** is a term for describing the relationship between two things. Where Norman is encouraging designers to create a natural mapping as for example the steering of the car wheel to the left makes the car turn to the left as well.

- **Feedback** is one of the more self-explanatory principles that explains that the user should receive some information back after an action.

- **Constraints** restricts users so they do not become overwhelmed with all the possible actions. Once again, so they do not need to remember what should not be done. It is often used in for example online forms where users cannot enter letters into a field for a phone number.

- **Affordance** is about the perceived and actual use of a thing. For example, looking at a cup, a user can understand how to hold it by looking at it, meaning it has a high affordance.

- **Consistency** is there to help users to learn and recognise patterns. For example, similar-looking buttons, a red cross, will allow a person to expect the same functions - to close a window or application.

2.2.2   Gestalt theory

Gestalt theory [19] follows the idea that human brains will try to organise and simplify complex visual structures, to find patterns in them. There are six principles that we will shortly explain:

- **Similarity** refers to how elements are prone to be grouped together by colour, shape or size.

- **Continuation** states that a user will follow the smoothest path with their eyes even if they are grouped by colour.

- **Closure** shows that people will fill in the missing parts and create a shape from the visible elements.

- **Proximity** creates groups of elements depending on how close those are to each other.

- **Ground** is similar to the principle of closure, just regarding the foreground and background of an image.

- **Symmetry and order** principle says that the brain will see the full shapes as simple as possible. Even if the Olympic logo is in one colour, we will see overlapping circles instead of continuous lines.

2.3   Sensors

As seen in EWK dimension [14], AR applications need context to successfully operate together with the real world. Since it gives the user a unique experience to interact with both the virtual and the real world, the application needs to provide a way to keep track of the objects in real space. Typically, we refer to its position and rotation, but it might also be its other parameters such as its state, e.g. if a box is open or closed. Tracking of objects is often used as an input modality for interaction with the application. Similarly to the way a 2D position of the mouse in the world is tracked and converted to

the cursor being moved on the screen. We also track its state if the right mouse is held down or up to create a "click" action.

To track real-life objects there exists a range of different sensors that are able to convert different forces or parameters into a quantifiable stream of electricity that can be read by a machine. The more interesting uses can appear when those sensors are combined in meaningful ways to provide the application or the user with relevant information.

One can track a variety of parameters such as temperature, air quality or air pressure. But in our case, we will focus on the sensors that are used for tracking the position and orientation of an object such as a camera, gyroscope, accelerometer and magnetometer. In order to explain how those function, their uses and combinations, we need to define how to describe position and rotation in space.

2.3.1 Direction and rotation

A Euclidean vector is a vector with both magnitude and direction. It is usually shown in 2D as an arrow from point A to point B (Figure 2.4), it works similarly in 3D space. The direction component is a normalised vector, meaning that the magnitude is 1. In order to describe orientation in 3D space, we first need 3 direction vectors. Confusingly those 3 vectors go by a variety of names depending on their area of application or the preference of the author. In this thesis, we use the definitions up, right and forward for the three vectors as seen in Figure 2.5. Words of caution, the IMU sensor and Unity Engine use different definitions as shown in Figure 2.6.
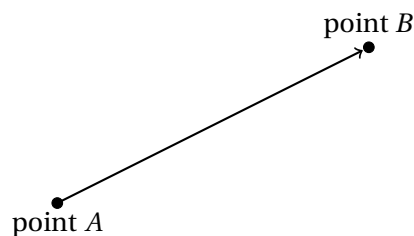
point B

point A

Figure 2.4: Vector is visualised as an arrow pointing in a direction and length (magnitude)

One way to describe the rotation around the axis is using Euler angles. There you use three angles around one of the vectors with respect to a fixed coordinate system. Each rotation around one of the directions has a name: roll around forward, pitch around right and yaw around up direction as seen in Figure 2.5. We will use degrees, not radians in our notations. Using the system visualised in Figure 2.5, we could describe forward direction such as $z_{dir} = [0, 0, 1]$ and 180° anti-clockwise rotation around forward axis as $v_1 = [0, 0, 180]$.

Euler angles are useful as they are easy to read and understand the rotation quickly, but unfortunately, they are prone to Gimbal lock. This happens when two of the three axis are rotated in such a way that it makes them parallel, making the rotation two dimensional - losing one of the degrees of freedom [1].

---

[1]A degree of freedom is freedom of movement of an object in 3D space. For example: six degrees of freedom are forward/back, up/down, left/right, yaw, pitch, roll.
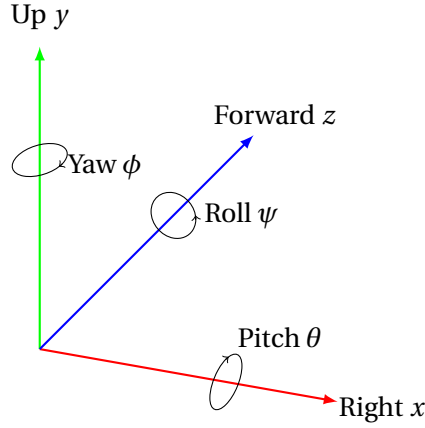
Figure 2.5: Orientation using forward, up and right and its rotations with roll, pitch and yaw, assuming a left-hand coordinate system.

To avoid the Gimbal lock issue, in the computer graphics field it is common to use a four-dimensional description of the rotation using quaternions. Quaternions are an extension of complex numbers and are expressed in the form: $q = xi + yj + zk + w$ where x, y, z, w are real numbers, and i, j, k are symbols that can be interpreted as unit-vectors pointing along the three spatial axes. So in our example $\alpha = 180°$ clockwise rotation around forward axis, $\beta_{\text{indicated axis}}$ is the angle between the axis of rotation and the indicated axis. This rotation can be described as a quaternion:

$$
\begin{aligned}
q_x &= sin\frac{\alpha}{2} \cdot cos\beta_x = sin\frac{\pi}{2} \cdot 0 = 0 \\
q_y &= sin\frac{\alpha}{2} \cdot cos\beta_y = sin\frac{\pi}{2} \cdot 0 = 0 \\
q_z &= sin\frac{\alpha}{2} \cdot cos\beta_z = sin\frac{\pi}{2} \cdot 1 = 1 \\
q_w &= cos\frac{\alpha}{2} = 0 \\
q &= [0,0,1,0]
\end{aligned}
\tag{2.1}
$$

When converting Euler to quaternions, one needs to take special care in making sure that the coordinate systems match, here we will use the left-hand coordinate system (as used by Unity Engine) in our calculations. Euler rotations around all three axis can be combined and described as a quaternion:

$$
\begin{aligned}
\mathbf{q}_{\text{combined}} &=
\begin{bmatrix}
0 \\
0 \\
\sin\frac{\psi}{2} \\
\cos\frac{\psi}{2}
\end{bmatrix}
\begin{bmatrix}
0 \\
\sin\frac{\phi}{2} \\
0 \\
\cos\frac{\phi}{2}
\end{bmatrix}
\begin{bmatrix}
\sin\frac{\theta}{2} \\
0 \\
0 \\
\cos\frac{\theta}{2}
\end{bmatrix} \\
&=
\begin{bmatrix}
\sin\frac{\theta}{2}\cos\frac{\phi}{2}\cos\frac{\psi}{2} - \cos\frac{\theta}{2}\sin\frac{\phi}{2}\sin\frac{\psi}{2} \\
\cos\frac{\theta}{2}\sin\frac{\phi}{2}\cos\frac{\psi}{2} + \sin\frac{\theta}{2}\cos\frac{\phi}{2}\sin\frac{\psi}{2} \\
\cos\frac{\theta}{2}\cos\frac{\phi}{2}\sin\frac{\psi}{2} - \sin\frac{\theta}{2}\sin\frac{\phi}{2}\cos\frac{\psi}{2} \\
\cos\frac{\theta}{2}\cos\frac{\phi}{2}\cos\frac{\psi}{2} + \sin\frac{\theta}{2}\sin\frac{\phi}{2}\sin\frac{\psi}{2}
\end{bmatrix}
\end{aligned}
\tag{2.2}
$$

The code snippet written in C++ to convert Euler rotations to a quaternion can be found in Appendix Listing 3.

2.3.2   Sensors and Unity Engine

(a) Unity Engine
(b) Arduino 33 BLE Nano
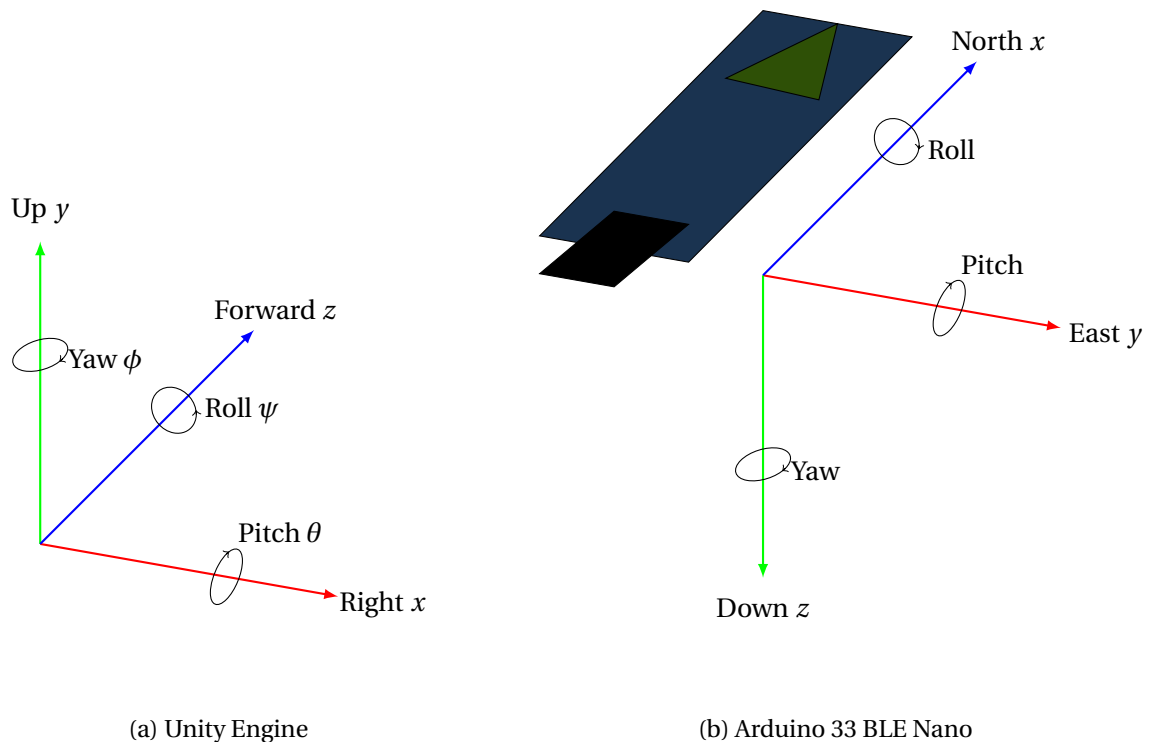
Figure 2.6: Comparison of the two coordinate systems

To correctly convert the values from the sensors from Arduino to Unity Engine, we might refer to the Table 2.1. Take special notice of the fact that Arduino uses Down instead of Up, so its value has to be negated.

Table 2.1: Conversion table between the Unity Engine and the LSM9DS1 IMU in Arduino 33 BLE Nano

	Unity Engine	LSM9DS1 IMU
Forward	z	x
Up	y	-z
Right	x	y

Now that we understand how we can easily describe rotation using both Euler angles and quaternions, we can move on to understanding the sensors such as camera, gyroscope, accelerometer, and magnetometer for tracking the position and rotation of an object.

A **camera** in itself can be seen as a sensor. AR highly depends on it when placing objects in regard to its environment. A camera is able to extract a position and rotation of an object with pre-determined features. It is possible to calculate it manually or use existing libraries, such as Vuforia described in subsection 4.4.4. Unity has a camera in the scene and thus has the same coordinate system as

described in 2.1. The camera tracking is dependent on lighting conditions and requires good stable tracking and slow movement of the object.

Gyroscope measures the changes in rotation, it can be integrated to estimate the current orientation of an object, but it requires an initial orientation. A known problem when converting gyroscope output to axis rotations, is drifting caused by the noise and bias of the gyroscope.

Accelerometer provides information about the change in velocity. When lying still it measures the earth's gravity in an upwards direction (around $9.81 m/s^2$). Thus after calibration, it is possible to use this to calculate the rotation around the forward and right axis, but not around the up vector.

A **magnetometer** measures the direction of the north, but it requires careful calibration with values depending on where on Earth it is placed. It can also be easily affected by other electromagnetic objects nearby requiring re-calibration.

2.4 Ultrasound

Ultrasound imaging is a technique used in a variety of applications from medicine to fish identification [20]. In this section, we will emphasise the medical imaging aspects, but the same techniques are also applied in other research areas. Some people have probably heard about ultrasound imaging in regards to women's health, especially fetal imaging. The obstetric ultrasound imaging contains several steps, that we will discuss in subsection 2.4.3. To understand how the actions of an ultrasound operator affect the image and how we are able to simulate this procedure in AR, we need to first understand how the ultrasound signals are sent. Also, how they are received and reconstructed as images or spectrograms that we see on the monitor.

Ultrasound procedure has different modes for various purposes, the most common one being B-mode (brightness mode) imaging as shown in Figure 2.7. In this thesis, we will focus on a mode called pulsed wave (PW) Doppler imaging where one gets a spectrogram showing the spectrum or frequency distribution of a signal over time, as can be seen in Figure 2.8.

Figure 2.7: Obstetric sonogram of a fetus at 16 weeks. The bright white circle center-right is the head, which faces to the left. Source: [21]
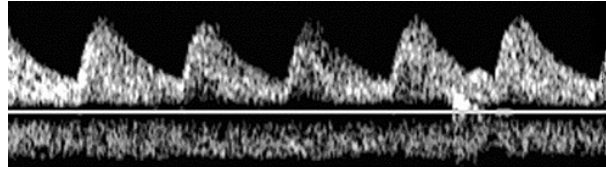
Figure 2.8: An example of a Doppler spectrogram

2.4.1 History

Ultrasound research has its roots in sonar (sound navigation and ranging) where they got motivated by the Titanic catastrophe in 1912. This discovery was possible because of Pierre and Jacques's research of the piezoelectric effects years before [22]. Although, the ultrasound for medical diagnosis did not come before 1940 when H.Gohr and T. Wedekind suggested it as a diagnostic tool [23].

2.4.2 Wave physics

In order to understand how ultrasound works, we need to define what sound is and some parameters to describe it. First of all, sound has different meanings in our everyday use and what we mean by it in this research area. Let us see look at the two definitions given by Morfey in *Dictionary of acoustics* [24]:

> *Sound (1)* a disturbance in pressure that propagates through a compressible medium. More generally, sound can refer to any type of mechanical wave motion, in a solid or fluid medium, that propagates via the action of elastic stresses and that involves local compression and expansion of the medium.

> *Sound (2)* the auditory sensation produced by transient or oscillatory pressures acting on the ear, or by mechanical vibration of the cranial bones at audio frequencies.

In this work, we will use the definition described in sound (1), where we assume that the waves propagating through the tissue in the body do it the same way as through fluid. Now let as look at some parameters and their relationships to describe a wave:
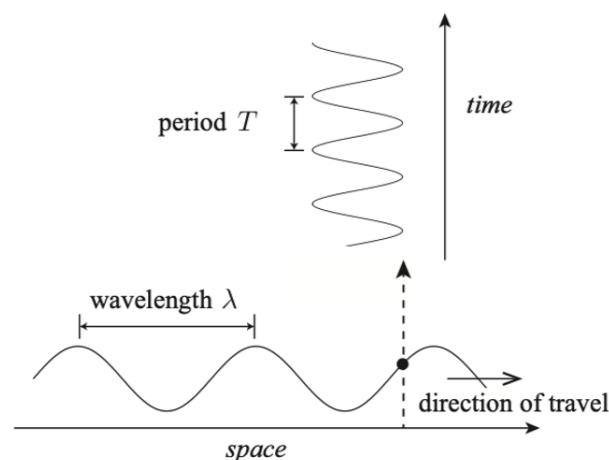
Figure 2.9: Definition of the wavelength being in the space coordinates, while the period is in time. Source: [20]

- **Wave period**, T - the time it takes for a wave to complete one cycle of propagation.
- **Frequency**, $f = 1/T$ - the rate at which the peaks pass a fixed point. Units of cycles per seconds or Hertz (Hz).
- **Sound speed**, c - the speed of sound propagating in a given medium. Sound travels at about 1500 m/s in water and on average 1540 m/s in soft tissue.
- **Wavelength**, $\lambda = c/f$ - the distance between two adjacent peaks.

The variation in sound frequency is separated into groups. Humans are able to hear in the range from 20 Hz to 20 kHz, which is termed acoustic. As seen in the Figure 2.10, ultrasound is multitudes higher than acoustic. The terms infrasound and ultrasound are used for frequencies below and above human hearing.
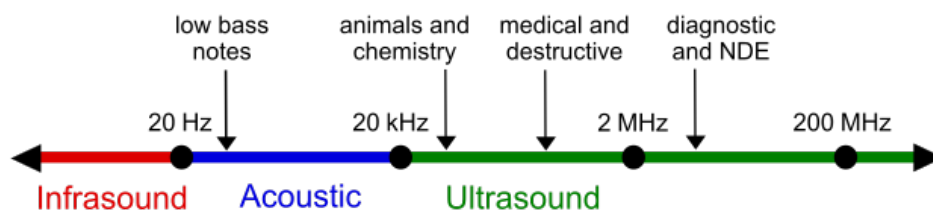
Figure 2.10: A rough diagram of the sound frequency scale, showing ultrasound and some applications. Source: [25]

2.4.3 Procedure

In order to create ultrasound waves that will propagate through the tissue and record reflected waves, an ultrasound transducer probe is used. The probes come in a variety of shapes and sizes to better accommodate the region it will be used to scan as seen in Figure 2.11. The ultrasound probe consists of an array of elements that are made from piezoelectric ceramics. This is a special material that uses the piezoelectric effect mentioned in 2.4.1. It allows the piezoelectric material to create a potential difference at the surfaces of the material when the material is compressed. Inversely a potential difference can be applied to the surfaces to generate expansion and contraction of the material to propagate waves in the media.

During the ultrasound procedure, a medical professional applies *coupling gel* onto the ultrasound *probe* or the skin. This is to allow ultrasound waves to get into the body when the probe is held against the skin. Without it, all the acoustic pressure would be reflected and would not enter the tissue.

So ultrasound propagates through the tissue and is reflected differently depending on the tissue type. The reflected waves are then recorded at the surface, usually by the same transducer in the probe that was used to send them. The received signal is delayed and masked based on the parameters until it gets summed. At this point, we have a signal of amplitude in the signal which can be visualised as a graph with amplitude and frequency on one axis and time or depth on the other.

In our case, we will mostly focus on Doppler ultrasound since this is what is used for blood flow estimation in an umbilical cord.

Figure 2.11: GE Ultrasound transducer probes. The first one to the left is a convex probe and fourth one is phased array. Source: [26]

2.4.4 Doppler ultrasound

Blood travels at high speed through our arteries, up to 30 cm/s in the umbilical artery [27]. In order to measure its velocity, we can use ultrasound waves that reflect off red blood cells (RBC) which make up around 45% of blood volume. The issue with the measurements is that by the time, t, it takes to transmit and receive the signal, the RBC have moved significantly. That makes the measurements inconclusive. We need to calculate the Doppler delay and apply it to the ultrasound equation to get the correct position of the RBC. First of all, let us look at what the Doppler effect is. Many have experienced the sound changing when a car with a siren drives past them. As the car approaches, the sound is high pitched and when it drives away the sound seems to be lower. One can look at the Doppler effect from two points of view: in relation to a moving observer and a moving source.

In the case of a moving observer, the original wavelength λ_0 is shortened by Δs where s is the distance travelled by the observer.

$$
\begin{aligned}
v &= \frac{\Delta s}{\Delta t}, \Delta t = \frac{1}{f} \\
\lambda_0 &= \Delta s + \lambda \\
\frac{c}{f_0} &= \frac{v}{f} + \frac{c}{f} \\
v &= \frac{c\left(f - f_0\right)}{f_0} \\
f_d &= f_0 \frac{v}{c}
\end{aligned}
\tag{2.3}
$$

Where f_0 is the centre frequency of transmitted pulse and c, the speed of light, are used to compute f_d, Doppler-shifted receive frequency.

In the case of a moving source, as in the example with the car with a siren, the distance from the next

wave is emitted from the new position of the source to the observer is shortened by Δs.

$$v = \frac{\Delta s}{\Delta t}, \Delta t = \frac{1}{f_0}$$
$$\lambda_0 = \Delta s + \lambda$$
$$\frac{c}{f_0} = \frac{v}{f_0} + \frac{c}{f} \qquad (2.4)$$
$$v = \frac{c(f - f_0)}{f}$$
$$f_d = f\frac{v}{c}$$

Here we assume that the blood velocity is much smaller than the speed of sound, which it is when we are talking about RBC moving, so $v \ll c \Rightarrow f \approx f_0 \Rightarrow f_d = f_0 \frac{v}{c}$.

Doppler shift from blood acts as both a moving observer *and* a moving source, so it becomes:

$$f_d = f_0 \frac{v}{c} + f_0 \frac{v}{c}$$
$$= 2f_0 \frac{v}{c} \qquad (2.5)$$

So far we have assumed that the ultrasound waves are aligned with the blood velocity. The waves usually come at an angle, called beam-to-flow angle, the angle between pulse propagation and flow direction. Then the Doppler equation, including the said angle, becomes:

$$f_d = 2f_0 \frac{v}{c} \cos\theta \qquad (2.6)$$

It is important to notice here that if the ultrasound waves are perpendicular to the blood's direction, the Doppler shift cannot be computed. We can look at the effect of the angle on the frequency shift in Figure 2.12.
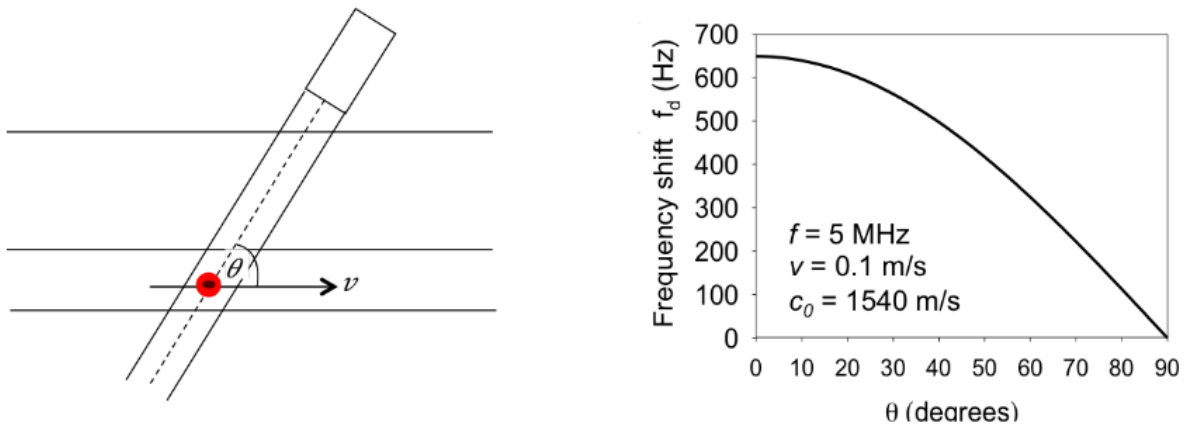
Figure 2.12: The Doppler shift is reduced by $\cos\theta$ when the motion of the scatterer is at an angle θ to the direction of the ultrasound beam. Source: [20].

The derivation of the Doppler equation also assumed that the signal was sent as a continuous single

frequency, known as continuous wave (CW) Doppler. In addition to that, it assumed that the transmitter and the receiver were in the same transducer, but usually, CW Doppler devices use two separate transducers as it can be seen in Figure 2.13. When the angle between them is small enough, the difference can be ignored, otherwise one needs to take into consideration $\theta_{transmit}$ and $\theta_{receive}$.
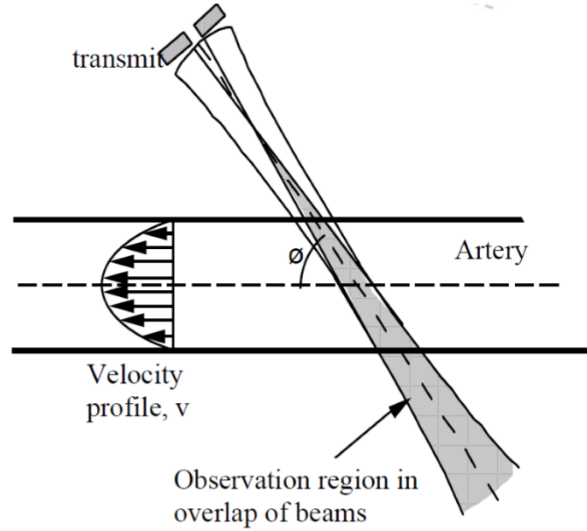
Figure 2.13: The transmit and receive apertures in CW Doppler and their overlap region. Source: [28]

Instead of CW mode, one can also use PW Doppler which uses one transducer to transmit and receive the signal. So when the pulse is emitted, one needs to listen to the pulse when it returns and repeat. PW Doppler measures velocity at a specified depth z, which limits the maximum measurable Doppler shift as we will see further. The main difference between CW and PW Doppler is that in CW, the velocity measurements comes from the entire beam path.

Now we will discuss the relationship between four variables when performing PW Doppler: pulse repetition frequency (PRF), arterial velocity v, beam-to-flow angle θ and sampling depth z.

PRF is the frequency at which the pulses are emitted in PW Doppler. One can notice aliasing attributes in the graph when the signal is undersampled and various signals become indistinguishable, meaning that velocities become ambiguous. To avoid aliasing, we need to remember Nyquist rule $f_{PRF} > 2f_d$, in other words

$$f_{PRF} > \frac{4 f_0 v_{max}}{c_0} \tag{2.7}$$

$$v_{max} = \frac{PRF \cdot c_0}{4 f_0 \cos\theta} \tag{2.8}$$

In contrast to CW Doppler, PW Doppler is bounded by PRF. There is also a difficult trade-off as higher PRF means better temporal resolution but it cannot sample as far, i.e. limited depth. We can then see that the PRF should be bigger than double the time it takes to get to the maximum depth:

$$T_{PRF} > \frac{2 z_{max}}{c_0} + T_{pulse} \tag{2.9}$$

T_{pulse} stands for the time it takes to send the pulse.

Looking at the Equation 2.6, we can see it is important that the beam-to-flow angle is not 90° as then $\cos(90°)$ will be 0. Usually, for good measurements, the angle should be at least less than 60°.
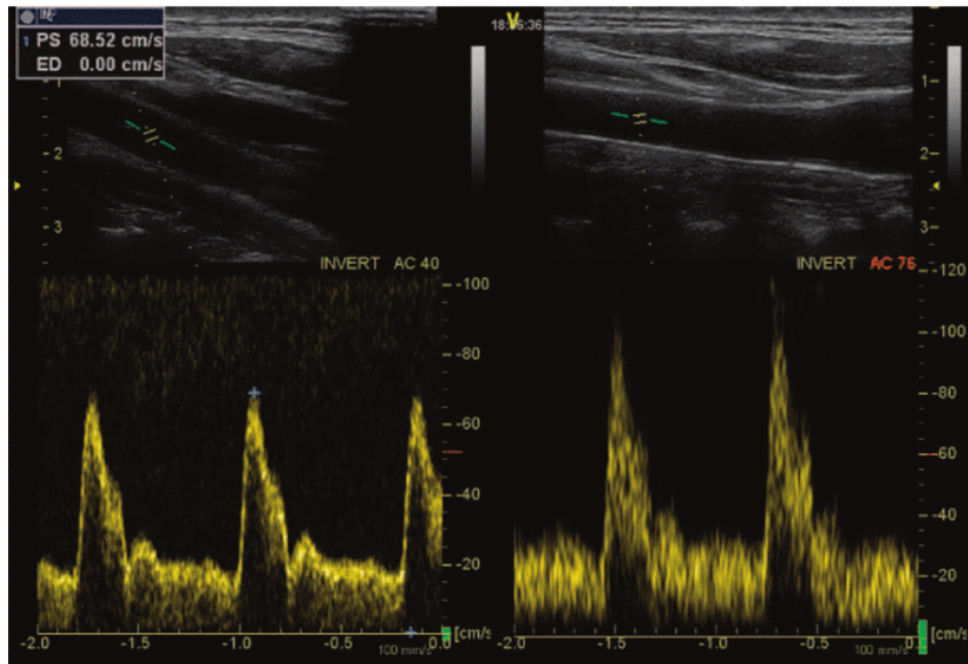
Figure 2.14: The beam-to-flow angle was 40° for the recording to the left, and 76° for the recording to the right. The spectral broadening is prominent in the recording with the largest beam-to-flow angle. Source: [29].

As one can see in Figure 2.14, an incorrect beam-to-flow angle can lead to an overestimation of velocities. In Figure 2.14 to the left one would estimate the velocity to be around 70 cm/s, whilst in the recording to the left one would assume a velocity around 100 cm/s.

What you see in the lower part of Figure 2.14 is a Doppler spectrogram. A spectrogram is a visualisation of the spectrum of frequencies of a signal as it varies with time.

2.5   Umbilical Cord

An umbilical cord, also called navel string connects the developing fetus and the placenta as shown in Figure 2.15a. It can be seen using ultrasound as early as 8 weeks and onwards. The diameter of an umbilical cord is usually less than 2 cm and it has two arteries and one vein [30]. An umbilical vein carries blood toward the fetus' heart, and umbilical arteries are wrapped around the vein and carry the blood away to the placenta (Figure 2.15b).

Umbilical arterial Doppler assessment has been shown to reduce perinatal mortality and morbidity in high-risk obstetric situations [33]. It is especially important to identify the diastolic flow by 20 weeks as it should be present in all pregnancies. Its absence would be clearly abnormal. Moreover, decreased diastolic flow (RI > 0.7) indicates early placental insufficiency. If there is a reversal of flow, it may be a clinical emergency because most fetuses die within 2 weeks [34]. There are a variety of parameters, that are used to notice any deviation from normal, such as:
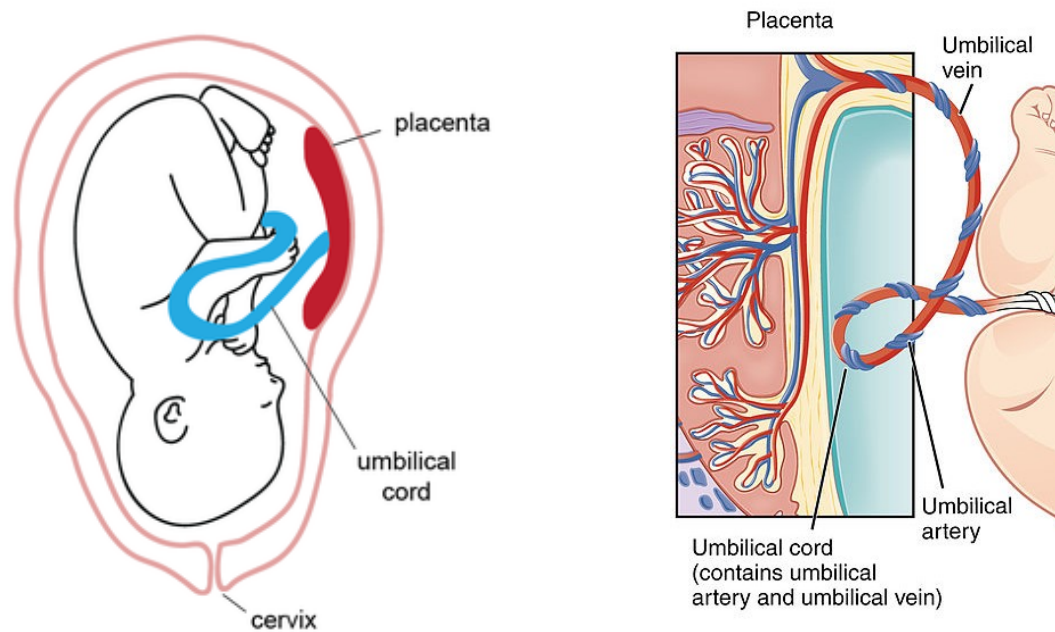
(a) Umbilical cord connected to fetus and placenta. Source: Cchu9279 [31]

(b) Umbilical cord contains an umbilical artery and vein. Source: OpenStax College [32]

Figure 2.15: Position and structure of an umbilical cord.

- umbilical arterial S/D ratio (SDR): systolic velocity / diastolic velocity

- pulsatility index (PI) (Gosling index): (PSV - EDV) / TAV

- resistive index (RI) (Pourcelot index): (PSV - EDV) / PSV

- PSV: peak systolic velocity

- EDV: end-diastolic velocity

- TAV: time-averaged velocity

During the procedure, first, one carries out an ultrasound scan to identify a free-floating portion of the cord, usually with colour Doppler mode. Then one freezes the image and uses PW Doppler to get the spectral Doppler image. According to Nicolaides, Rizzo, Hecher, *et al.* [35], the factors that affect the image are listed here:

- Power: transmitted power into tissue

- Gain: overall sensitivity to flow signals

- PRF: low pulse repetition frequency to look at low velocities, high pulse repetition frequency reduces aliasing

- Gate size: sampling depth

- Beam steering can allow improved beam/flow angle for better accuracy of velocity calculation

- Live duplex/triplex spectral resolution constrained by the need for B-mode/colour pulses

- Gate: sharpness of resolution

- Filter: high filter cuts out more noise but more flow signal

- Post-processing: assigns brightness to output

Chapter 3

Related Work

At the time of writing, there was no existing AR Doppler ultrasound simulator for HoloLens 2 to measure the blood flow in an umbilical cord. As such, we have looked at the relevant educational tools both in AR and not. During their education midwife students train on real patients when it is available, but seeing as it can be difficult to obtain, especially in unusual cases, they use simulators of the ultrasound procedure. Those can be based on real data or fully generated, as we will further see in this section both have their pros and cons.

3.1 Ultrasound training without AR

Figure 3.1: ScanTrainer [2]

According to the stakeholders of this project, one of the common methods for training at NTNU apart from real patients is a ScanTrainer [2]. It uses real patient 3D scans for a variety of cases allowing trainees to learn spectral Doppler in obstetrics including umbilical cord. This allows for great reproducibility for anomaly cases, but adding new data can be time-consuming. The machine itself is

equipped with a probe with a 3D sensor, that sends the rotation and position of the transducer and converts the 3D scan into slice sections [36]. The overall machine weighs over 100 kg and has multiple different modules to switch between. There exist several studies that explore the results of simulation practice using the ScanTrainer and they show it to be quite positive: 'Using simulators early in training could allow trainees to master the basics, improve their confidence, enabling them to get more educational value from clinical ultrasound experience while reducing the impact of training on service provision' [37].

One might argue, that such a machine is expensive and require technical knowledge to handle. It might require a separate room for training and is difficult to handle. This problem has been identified by Yeo and Romero [1] where they explored a simpler educational tool. Yeo and Romero [1] came up with a solution to use a pad with a probe attached that can be moved in six degrees of freedom, seen in Figure 3.2a. The pad and the probe are tracked with a detectable by a web camera connected to a laptop. It is then used by the software on a connected laptop to show ultrasound images based on the position as in Figure 3.2b. This allows students to train in their own time unburdened by the need for assistance or medical equipment. We do not know how successful this method was as no user studies were conducted in this paper.

(a) Pad with a probe and a web-camera (b) Ultrasound images on a computer
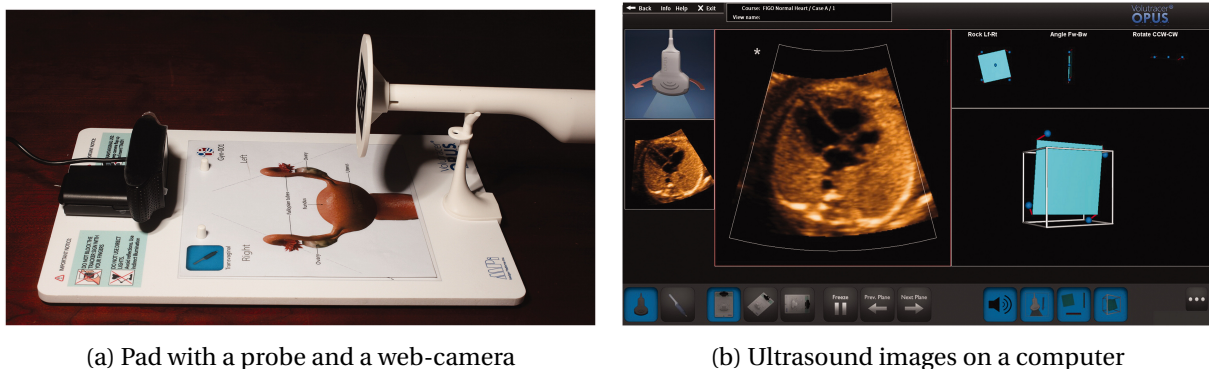
Figure 3.2: Source:"Optical ultrasound simulation-based training in obstetric sonography" [1]

Both tools use real data for training, but there are examples of fully simulating the Doppler results as well. Already in 2005, Khoshniat *et al.* [39] set out to show the ability to make a simulation tool for sonographers so that they can improve their hand-eye coordination and understanding of the effect of Doppler parameters. They used a motion-tracking device to mimic an ultrasound probe to simulate the interaction between the sonographer and the patient. In addition, they incorporated sonographer controlled parameters and showed their effect on a screen. Such as beam steering, colour box, depth, gain and angle correction. To track the ultrasound probe they have placed a magnetic motion tracking device that consists of a transmitter and a sensor on a neck or a cylindrical object to calculate coordinate systems in relation to each other. To show the 2D ultrasound image of the caortic artery, they project the 3D model onto the plane coming out of the ultrasound probe.

As we see so far it is possible to simulate the procedure using real or generated data. When visualising it, one usually attempts to resemble the actual ultrasound machines. The interaction with the simulation provides positive results using an ultrasound probe and adjusting parameters by hand. For tracking the probe there are examples of using images, positional and rotational sensors.

3.2   Ultrasound training in AR

So far we looked at non-AR educational tools, now we will explore the examples of how those training applications can be implemented in AR. One of the first examples is the work done by Palmer, Haugen, Tegnander, *et al.* [9], where they have synchronised the data from a GE Vivid E9 ultrasound machine with the 3D model seen through the AR screen. Their goal was to see if using mobile AR could help to accelerate the learning of sonography. In order to do so, Palmer *et al.* used one detectable to track the ultrasound probe and another on a patient's body. This way the detectable on the probe would show an ultrasound scan, and the detectable on the patient would show a heart as seen Figure 3.3a. In order to show the ultrasound data in sync with the model and the probe orientation, they had to implement a custom scanner plugin. They used Real-time Contour Tracking Library (RCTL) to find the heart landmarks to base the synchronisation on. Palmer *et al.* have also prototyped a fetal version where they rendered a 3D fetal model on the patient using a detectable and an echo plane rendered coming from the probe's detectable as seen in Figure 3.3b. This was just a proof of concept as the researchers lacked RCTL model for the fetus.
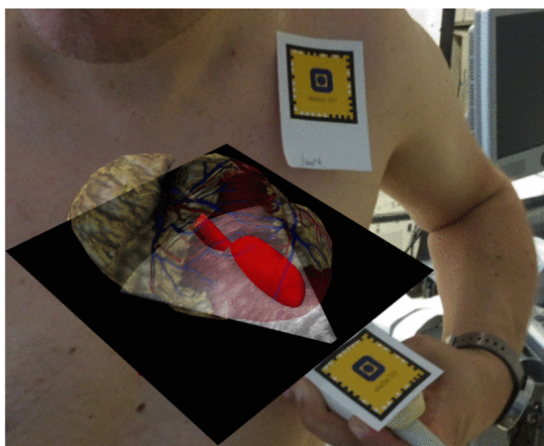
(a) Cardiac ultrasound   (b) Fetal ultrasound
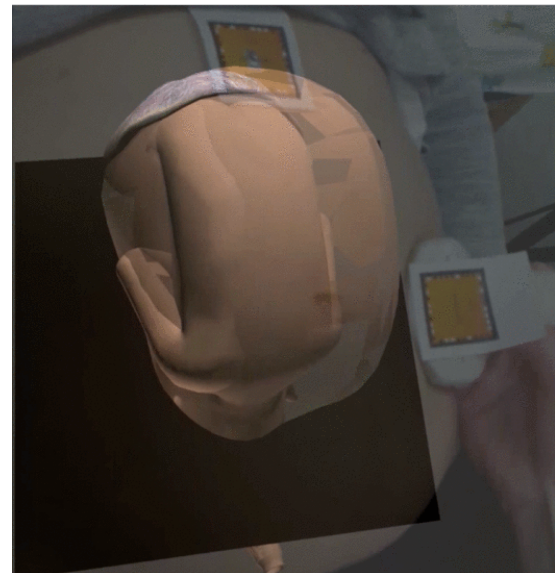
Figure 3.3: Source: Cardiac and fetal applications [9]

Palmer, Haugen, Tegnander, *et al.* discussed the various ways of mounting the mobile, that they have tested to give an operator a good view of the augmented scene. They also mentioned that placing the heart in the correct anatomical position within the patient's body gave the student quick insight as their ability to interpret diagnostic images was not fully formed. Palmer *et al.* believed that their application was 'a great promise as a teaching aid for both cardiac and fetal ultrasound applications' [9].

Another example where a high-end AR headset has been used instead of a mobile phone was implemented by "Augmented reality and ultrasound education: initial experience" [8]. They have tested and showed, that AR can be used for echocardiographic training. For that, they used Microsoft HoloLens 1 together with a "Vimedix TEE/TTE simulator" (CAE Healthcare, Montreal, Canada). In addition, the

set-up included a medicine mannequin and a computer loaded with the Vimedix software. The application allows for multiple users to see the same scene, so AR headsets were connected to the same Wi-Fi network. To synchronise the views between users they had to have the same anchor, which could be accomplished with a click and drag feature or via a detectable image placed beside the head of the mannequin. Authors commented that the booting of the software and calibration were the most time-consuming of the process.

The authors have created custom views for both trainee and instructor's perspectives, as seen in the Figure 3.4 below.
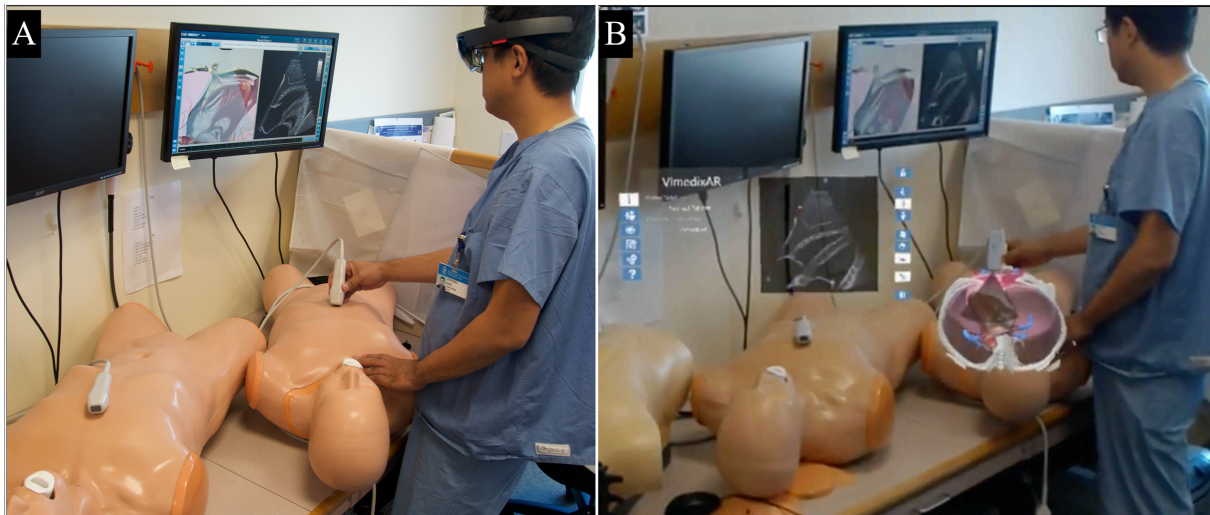
Figure 3.4: Left: User with the headset on. Right: Worn from the instructor's perspective. Source: [8]

The ability to see the same ultrasound scan from multiple perspectives allowed learners to practice finding views both with and without AR. The same image is also available on a 2D screen behind them. Together with the true 3D anatomical models, it improved understanding of the relationships between ultrasound images and the patient [8].

Mahmood *et al.* reported that AR not only enhanced education but also provided anatomical perspective during complex procedures. The AR technique received strongly positive responses from both the faculty and residents. The limitations of the application that they mentioned were the cost of the HoloLens; short battery life and the prolonged use of it lead to neck muscle fatigue.

Looking at those examples we see that AR allows for the visualisation of the relevant internal organs in 3D space as well as additional feedback on the interaction. Similarly to the non-AR applications tracking the ultrasound probe using images is a popular option as well as mannequins for providing context for the users.

Chapter 4

Method

4.1 Research process
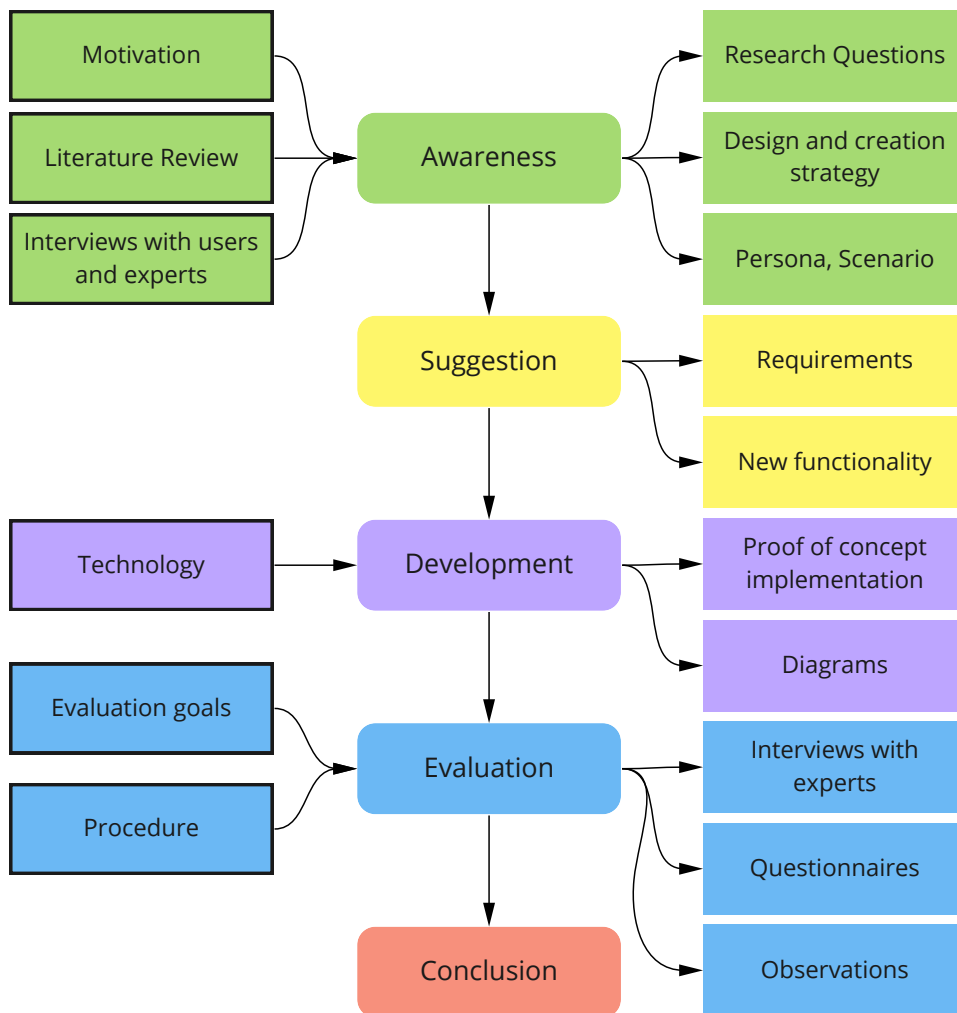
Figure 4.1: Research process in this project following suggestions of Oates, Griffiths, and McLean [40] and Vaishnavi and Kuechler [41]

Following the process shown in Figure 4.1, the research strategy used in this project was design and creation, where we developed an AR application that uses AR in a new domain: Doppler ultrasound training.

We have also evaluated the working proof-of-concept application for the target group. Here, we followed an iterative process suggested by Vaishnavi and Kuechler [41]: awareness, suggestion, development, evaluation and conclusion. Given the time constraints, we only had time for two iterations of the project. The data generation methods are highlighted in Figure 4.1.

We used quantitative analysis of the data from questionnaires containing interval (age), ordinal data (Likert scale) and some of the observations, grouping it as categorical data. For qualitative analysis, we conducted unstructured interviews with the experts from the field. The development methodology used was prototyping through iterations and evaluation of artefacts through proof of demonstration.

To find relevant research to be used in this thesis, we have looked at the research questions (section 1.2) and extracted the relevant parameters: AR, simulation, visualisation, interaction, sensor fusion, 3D printed objects or tangible AR, ultrasound, obstetrics, Doppler. Using a mixture of those keywords, we have found the related work described in chapter 3.

4.2 User Awareness

The first part of the process was to understand the problem and the target group. As highlighted in [42], it is important to apply user-centred development in AR. In order to understand the learners' needs and points of view to guide the development in the correct direction, we have created a Persona and scenarios based on the qualitative study by Ryan *et al.* [43], interviews with the experts and information from Norwegian Midwives Association [44] and the nursery institute at NTNU [45].

4.2.1 Persona

The Persona described in Table 4.1 has her values and personality based on the values of the Norwegian Midwives Association [44] and the nursery institute at NTNU [45]. Frustrations and goals are based on the interviews [43].

According to both the expert and the interviews [43], trainees find it especially important to perform procedures correctly and want to have confidence in a diagnosis made. Both sources mention that it is crucial to seek information from various sources depending on the situation. In order to see the overall image, one has to be fluent in the basics of a procedure to be able to build further on top of that. Further, [43] discussed the importance of a supportive teacher or peer, as peer to peer learning was a common method of learning.

Table 4.1: Persona

Name	Anna Truttvoll
Age	26
Occupation	- Student at NTNU in Trondheim - Working part-time at St. Olavs hospital
Location	Lives in an apartment in Trondheim with her partner
Hobbies	- Gardening - Hiking
Values	- Traditional - Brave - Unity - Visible - Closeness
Needs	- Time - More and better visualisations of procedures
Frustrations	Difficult to access simulators to practice
Goal	Perform procedures properly to get a correct diagnosis
Personality	Creative, critical, constructive and respectful

4.2.2　Scenario

Following the ISO specifications after creating Personas where we have concertized the target user and their goals, we describe the context of use with scenarios:

> The extent to which a product can be used by specified users to achieve specified goals
> with effectiveness, efficiency and satisfaction in a specified context of use. - (ISO 9241-11)

Although the trainees in [43] saw the benefits of AR/VR, they were concerned that the teaching support would be withdrawn. Experts also added that 'if students learn a bit everywhere then it will more difficult for them to see the whole image'. From those concerns, we understood that the application should work in tandem with the curriculum and not as a separate entity. As mentioned by the experts such an application would be useful to introduce in the lecture and allow the learner to continue exploration on their own. Meaning that the scenario seen in Figure 4.2, starts with the Personas in the lecture where she learns about the procedure. Later on, she independently continues to explore and learn using AR.

(a) Anna listens to the lecture about how to measure the blood velocity in the umbilical cord using Doppler ultrasound.
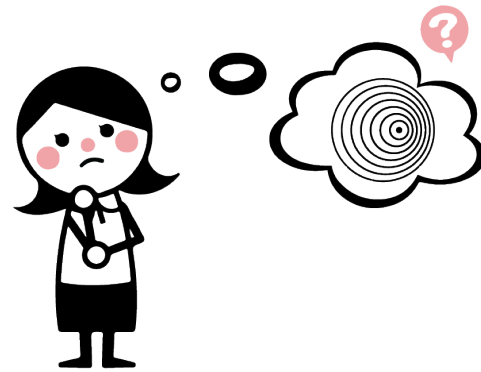
(b) After the lecture, Anna is still unsure about the relationship of some parameters in Doppler.
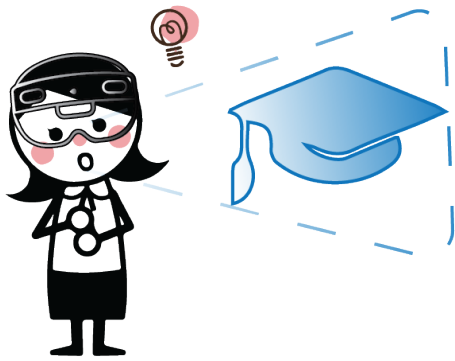
(c) So she decides to use the HoloUmoja application on HoloLens 2 at university to get a better understanding, even though she has never tried it before.

(d) There Anna sees the helpful holograms on top of 3D printed objects. She feels confident and curious to explore further.
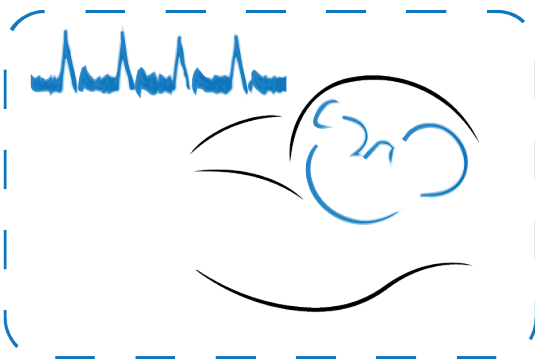
(e) The Doppler spectrogram changes based on her input when she explores the different parameters and practices how to correctly place the probe to obtain the ideal positioning of it with regards to the umbilical cord.

(f) In the end, Anna got a better basic understanding of the parameters and visualisations, so she is ready to move on to build on top of that knowledge.

Figure 4.2: Scenario showing how the previously described persona, Anna, would use the HoloUmoja application.

4.3   Requirements

The requirements were defined during this project together with the stakeholders based on the research made on the related work and user awareness.

Functional

FR1. **Application should run on HoloLens 2 headset.**
There were various high-end AR headsets that can be utilised, the chosen one was the one available at the beginning of the project.

FR2. **Track the position of a 3D printed probe and abdomen accurately enough for the procedure.**
It was decided early on in the project to use tangible AR in this application since hand-to-eye coordination and tactile feedback are so important in the ultrasound procedure.

FR3. **Render relevant 3D holographic models connected to the 3D printed objects.**
The power of AR lies in the ability to augment physical objects, so it was decided to explore further that relationship in this application.

FR4. **Simulate a Doppler spectrogram in real-time based on some input parameters as they change.**
Midwives use a Doppler spectrogram to estimate the measured blood velocity in real-time, so the application should provide it for educational use.

FR5. **Allow for a user to change some input parameters that affect the Doppler spectrogram.**
To learn the effects and proper use of the parameters the user should have control over them.

FR6. **Derive the angle between the 3D printed probe and the virtual umbilical cord.**
One of the important aspects of the procedure is the placement of the ultrasound probe. So, it was devised with the stakeholders that the beam-to-flow angle could be controlled by the 3D printed probe.

FR7. **Application should have a tutorial.**
Even though nurses have good computer literacy and positive attitude to computers [46], they had little exposure to AR [43]. They should be able to learn to use the application independently.

Non-functional

NFR1. **Midwife students and educators should find potential educational use for the application.**
Although, in this project, we did not focus on the educational benefits of the application but rather on the technical feasibility. It was important to gather the feedback from medical professionals if HoloUmoja could be beneficial.

NFR2. **Relevant app quality criteria for HoloLens application should be met.**
There is an official guide [1] written by Microsoft for HoloLens applications. Our goal was to meet the criteria on the relevant ones such as frames per second (FPS), hologram stability, viewing zone and input interaction.

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[1] https://docs.microsoft.com/en-us/windows/mixed-reality/develop/advanced-concepts/app-quality-criteria-overview

4.4 Technology

In this section, we will shortly describe the technology that has been used for the creation of the HoloUmoja application. The specific implementation details will follow in chapter 5.

4.4.1 HoloLens 2

Microsoft HoloLens 2 is an untethered holographic computer [47]. It uses four visible light cameras, one depth sensor and inertial measurement units (IMUs) to track the head, hands and its surroundings. In addition, it has two infrared (IR) cameras for eye tracking. A user wears HoloLens on their head and looks through the glass to see holograms overlay their surroundings.

4.4.2 Unity 3D Engine

Unity 3D Engine is a game engine that allows for visualisation of the application, scripting through C# and drag-and-drop functionality. As seen in Figure 4.3, this is Unity Editor where developer can control the 3D models, its position and functionalities in a visual way. For simplicity, further in the text, it will be referred to just as Unity. The program strongly follow a Component pattern [2] where one works with objects (sometimes called *prefab*, if it was saved in itself) with components, everything from position and rotation to making it show an image. One places objects into a *scene* sometiems controlling their hierarchy. Developers can add their own component by making a script inherit *MonoBehaviour* script. Unity is the main program where the majority of development was done in this project. What makes Unity especially powerful is the range of packages that can be installed to fit the engine to one's needs. In our case, we have utilised the MRTK and Vuforia packages that will be described further in this section.
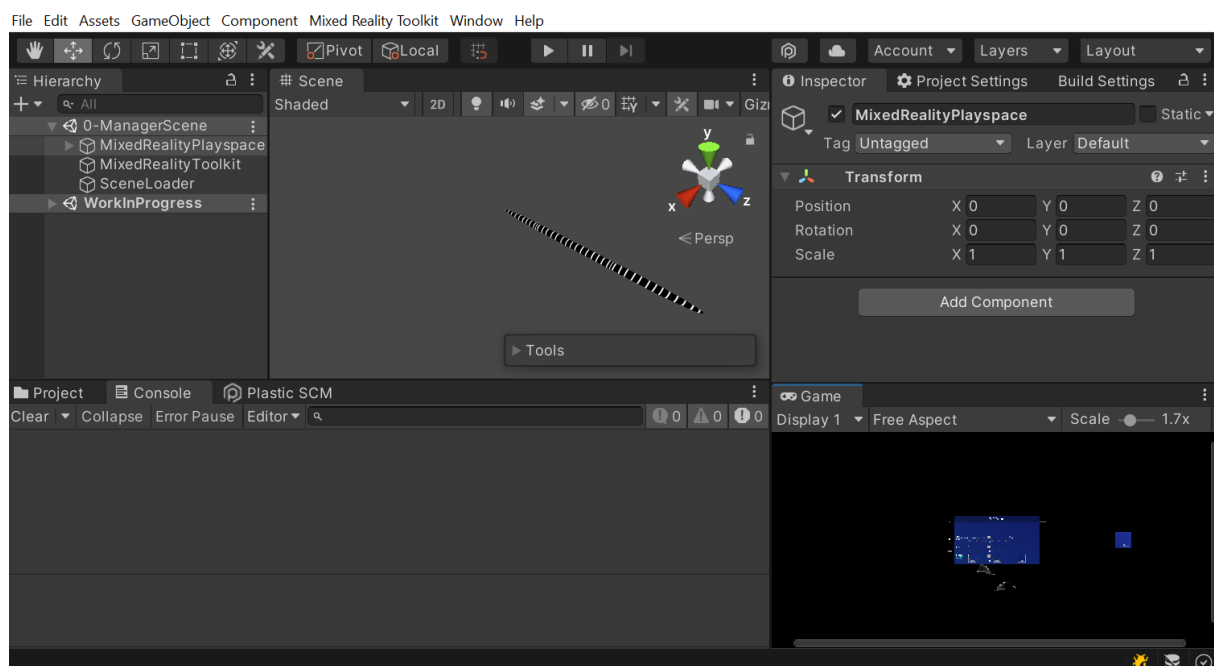
Figure 4.3: Unity Editor window

---

[2] https://gameprogrammingpatterns.com/component.html

4.4.3   Mixed Reality Tool Kit (MRTK)

MRTK was developed by Microsoft specifically for HoloLens, it contains the configurations for building to HoloLens and pre-made templates for UI and interactions. It also has a simulation window allowing for testing inside Unity without a HoloLens, thus easing the development process.

4.4.4   Vuforia Engine Library

Vuforia can be added to Unity to make HoloLens recognise a defined image and calculate its position and rotation. To define the image to track, one needs to upload a picture to the Vuforia website for it to become an Image Target. The website provides standard assets of different suitable images for tracking [3].

4.4.5   Arduino Nano 33 BLE

The Arduino Nano 33 BLE is one of the newest and smallest boards created by Arduino company. They are known for making easily programmable boards with a variety of sensors and capabilities. It is heavily supported by the open-source community, so there are a range of libraries for additional functionality. We have used the open-source *LSM9DS1 library* by Verbeek [48] which is an extension of the official Arduino LSM9DS1 library. Further in this paper, we will refer to this board simply as Arduino. It comes with a 9 axis LSM9DS1 IMU chip with an accelerometer, gyroscope and magnetometer (to read more about the sensors refer to subsection 2.3.2). For connection with other devices, it has Bluetooth Low Energy (BLE) (more about that in section 5.3.5) and WiFi.

4.4.6   Visual Code + PlatformIO

For programming in C/C++ and building to Arduino, we have used Visual Code editor with PlatformIO add-on. The latter makes it compatible with Arduino. Together it allowed for easier library handling, API look-up and compilation.

4.5   Process

The development together with the research process could be described in two phases. Where the first version HoloUmoja 1.0 was developed and tested to be further iterated toward HoloUmoja 2.0. For the detailed process of implementation of those versions, see chapter 5. In Q3 and Q4 of 2021, the development was mostly done in monthly sprints since it was a part-time project. In Q1 and Q2 of 2022, it went over to be a full-time project. Figure 4.4 presents the GANTT chart for 2021 in and Figure 4.5 for 2022. Both phases followed the awareness - suggestion - development - evaluation process described in section 4.1.

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[3]https://library.vuforia.com/objects/image-targets#using-image-targets

		August				September				October				November				December			
		31	32	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
0	**Initiation**																					
0.1	Project Introduction																					
0.2	Explore ultrasound domain																					
0.3	Explore AR domain																					
0.4	Set up Unity Engine																					
0.5	Set up Vuforia																					
0.6	Explore detectables																					
1	**HoloUmoja v1.0**																					
1.1	Further research																					
1.2	Doppler code in Unity																					
1.3	Add full-body hologram																					
1.4	Angle tracking																					
1.5	Finalise demo																					
1.6	Feedback on the demo																					
1.7	Finalise report																					

Figure 4.4: Q3 and Q4 of 2021 working on HoloUmoja v1.0

		January				February				March				April				May				June			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	**HoloUmoja v1.0**																									
1.8	Evaluation phase 1																									
1.8.1	Research how to																									
1.8.2	Plan																									
1.8.3	Schedule																									
1.8.4	Testing																									
1.8.5	Expert feedback																									
1.9	Analyse results																									
2	**HoloUmoja v2.0**																									
2.1	Decide focus areas																									
2.2	Research solutions																									
2.3	Experimenting																									
2.4	Implementation																									
2.4.1	Fetus model																									
2.4.2	User Interface																									
2.4.3	Spectrogram axes																									
2.4.4	Improved tracking																									
2.5	Evaluation phase 2																									
2.5.1	Plan																									
2.5.2	Schedule																									
2.5.3	Testing																									
2.5.4	Expert feedback																									
2.6	Analyse results																									
2.7	Finalise rapport																									

Figure 4.5: Q1 and Q2 of 2022 mostly working on HoloUmoja v2.0

4.6   Evaluation

For this project, the goal was to evaluate the visualisation and simulation possibilities, the usability of the application and sensor improvements, see RQ in section 1.2. Testing happened in two phases: the first one focused on the issues with the application to be fixed in the next iteration (formative tests); the second one was used to gather overall information about the resulting application (summative tests). Together with the questionnaire for AR applications - SPINE, we have gathered demographic information and noted relevant observations and feedback during the user tests. In addition, we gathered feedback from the experts in the field.

Now we will go through why we tested, who we tested on and how, including the procedure and tracked metrics. In the end, we will mention how we have analysed the results.

4.6.1   Goals

We were testing the first version of the application to find out if the experience and controls were understandable and comfortable. Here we describe the goals of the first test and which requirements it refers to:

- Onboarding: understanding the goal of the application, capturing the tracking images → FR1, FR7

- Positioning of the menus and spectrogram graph → NFR2

- Interaction with variables (PRF, sampling depth, beam-to-flow angle, blood velocity): sliders, pinching → FR4, FR5, FR6

- Visibility of the holograms → FR3

- Stability of tracking, especially when controlling the angle → FR2, NFR2

Meaning that the only requirement that was not set to be tested in the first phase was NFR1. Regarding the research questions, RQ1, RQ2 and RQ2.1 were the primary goals without the focus on the midwife students.

For the second phase of testing, we had the same goals as in phase two with addition of:

- Additional tracking using the gyroscope → FR2

- The tutorial → FR7

- Potential education use → NFR1

This way, during the second phase we explore all the research questions mentioned in section 1.2.

4.6.2   Target test users

For each phase, our goal was to recruit at least 5 users. Following Turner *et al.* [49]: "Five users are able to detect approximately 80% of the problems in an interface, given that the probability a user would encounter a problem is about 31%.". Test-users were mostly chosen following convenience sampling

where researchers attempted to follow the Persona created for the application subsection 4.2.1, for example in age or education level.

As defined in Goals subsection 4.6.1, it was during the second phase of evaluation, that it was important for us to test with the users with the relevant background. Thus we were able to collaborate with St.Olavs to test with two midwife students and get feedback from the experts Eva Johanne Leknes Jensen, Eva Tegnander and Sturla Hall Eik-Nes. During the first phase, due to restrictions caused by the Covid-19 pandemic, it was challenging to find test users, especially those with a medical background as St. Olavs Hospital in Trondheim was in yellow prepareness mode for large part of the period.

4.6.3 Questionnaire

When testing usability, we followed the definition from the ISO 9241-11 standard of usability [50]. It describes usability in three components: system effectiveness, system efficiency and system satisfaction. To test those, there exist various methodologies for evaluating HCI, but there are not many instruments specifically tailored for AR. AR is different from other software applications such as phone applications or web-sites because of its relationship to the real world (spatial mapping) and the user's body (gestures, eye tracking). As such we have found the spatial interaction evaluation (SPINE) [51] questionnaire to measure the usability of AR applications in regard to spatial mapping. It consists of 27 statements that a user can express agreement with through the Likert scale. Those statements are grouped into six categories: system control, navigation, manipulation, selection, input modalities and output modalities. The statements and the explanation for those groups and what SPINE measures can be found in Appendix A.4.

For testing visualisation and simulation possibilities and the stability of tracking and sensor improvements, we have used feedback gathered from the experts and users through questionnaires, metrics and observations. The resulting questionnaire with questions about demographic information and statements from SPINE can be found in the Appendix A.5.

4.6.4 Collected metrics

Following the recommendations in "A practical guide to measuring usability" [52], we have collected the following metrics during the tests:

1. **Usability problems encountered**. Describing the problem, how many and which users encountered it.

2. **Errors**. Any unintended action made by the user while attempting a task.

3. **During-Task comments**. Explanations for actions mentioned by the user during the task.

4. **Post-Task comments**. Any opinions or comments mentioned by the user when the task is completed or abandoned.

5. **Post-Test comments**. Any opinions or comments mentioned by the user when the test is completed.

4.6.5   Procedure

We have also completed pilot tests before the testing with other users to check if the tasks, application
and testing setup were satisfactory. The data from the pilot tests were not included in the results.
During the test, we asked the user to think out loud. We used the following agenda when performing
the tests:

1. Welcoming the user; explaining the purpose of the project and the process of testing.

2. If the person is not familiar with the Doppler ultrasound procedure, explaining its purpose.

3. Reading and signing informed consent, shown in Appendix A.2.

4. Running eye calibration.

5. Running the application.

   - During phase 1:

     (a) If the user has never used HoloLens before, we started the standard hand gesture
         HoloLens tutorial

     (b) Performing tasks in HoloUmoja v1.0 described in Appendix A.3.

   - During phase 2:

     (a) Asked to follow the instructions in the HoloUmoja v2.0 application

6. Answering any post-test questions from the user.

7. Filling out the questionnaire.

8. Thanking the user for participating.

The implementation of the v2.0 of the application included a tutorial, so one did not need to use an
external one, and it allowed users to get enough instructions to proceed further in the testing without
the use of tasks. The duration of the test was planned to be somewhere around 1 hour depending on
the user's experience with HoloLens. Avoiding using specific tasks during phase 2 allowed for better
evaluation of RQ2.1 (1.2) - usage without external guidance.

4.6.6   Analysis

The demographic information about the users was summarised for an easier overview. The question-
naires used a seven-point Likert scale, so the data coding converted the values to 1 (strongly disagree),
7 (strongly agree) and the middle, 4, indicated 'neither'. When calculating the score, the negatively
structured questions (NG3, MP2, MP3, MP4) were reversed in polarity and "would be" questions
(IM01, IM03) were not included in the calculation. The resulting data from the questionnaire can
be found in section 6.3. The qualitative data such as observations and feedback were summarised
and labelled for further discussion as can be seen in section 6.4.

5

Implementation

The project was conducted over two semesters, it was divided into two phases where each ended with an evaluation of the versions following the described process in section 4.6. The first phase had as its goal to create a working prototype whereas the next one implemented improvements based on the evaluation. In this chapter, we will describe the implementation of the first version chronologically and the next by features.

5.1 Initial experimentation

At the beginning of the project, the goal was to make a working demonstration of using Unity Engine with Vuforia and HoloLens 2. We have first decided to experiment with the form of detectables: a simple Image Target tracking with the placement of a 3D cube on it (Figure 5.1a); or a cylindrical tracking with a 3D cylinder beside it (Figure 5.1b). The latter seemed promising as it allowed continuous tracking of a probe no matter its orientation.

| (a) Image Target tracking | (b) Cylindrical Target tracking |

Figure 5.1: The first working prototype as seen through the HoloLens 2 lenses

5.1.1 Full body with cylindrical tracking

Once the simple tracking was tested, we attempted adding a 3D model of a patient to the Image Target (Figure 5.2a). We also added 3D models of arrows that represented the orientation of where the ultrasound probe *should* be placed to get the correct view. We used the cylindrical target to function

as an ultrasound probe and added an ultrasound image coming out of it (Figure 5.2b). In the floating blue menu, we showed the calculated angle between the two orientations on the abdomen of the patient and the probe.
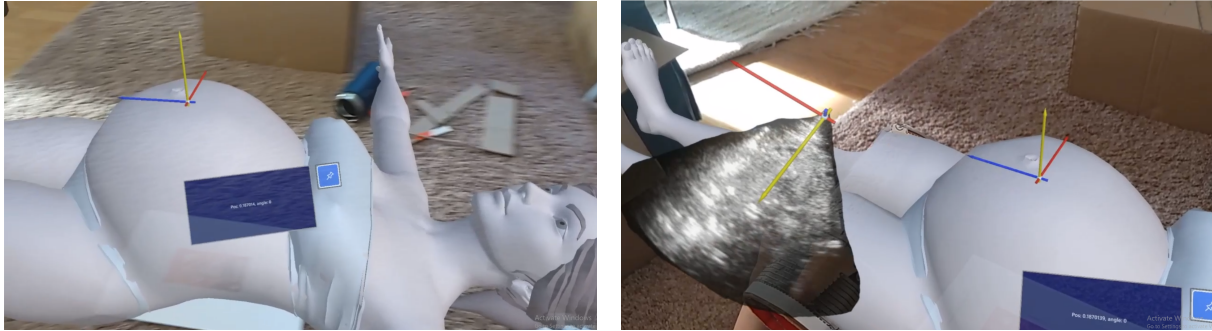
(a) Full female body model on top of an Image Target with a simple UI

(b) Ultrasound image based on the cylindrical target

Figure 5.2: Second demo with a full-body patient and a cylindrical target as the ultrasound probe

The application was uncomfortable to use because HoloLens 2 has a limited field of view, so the user could only see a part of the holographic patient at any time. In addition, FPS has dramatically dropped because the model had more polygons than recommended. It is suggested that the 3D models shown in the AR space should have less than 100k polygons [53], because the more triangles the heavier it will be to render it twice, once for each eye. The cylindrical tracking target was often lagging behind, which in turn made it really difficult to place the orientation correctly in regards to the one on the abdomen of the patient.

5.2   Phase 1: HoloUmoja v1.0

Seeing the results from the experimentation, we decided against using the cylindrical tracking as it was too unstable, and not including the model of a patient as it was too complex for HoloLens. Instead, we used Image Target for ultrasound probe tracking and a fetus model with an umbilical cord. But first, we worked on the ultrasound simulation.

5.2.1   Doppler Spectrogram

To simulate a Doppler spectrogram, we turned to the DopplerSim Applet [54] code written by Hammer in 2014. It is a desktop application that allows a user to simulate a Doppler signal controlled by four variables, see Figure 5.3. On the left side of the image, we see a 2D visualisation of an umbilical vein (red) and artery (blue) with black lines overlapping it. The black vertical lines represent the ultrasound waves with the sampling depth window, if the window does not overlap the umbilical cord, we get no signal. Four sliders to control the four variables are visible a bit to the right, together with the resulting simulated Doppler signal over time to the far right.

To make that program compatible with the Unity Engine and to be able to build to HoloLens, we have rewritten the code responsible for creating the Doppler signal from Java to C# language and Unity's in-built functions. We added the ability to change the parameters in the editor and added
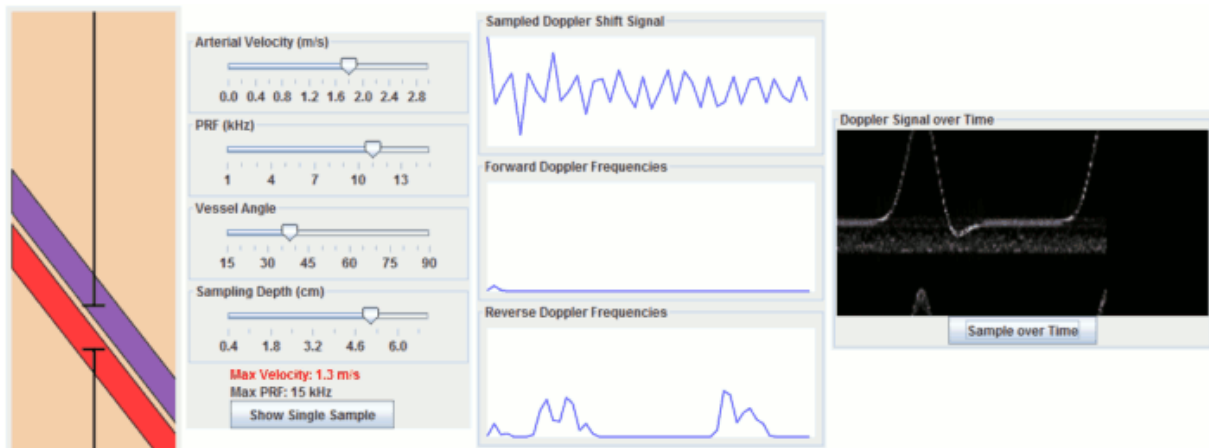
Figure 5.3: Desktop application DopplerSim Applet by Mark Hammer

an animation to simulate the sampling of Doppler over time, this resulted in an application seen in Figure 5.4.
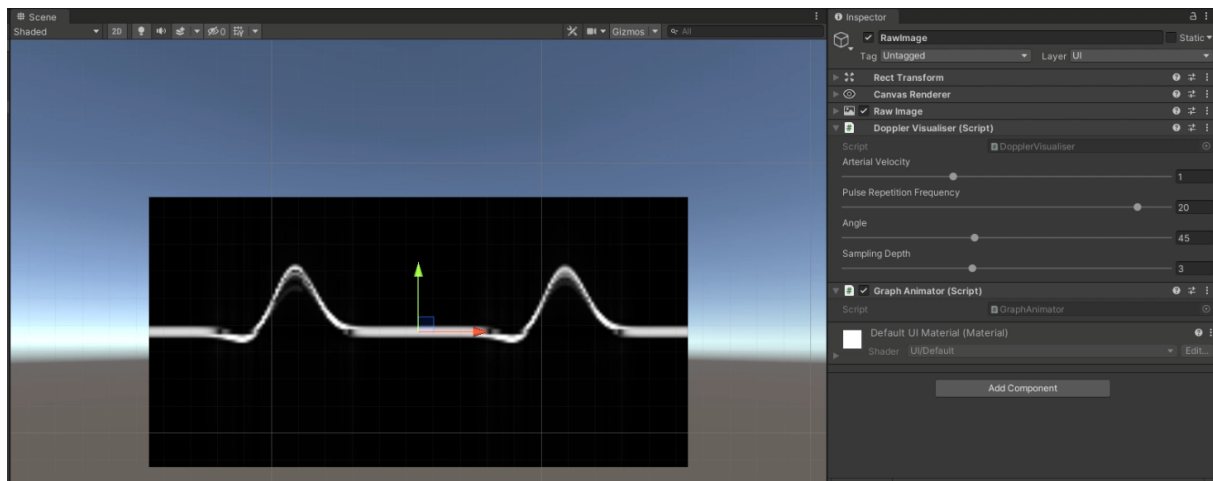
Figure 5.4: Doppler spectrogram in Unity Engine with parameters to the right

5.2.2   Angle parameter

With the Doppler simulator functioning, we returned to HoloLens development. As mentioned, we decided to use Image Target for tracking the probe as it proved to be more stable. As one can see in Figure 5.5 a line coming out [1] of the Image Target represents an ultrasound signal, so when it intersects the red capsule which represents an umbilical cord, we were able to calculate the angle between them as shown in Listing 4. The pseudo-code for that can be seen in algorithm 1 and C# implementation in Appendix 4.

To our confusion, this demo run only between 10 - 25 FPS on HoloLens when the ray intersected the umbilical cord and the Doppler spectrogram changed. This was below the given requirements

---

[1]The ray coming from the "Astronaut" Image Target seems to have an offset as seen in Figures 5.5 and 5.8b. It is caused by the picture being taken from the view rendered only for one of the eyes. When the views rendered for both eyes are combined for the user wearing the HoloLens 2, the ray is placed correctly coming out of the centre of the Image Target.

Algorithm 1 Algorithm to calculate beam-to-flow angle between Image Target (ultrasound probe) and model of an umbilical cord

---

$imageTarget \leftarrow$ position and rotation information of the Image Target
$raycastHit \leftarrow$ cast a ray from $imageTarget.position$ in the $forward$ direction and return a hit
if $hit \neq NULL$ **then**
    $angle$ = calculate angle between $imageTarget.forward$ and $raycastHit.forward$ ▷
radians
    $cosAngle \leftarrow abs(cos(angle))$
    $currentAngle \leftarrow FromRadToDeg(Acos(cosAngle))$
    $currentAngleRounded \leftarrow RoundToInt(FromRadToDeg(currentAngle))$
    if $currentAngleRounded \neq prevAngle$ **then**
        Notify about the angle changing
        $prevAngle \leftarrow currentAngleRounded$
    end if
end if
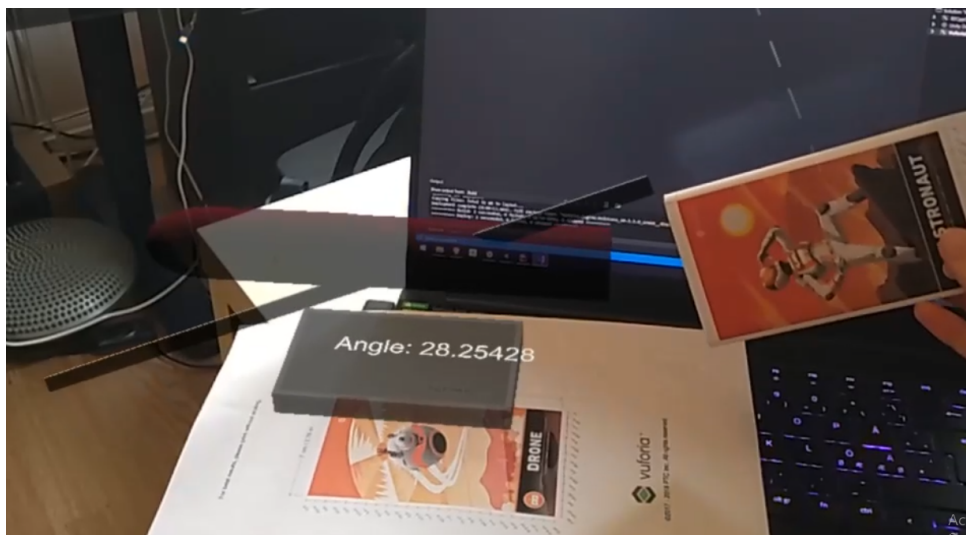
Figure 5.5: Angle control using an Image Target

section 4.3 and that was without any 3D model of the patient or the fetus which we expected to slow down HoloLens 2 even more. Unity Engine has an in-build profiler that lets the developer see an overview of the functions for every frame and how much processing power they require. We used the mentioned profiler on our application to optimize the code to return FPS to acceptable levels. The biggest difference was achieved by calculating only one row of the plot for each frame by using a *Coroutine* as can be seen below in listing 1.

```csharp
// ... class DopplerVisualiser ...
private IEnumerator UpdateDopplerGraphRoutine(Action onFinish) {
    for (int t = Simulator.n_timepoints - 1; t >= 0; t--) {
        Simulator.UpdatePlot(t);
        yield return new WaitForEndOfFrame();
    }
    onFinish();
}
// ... class DopplerSimulator ...
MatrixPlot plotTime;
public void UpdatePlot(int timepoint) {
    plotTime.data[timepoint] = generateDisplay(getVelocityComponents(depth),
                    arterialPulse(1.0D, timepoint));
    plotTime.setOneDataRow(timepoint);
}
// ... class MatrixPlot ...
public void setOneDataRow(int col) {
    for (int x = 0; x < width; x++) {
        texture.SetPixel(x, col, new Color((float) data[col][x],
                        (float) data[col][x], (float) data[col][x]));
    }
    texture.Apply(false);
}
```

Listing 1: Each function is in different classes but visualised here together for easier understanding.

5.2.3   User Interface

We used MRTK to create a menu to show the Doppler spectrogram and allow the user to change parameters such as sampling depth, PRF and blood velocity. Compared to the parameters we see in Figure 5.4 to Figure 5.6b, we only see three parameters, because the angle parameter comes from the intersection of the ray and umbilical cord. We also added a Welcome menu to explain the usage of the application (Figure 5.6a).
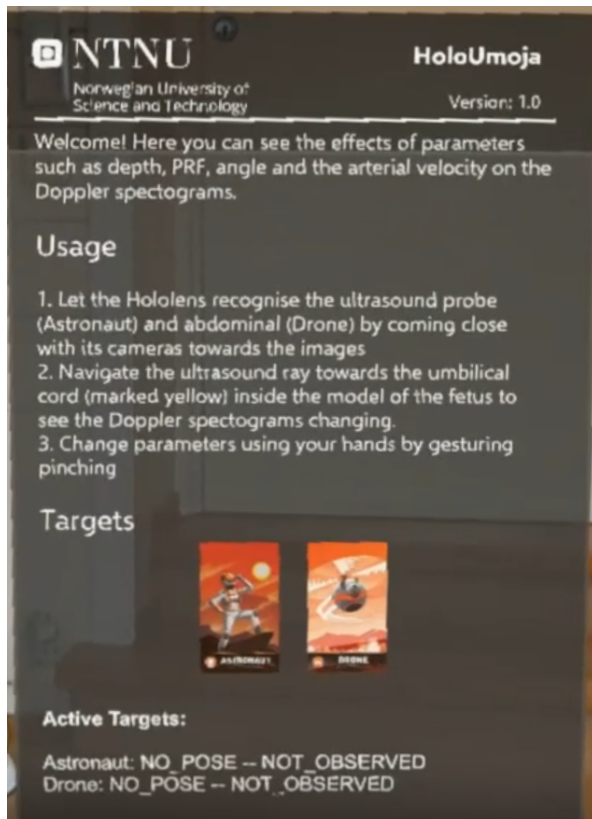
(a) Welcome menu giving instructions
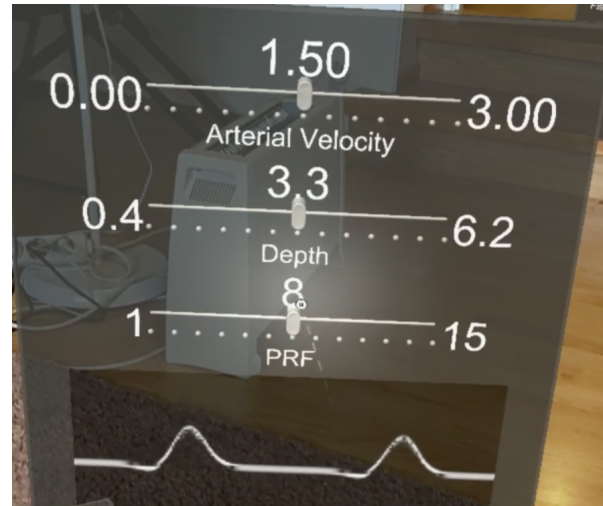
(b) Sliders to control parameters and Doppler spectrogram

5.2.4 3D printed models

Figure 5.7: 3D printed models of an ultrasound probe and abdomen.

Once the Doppler simulation and parameters control were achieved we were ready to combine it with the 3D printed objects. The ultrasound probe and abdomen, seen in Figure 5.7, were modelled and 3D printed by Jan Magne Gjerde from the Operating Room of the Future - FOR, St. Olavs Hospital. We added the Image Targets to the positions and made holograms (the fetus and ultrasound ray) appear in relation to those images.

5.2.5 Finished v1.0
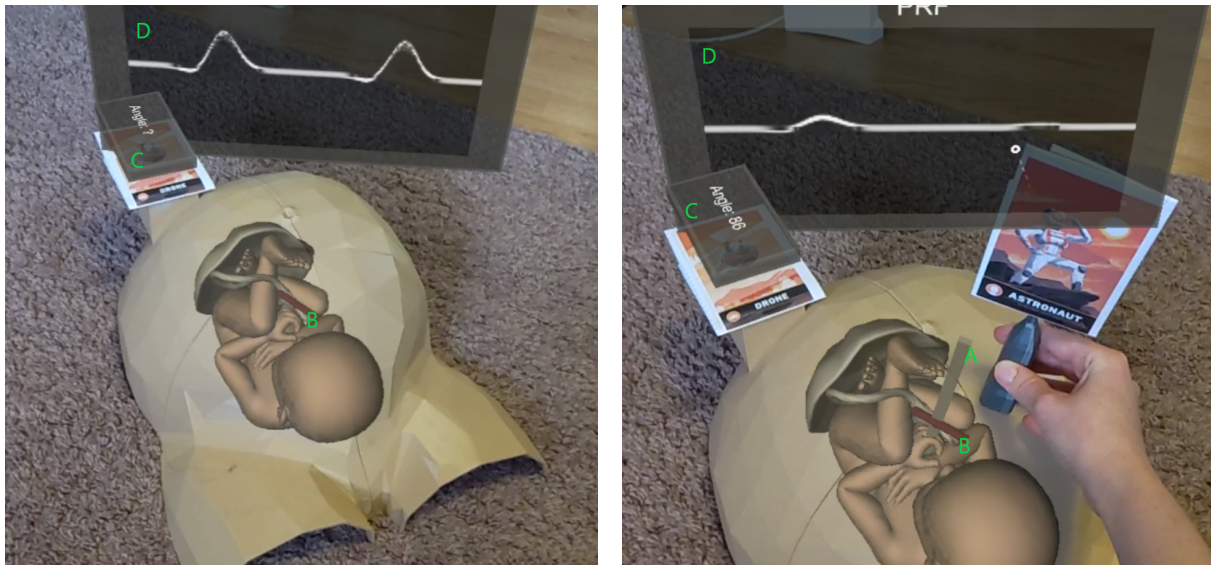
(a) Fetus model inside the 3D printed abdomen, Doppler spectrogram is unchanged

(b) Doppler changed based on the angle between the ray from the probe and the umbilical cord

Figure 5.8: Final working demo with 3D printed objects and a model of a fetus with an umbilical cord

The demo videos of this and other versions can be found in section 6.2. In Figure 5.8, we have labelled the different artefacts of the application with green capital letters, see their explanations below.

A. Ultrasound signal - the ray coming out of the 3D printed ultrasound probe.

B. Umbilical cord - red capsule showing the part of the umbilical cord that will react to the ray to calculate the angle.

C. Angle menu - shows the calculated angle between the ultrasound signal and the umbilical cord.

D. Doppler spectrogram - changes based on the angle and the three other parameters. In Figure 5.8b it is almost flat because the angle is close to 90°.

The implementation architecture of the HoloUmoja v1.0 is visualised in Figure 5.9. For simplification, we have divided the components into three groups: Doppler simulation, user interface and Unity scene. Unity scene contains prefabs which are Unity specific objects that can have 3D models and components connected to them. There we have an image with the Doppler spectrogram rendered to it, three sliders and two Image Targets from Vuforia. Sliders have *SimpleSliderBehaviour* components connected to them, to get updated values from the user. Astronaut ImageTarget is the ultrasound probe in our case and has *RaycastAngle* components to interact with the umbilical cord model that is connected to the Drone ImageTarget. *DopplerGraph* prefab has *DopplerVisualiser* MonoBehaviour components that use *DopplerSimulator* class to simulate the Doppler spectrogram based on the values given by *DopplerUI* MonoBehaviour. *MatrixPlot* class is a way to store two-dimensional data when simulating Doppler.
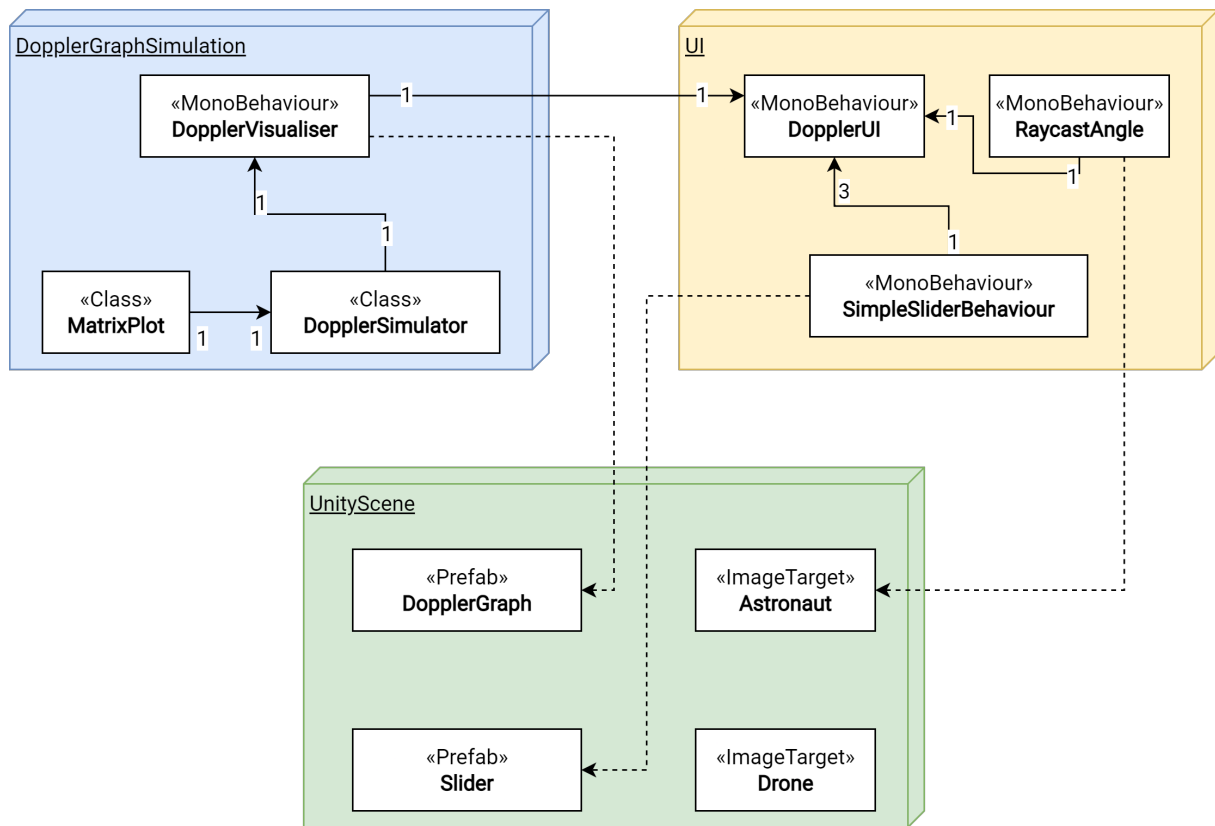
Figure 5.9: Relationship between the components and prefabs in Unity in HoloUmoja 1.0

5.3 Phase 2: HoloUmoja v2.0

Using the results gathered from the phase 1 of testing, described in section 6.3 and section 6.4, the improvement areas were decided together with the stakeholders. For easier understanding, we are including Figure 5.10 that describes the final relationship between the implemented components in subsection 5.3.1. Then we explain the development process of the different features.

5.3.1 Overview
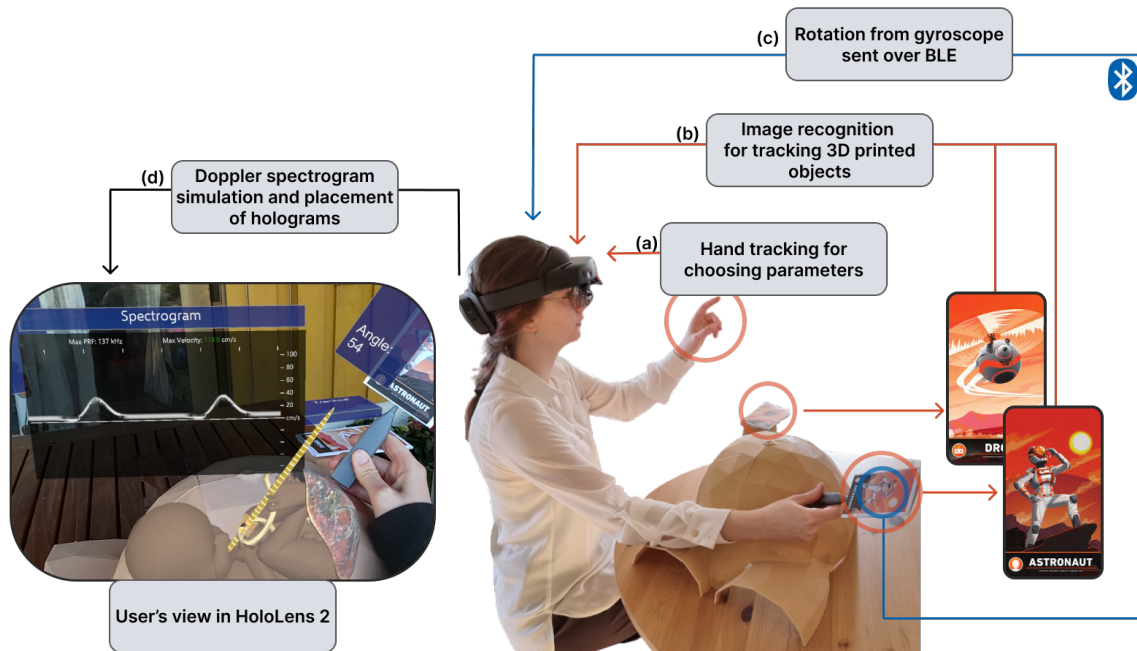
Figure 5.10: The components of HoloUmoja application: 3D printed abdomen and probe (the sensor is behind the tracking images) with Vuforia Image Targets and HoloLens 2

In Figure 5.10, one can see that (a) hands and (b) images are tracked by the HoloLens 2 headset which is able to recognise hand gestures for interactions, and position and rotation of the images to place their respective holograms. At the back of the 3D printed probe, there is an attached Arduino with a battery that sends (c) rotation from Gyroscope over BLE to HoloLens 2. There, the HoloLens combines the rotation from the gyroscope and image tracking to provide a more stable orientation of the probe. Based on the angle of the probe in regards to the umbilical cord and other parameters chosen by the user using their hands, it simulates the (d) Doppler spectrogram. The videos of how HoloUmoja works can be found in section 6.2. The overall architecture of the resulting application can be found in Figure 5.28.

5.3.2 Fetus model

The original fetus model used in the previous version had around 20k polygons, which is below the suggested count [53]. Our application still had FPS fluctuations and such a detailed model of the fetus was not necessary for our goal. So we have reduced the model down to around 10k polygons.

The resulting comparison can be seen in the Figure 5.11.

First, we used FBX Converter [2] to convert FBX to FBX Blender compatible format, then used *decimate* and *subdivision faces* modifiers in Blender to simplify and smooth out the surface.
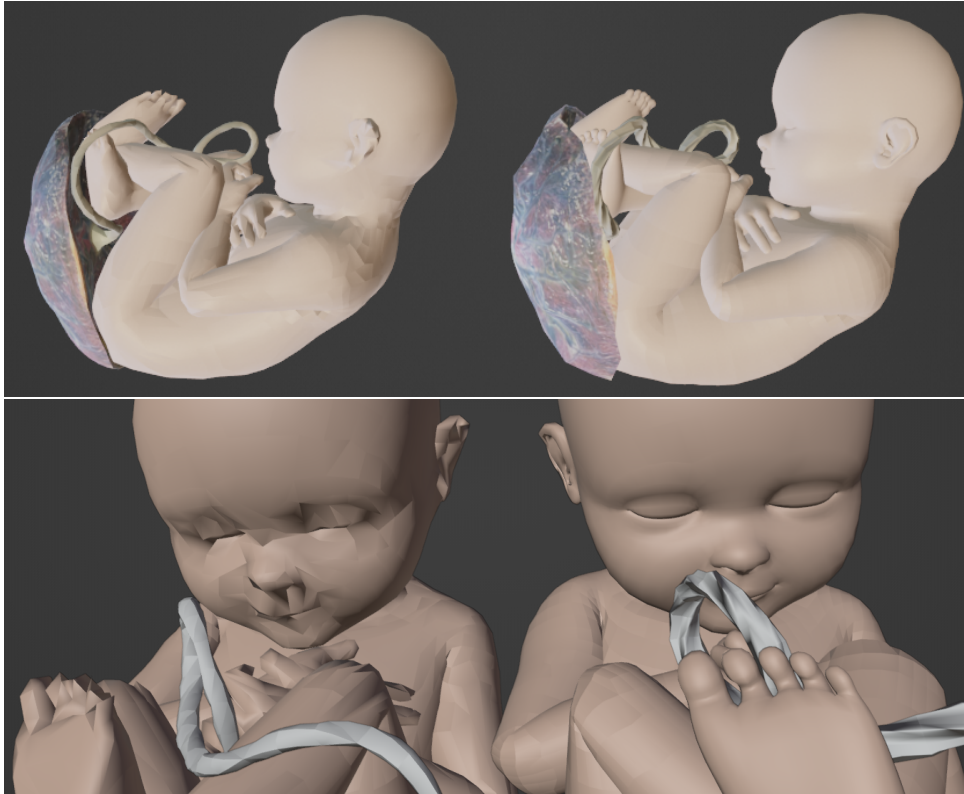
Figure 5.11: Detailed comparison of initial and simplified fetus models. Left: simplified. Right: initial.

In our observations from phase 1 (Table 6.2), OB07, seeing that users struggled to understand which part of the umbilical cord one needs to intersect with, we created a gap in the umbilical cord and added blood texture inside, as shown in Figure 5.12.

Figure 5.12: Fetus model with the gap in the umbilical cord signalling which part it can intersect with.

---

[2]https://www.autodesk.com/developer-network/platform-technologies/fbx-converter-archives

5.3.3 User interface

In OB03, users ignored the menu instructions as seen in Figure 5.6a, so we attempted to divide them into step-by-step actions. The flow of the new interface is represented in Figure 5.13. Additional views of the menu can be found in the Appendix section A.9.
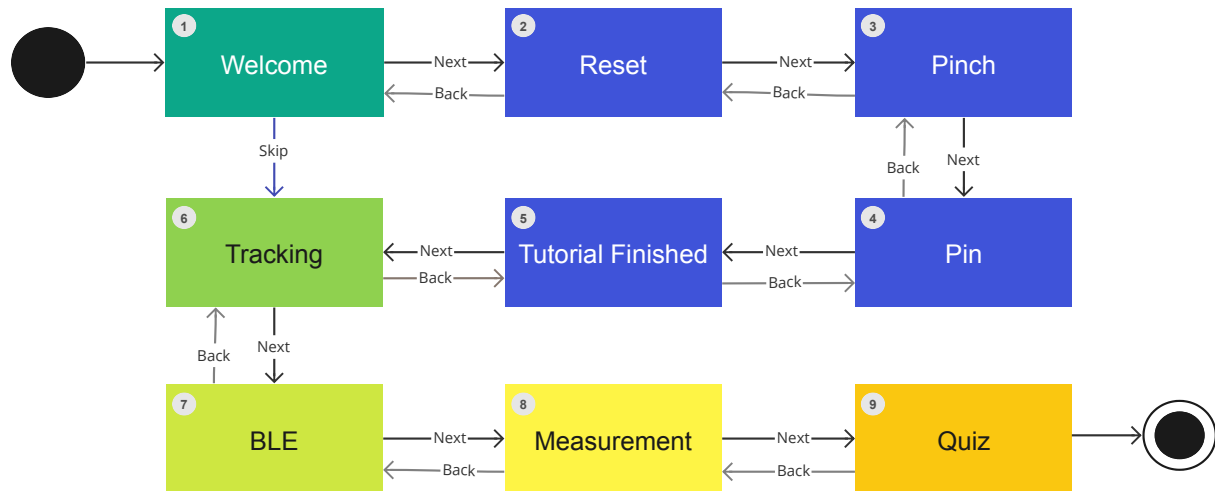
Figure 5.13: Menu Flow where rectangles are the menu views and arrows represent the button actions the user can take.

To easily control the flow of the menu, we have chosen to implement the State Design pattern [3]. The UML diagram in Figure 5.14 provides a simplified overview of it. *MenuContext* is a class that controls the flow, knows the current state and has an overview of all the possible states. To define states we have used an enum *MenuType*. Then there is an abstract class *MenuState* that *MenuContext* calls *Show()* or *Hide()* functions when changing states. The different *MenuState* inherited classes contain all the specific behaviour that happens when that menu is activated. Every *MenuState* has a reference *gameObjectMenu* to the UI object in Unity that it enables and disables. This pattern leads to no coupling between the different menu states, so the order and number of the menu states can be quickly changed.

---

[3]The example for State design pattern we followed: https://refactoring.guru/design-patterns/state/csharp/example
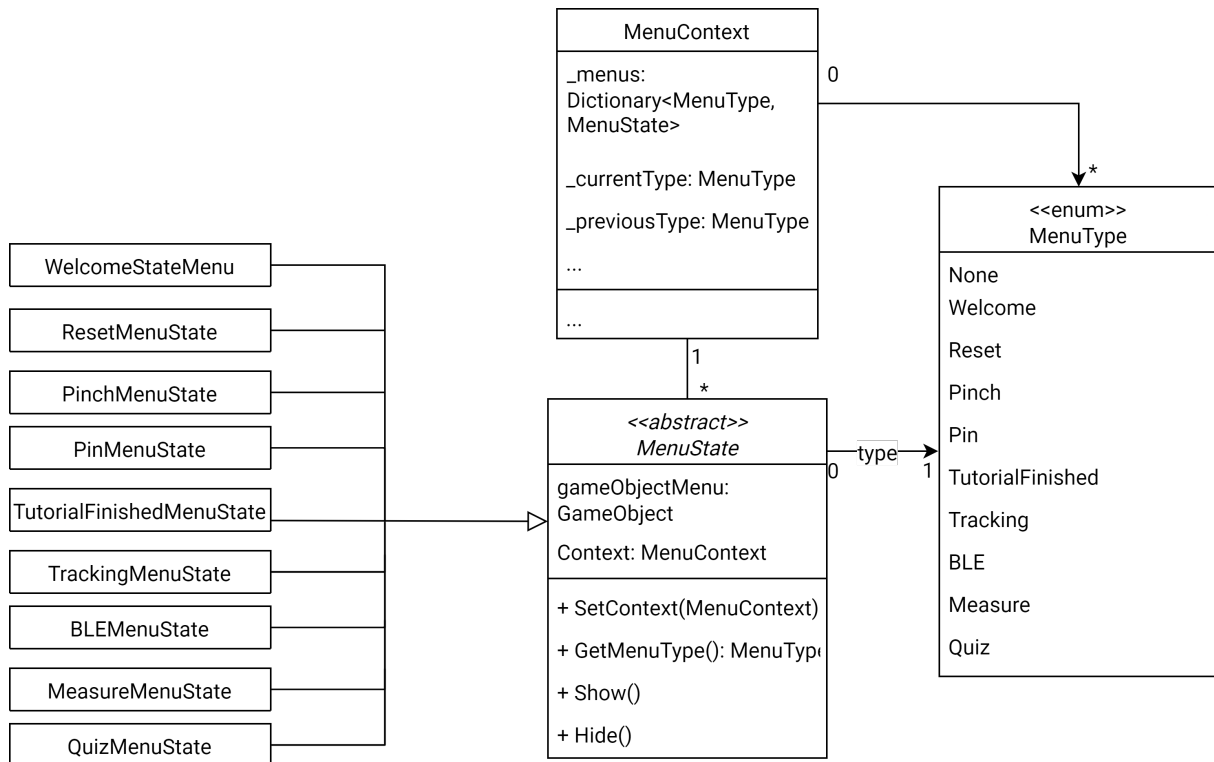
Figure 5.14: Simplified UML diagram showing show Context State pattern was implemented to control the menu flow.

Tutorial

Following RQ2.1 (section 1.2), non-functional requirements in section 4.3 and the need of the user to be confident and independent as seen in subsection 4.2.1, we added a short tutorial explaining some of the gestures and functionality. We added option to skip it for experienced users from the first view and go straight to the Tracking menu. During the tutorial, we utilised animated *visual hints* [17] as discussed in subsection 2.1.1. The hand gesture animations used, are provided by Microsoft called hand coach [4]. The images of their placements are shown in Figure 5.15.

Seeing in OB09 that users had issues with menu positioning, we added a **Reset** button to the palm that will reset the position of the menus. The explanation of how to use it was also added to the tutorial to the Reset menu. How that looks to the side of the hand and the gesture explaining the motion can be seen in Figure 5.16.

---

[4] https://docs.microsoft.com/en-us/windows/mixed-reality/design/hand-coach
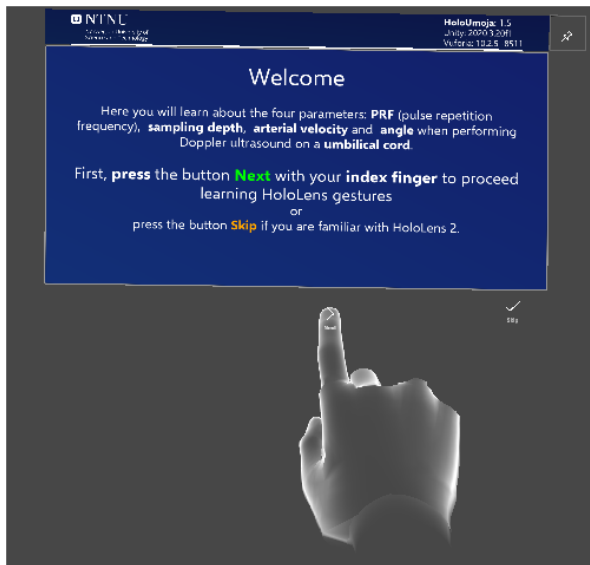
(a) Pressing button gesture shown in the Welcome menu
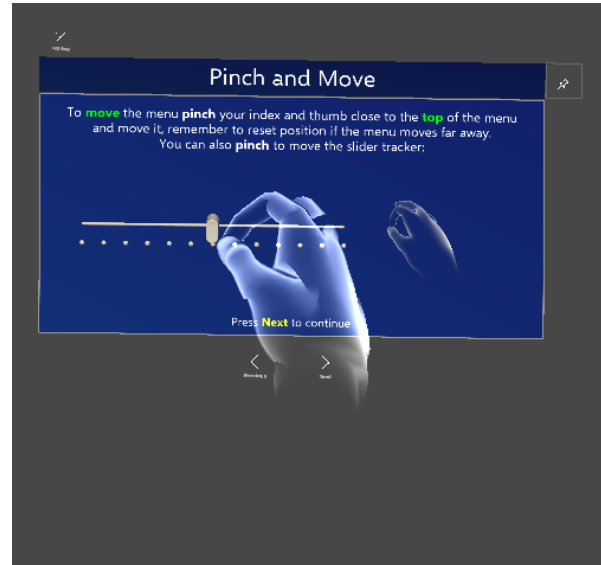
(b) Pinching gesture shown in the Pinch menu

Figure 5.15: Animated visual hints showed during the tutorial
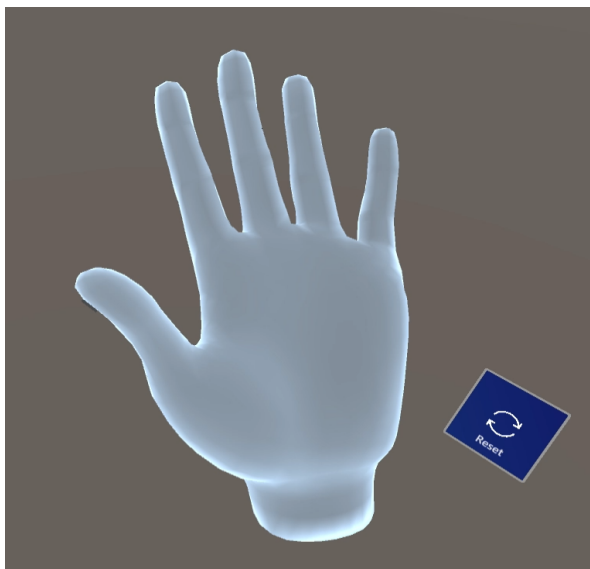
(a) Hand palm menu to the right of the left hand with **Reset** button
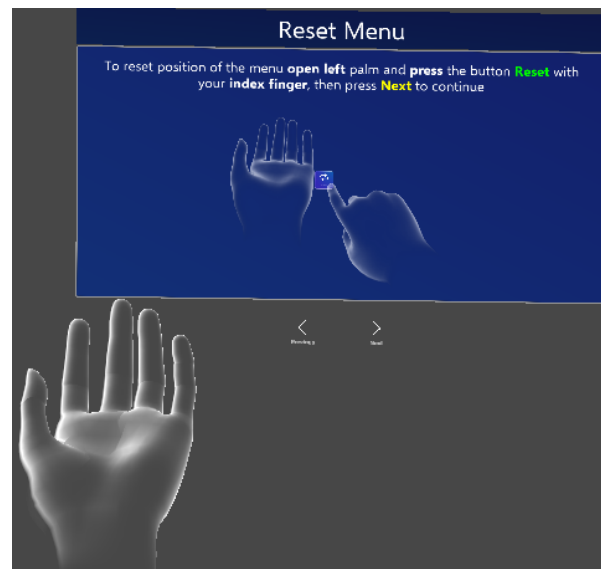
(b) Flip hand gesture coach in the Reset menu

Figure 5.16: The position of the **Reset** button and visual hint for the gesture to make the button appear

Tracking

The majority of the users struggled to get images tracked for the first time as noted in OB06. So, we added a separate view explaining explicitly what to do. When an image is successfully tracked, a green checkmark appears on the image as can be seen in Figure 5.17 and a sound effect plays.
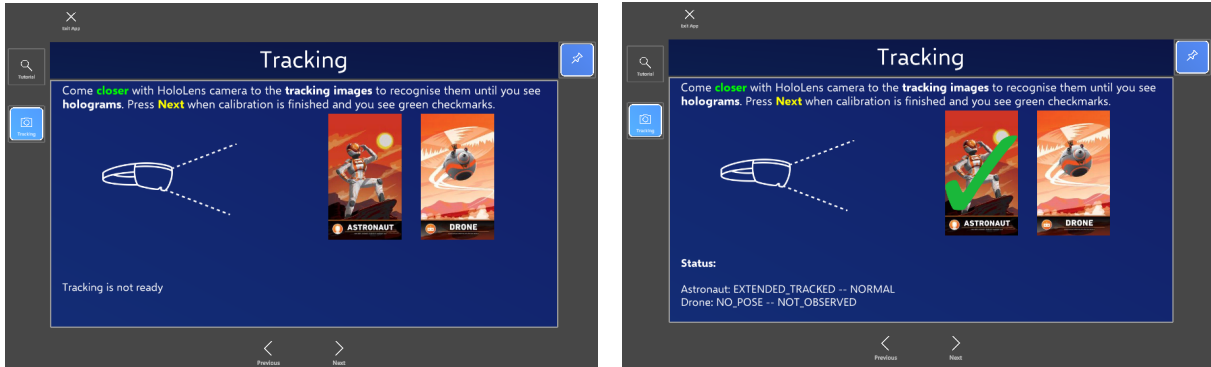
Figure 5.17: Tracking menu explaining what to do and giving visual (and audio) feedback when tracking is successful.

Measurement

When the images are successfully tracked, the menu explains how to "measure" the blood velocity in the application. Similarly to the hand gestures, we created an animated *visual hint* to where to place the ultrasound probe as it can be seen in Figure 5.18.
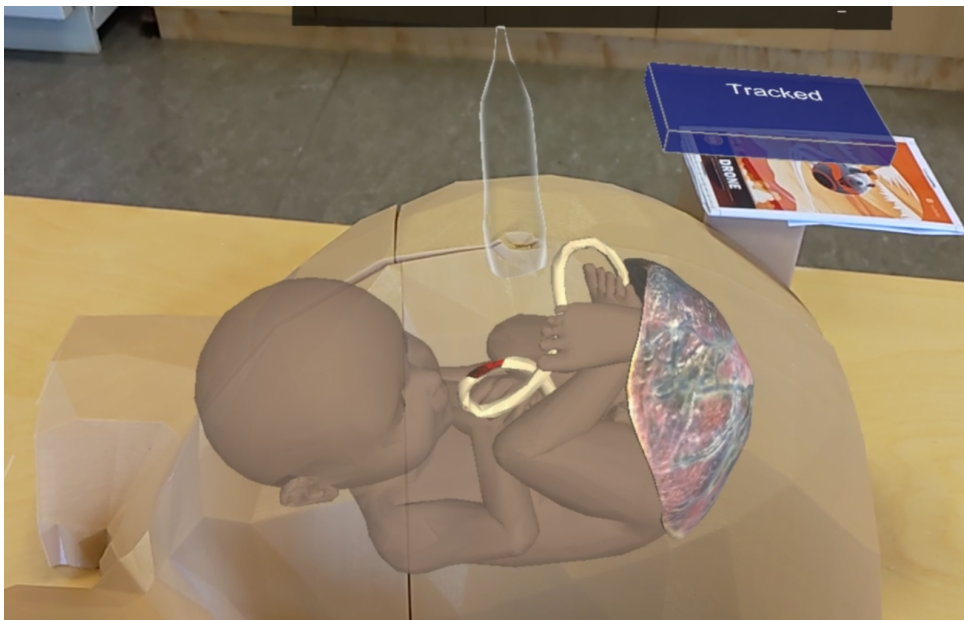
Figure 5.18: Visual hint of an ultrasound probe for how to "measure" the blood velocity with the 3D printed ultrasound probe

To adjust PRF and sampling depth we continued to use sliders, but seeing the issue described in OB08 where the user confused the labels on the sliders, we moved the name of the sliders to the left and adjusted its size. Additionally, the current value reacts to hover and pinching and it moves with

the thumbstick of the slider as shown in Figure 5.19.
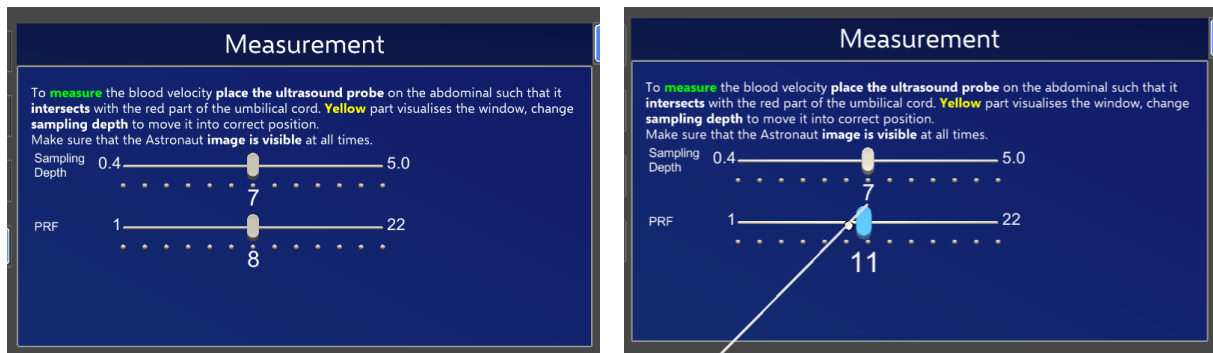
Figure 5.19: Measurement menu with slider's current value reacting to hover and pinching.

Seeing in OB04 and OB07 that users had issues with understanding the measuring process, we have reworked the ultrasound ray visualisation. The ray changes colour depending on the angle and the texture moves when it intersects with the correct part of the umbilical cord as seen in Figure 5.20.

(a) When it is not intersecting, the colour is dark and the texture is not moving
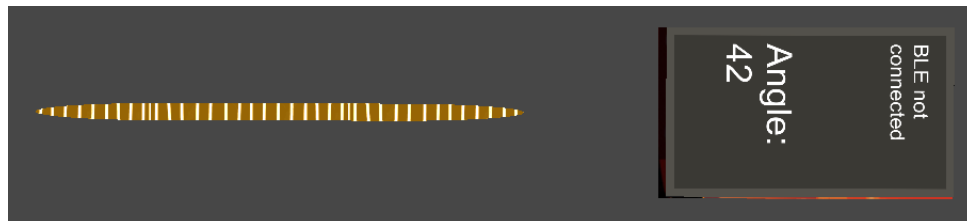
(b) Intersecting with the correct part of the umbilical cord and the angle is **bigger** than 30°, the colour is yellow and the texture is moving.
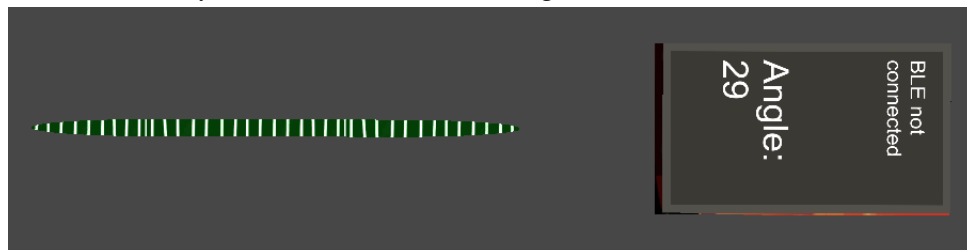
(c) When it is intersecting with the correct part of the umbilical cord and the angle is **less** than 30°, the colour is green and the texture is moving.

Figure 5.20: Visualisation of the measurement depending on the angle and intersection.

Quiz

The last view was added as an example of how the application can be used for testing the knowledge about the procedure. There, the program sets the blood velocity to be a random value within the

given range and asks the user to input the measured velocity by performing the procedure. Then it gives feedback on the input if it is close or not to the correct value as seen in Figure 5.21.

Figure 5.21: Quiz view to test the measurement abilities

5.3.4 Spectrogram axes
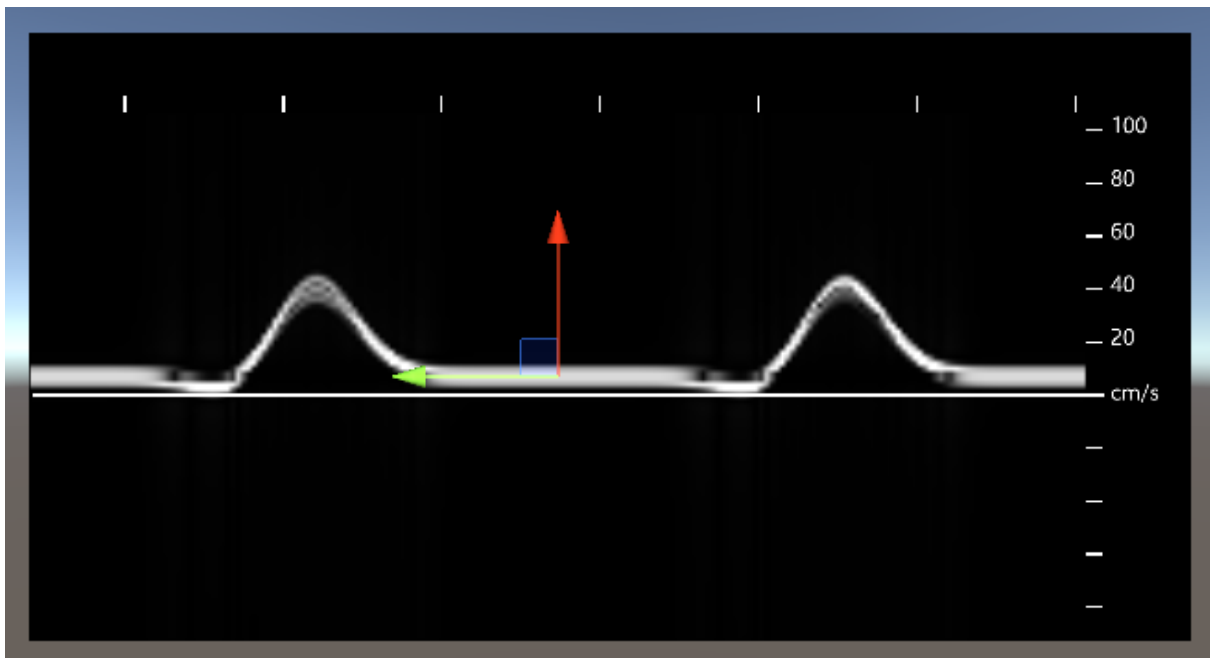
Figure 5.22: Updated spectrogram with velocity axes.

We added axes to the spectrogram (Figure 5.22) to be able to read the blood velocity from the graph. The axes are generated when the application starts. It uses predetermined prefabs and places them with the given space, frequency and range. So it will be possible to change those values in the future easily. The code snippet can be seen here:

To make it easier for user to understand when the spectrogram is updating, we have added a blue line moving from left to right together with the updates as seen in Figure 5.23.

Seeing in OB01 and OB02 that users performed tests positioning the abdomen differently, we made it possible to move the spectrogram as well as the menu itself by pinching on the top of the menu and moving the hand.

```
private void CreateAxis() {
    const float gapY = 10f;
    const int velocityStepY = 30;
    const int timeStepX = velocityStepY;
    Transform parent = transform.parent;

    for (int tick = -4; tick < 6; tick++) {
        RectTransform tickY = Instantiate(tickTemplateY, parent);
        tickY.anchoredPosition = new Vector2(tickTemplateY.anchoredPosition.x,
                                    gapY * tick + xAxis.anchoredPosition.y);
        tickY.gameObject.SetActive(true);

        if(tick <= 0) continue;
        RectTransform labelY = Instantiate(labelTemplateY, parent);
        labelY.anchoredPosition = new Vector2(labelTemplateY.anchoredPosition.x,
                                    gapY * tick + xAxis.anchoredPosition.y);
        labelY.gameObject.SetActive(true);
        labelY.GetComponent<Text>().text = (tick * 20f).ToString();
    }

    for (int tick = 1; tick < 7; tick++) {
        RectTransform tickX = Instantiate(tickTemplateX, parent);
        tickX.anchoredPosition = new Vector2( tickTemplateX.anchoredPosition.x - timeStepX * tick,
                                    tickTemplateX.anchoredPosition.y);
        tickX.gameObject.SetActive(true);
    }
}
```

Listing 2: Generating axis for the spectrogram with given parameters
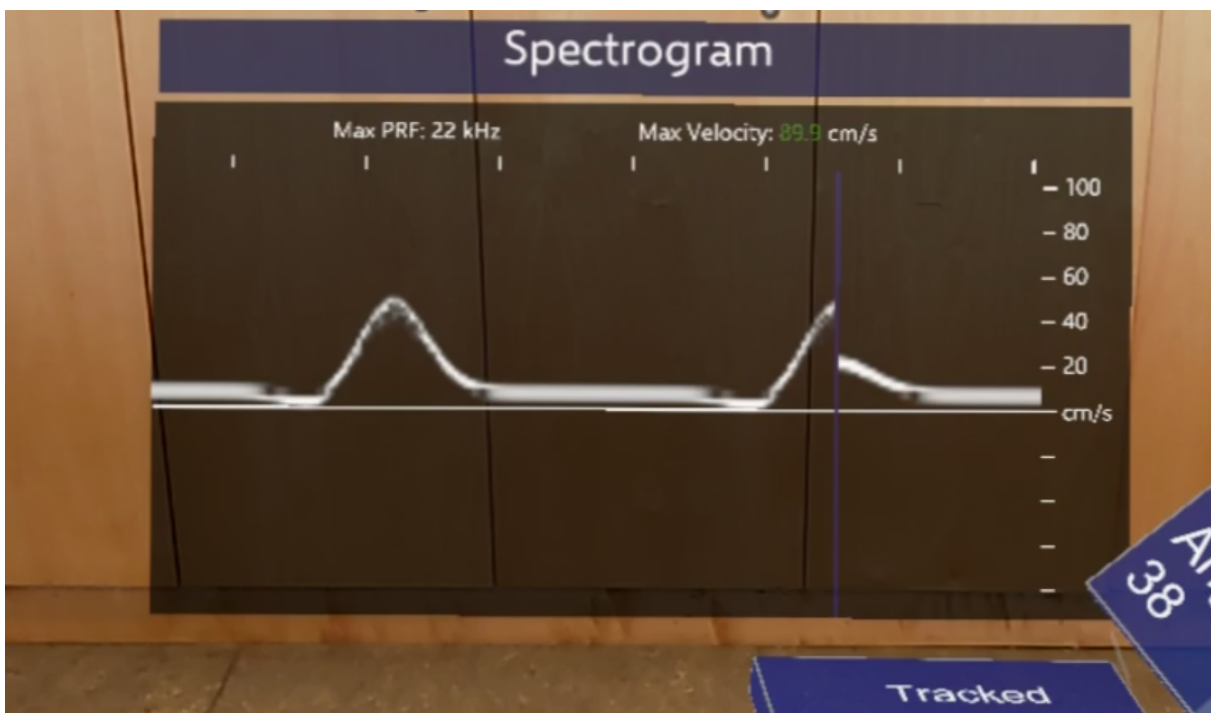
Figure 5.23: A blue line follows an update in the spectrogram

5.3.5   Improved tracking

The recurring observation OB05 was that users had issues with tracking. Also, one of our RQ in section 1.2 is about using sensors to improve the application. To improve the tracking, we chose to use Arduino 33 Nano BLE as it had different functionality that we could test. In the future, one could acquire a simpler version with just BLE and a gyroscope sensor. We considered both WiFi and BLE and chose to go for the second as we were to send little information per transaction. It also uses less battery than WiFi. First, we initiated the gyroscope and developed a way to combine it with the image tracking given by Vuforia; then we implemented a connection between Arduino and HoloLens; and, lastly, we made Arduino wireless.

Sensor fusion

The gyroscope first needed to be calibrated, we have used the instructions given by the *LSM9DS1 library* [48]. We used full scale (FS) value to be $\pm 245°/s$ and output data rate (ODR) to $119 Hz$ and saved the values it gave. It also contains an example code we could run to test if it works. For easy prototyping, we sent sensor data from Arduino to Unity over a serial port. The example code for that is best demonstrated by CreatiXR [5]. The gyroscope data alone was not enough, it had to be combined with the data provided by Vuforia. We experimented with various methods of sensor fusion and the one that we implemented is described in Algorithms 2 and 3.

Algorithm 2 Algorithm running on Arduino converting gyroscope data to rotation based on initial rotation *prevRotation*

---

    procedure GetArduinoRotation(*prevRotation, lastUpdate*)   ▷ Runs on Arduino 119 Hz
        if *isGyroAvailable = True* **then**
            eulerG ← ReadGyroData()   ▷ (x, y, z) in rad/sec
            Convert *eulerG* data from IMU coordinate system to Unity
            deltaT ← *now − lastUpdate*
            deltaG ← *eulerG ∗ deltaT*
            quatG ← ConvertEulerToQuaternion(*eulerG*)
            rotation ← *prevRotation ∗ quatG*
            prevRotation ← *rotation*
        end if
    end procedure

As we can see, the Algorithm 2 first reads how much the sensor has been turned around each axis, this function is provided by the *LSM9DS1 library* [48]. Then it converts from IMU coordinate system to Unity coordinate system, more information about that is in Table 2.1. In our implementation, we have secured the sensor in a different orientation because of the physical constraints such as the reset button position (as seen in Figure 5.27), so the conversion ended up being different as seen in Table 5.1. Then it is multiplied by the time since the last reading, converted to quaternion and multiplied with the previous rotation. This loop runs 119 times per second on the Arduino which is the same as the ODR of the sensor.

---

[5] https://github.com/CreatiXR/Controllers

Algorithm 3 Algorithm running on HoloLens deciding which rotation to use and combine based on the tracking state

---

   procedure SETROTATION($arduinoRot$, $vuforiaRot$)   ▷ Runs on HoloLens
      if $Status = NOPOSE$ **then**
         Hide object
         return
      end if
      if $Status \neq TRACKED$ **then**
         Update $prevRotation$ on Arduino with last $vuforiaRot$
      end if
      if $Status = TRACKED$ **then**
         $currentRot \leftarrow Lerp(vuforiaRot, arduinoRot, fusionRatio)$
      end if
      if $Status = EXTENDED\ TRACKED$ **then**
         $currentRot \leftarrow arduinoRot$
      end if
   end procedure

Table 5.1: Conversion table between the Unity Engine and the LSM9DS1 IMU in Arduino 33 BLE Nano used in this project, it is different form Table 2.1 because of the physical constraints.

	Unity Engine	LSM9DS1 IMU
Forward	z	x
Up	y	z
Right	x	-y

The second algorithm Algorithm 3 runs in Unity/HoloLens where it chooses to use the rotation given by Arduino, Vuforia or combined based on the tracking status [6] of the Image Target. When combining the rotations, $fusionRatio$ decides how much of the Arduino rotation is merged. The value that we decided to settle on is 0.15 meaning that 0.85 of Vuforia rotation is used.

Bluetooth Low Energy (BLE)

The goal was to send the rotation data from HoloLens to Arduino, in other words:

- Arduino - peripheral device (similar to a server from a network perspective) can tell central devices when parameter updates

- HoloLens - central device (similar to a client) can read, write and subscribe to parameters

Setting up BLE from Arduino was quite straightforward as Arduino has a library dedicated to it. There one can define the services and characteristics, a central device can subscribe to.

The issue was writing BLE connection in Unity Engine, as Unity does not support .NET 5, in which the majority of the code for BLE is written in. So it had to be written in C++ and built as a Dynamic-link library (DLL), which could then be imported into Unity. Fortunately, there was an open-source

---

[6]https://library.vuforia.com/articles/Solution/tracking-state.html

project for Unity built as a DLL: BleWinrtDLL [7]. It was not tested if it works with HoloLens before. To make it work on the HoloLens we had to build two DLLs: one for HoloLens with ARM64 architecture and one for Unity Editor with x64 architecture and define which one the application should use based on the device.
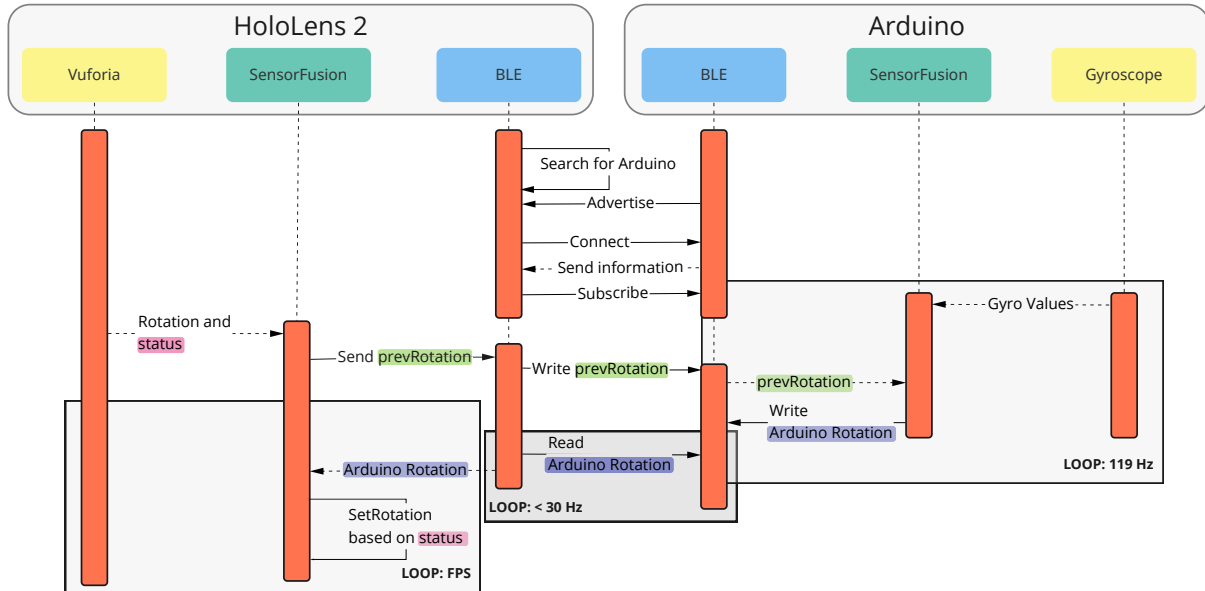
Figure 5.24: Information flow between Arduino and HoloLens through BLE.

For our purposes, it was enough with setting up one service and three characteristics: Arduino rotation, prevRotation (from HoloLens) and a boolean to notify if prevRotation has been changed. Usually, when a central device has subscribed, it can be notified when the characteristic has been changed. But it was the peripheral device (Arduino) that had to read the prevRotation characteristic, so it was easier to check the boolean. To better understand the flow of information between the HoloLens and Arduino see Figure 5.24. There Arduino Rotation is marked with blue colour, prevRotation with green and status with pink.

Wireless Arduino

To power the Arduino one normally has it connected to a PC, this was useful throughout the development as we could print information straight to the editor and quickly build updates to it. But the cable would constrict the user during testing, so we have added a LiPoly backpack[8] and a rechargeable battery [9] to the Arduino as seen in Figure 5.25. How Arduino and backpack were connected is described in the scheme seen in Figure 5.26.

We used Kapton tape between Arduino and battery backpack to isolate them from each other, as well as around both of them when soldering was complete (Figure 5.27a). In the end, the completed pack was connected to the 3D printed probe as seen in Figure 5.27(b, c) with the USB port and reset button still reachable.

---

[7] https://github.com/adabru/BleWinrtDll
[8] Adafruit LiIon/LiPoly Backpack Add-On
[9] Lithium Ion Polymer Battery - 3.7v 380mAh

Figure 5.25: Parts used for making Arduino wireless: LiPoly Backpack, simple cables for testing, Arduino itself and battery LiPo.
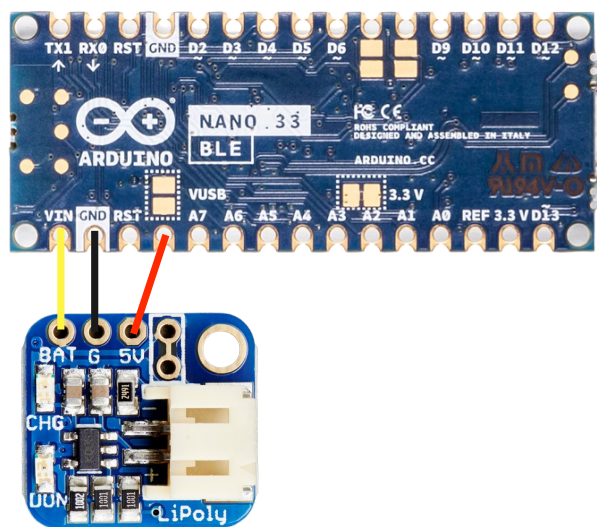
Figure 5.26: Scheme for connecting Arduino to the battery backpack

(a) Kapton tape   (b) Completed look   (c) Completed look: side view
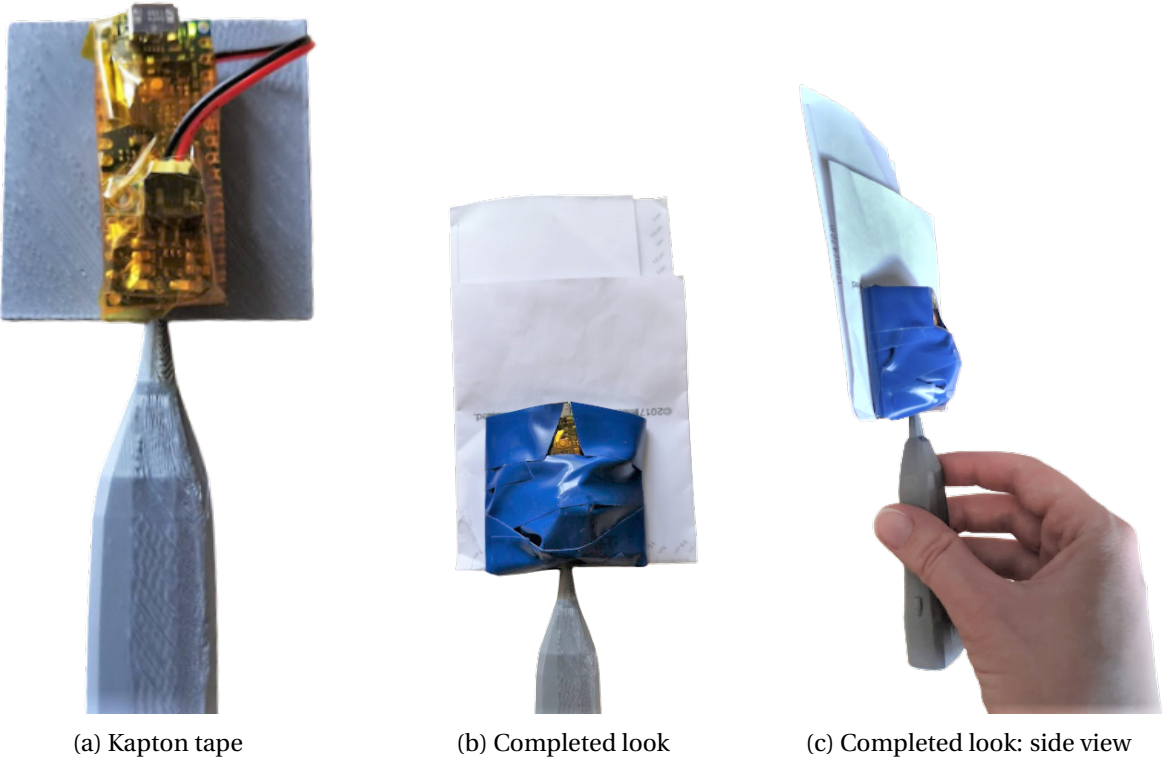
Figure 5.27: How the added Arduino with the battery pack looks on the back of the 3D printed probe.
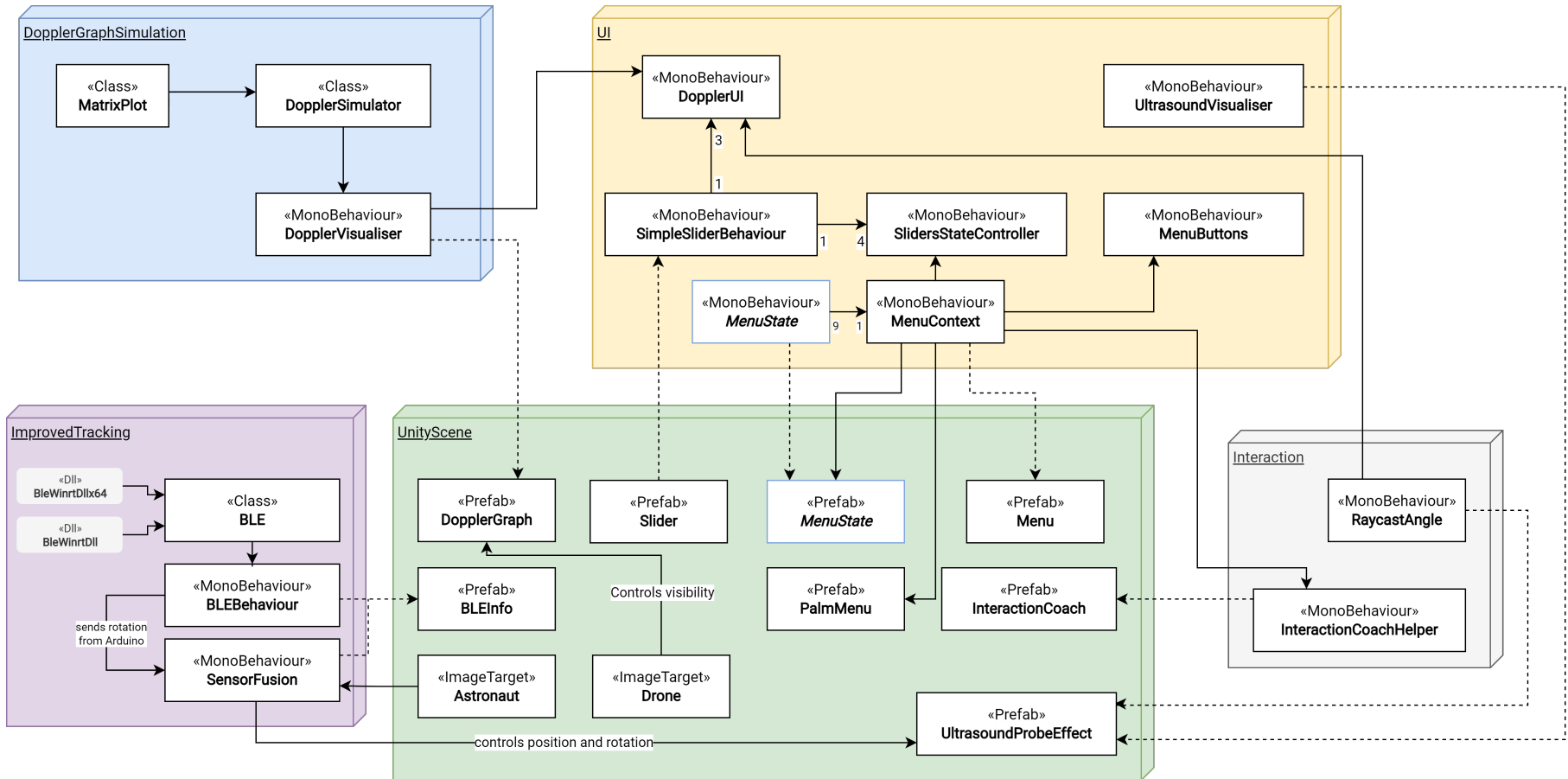
Figure 5.28: Overall architecture for 2.0 version of HoloUmoja. For simplicity's sake, only one *MenuState* is shown in the diagram, in practice, there is one script (of type *MonoBehaviour*) and one prefab for each view as described in Figure 5.14.

6 Chapter

Results

The results in this research project were gathered in two phases, more closely described in section 4.6. During the first phase, we performed user tests with 5 participants and 6 in the second phase, of which 2 were midwife students. In addition, we have noted down observations during the user tests and feedback both from users and experts. In this chapter, first of all, we will describe the final version of the HoloUmoja application. Further, we will present the results, combined to compare the improvements made from version 1.0 to 2.0.

6.1 Final Version of HoloUmoja (v2.0)

Figure 6.1: The components needed for HoloUmoja application: 3D printed abdomen and probe (the sensor is behind the tracking images) with Vuforia Image Targets and HoloLens 2

The use of the application starts with the user having the 3D printed abdomen and probe with their respective tracking images attached as shown in Figure 6.1. Then, one puts on the HoloLens 2 and starts the HoloUmoja application, where one is greeted with the Welcome Menu appearing in front of the user. There, one has a choice to continue with the tutorial to learn the gestures and functionality used in the application or skip it. An animated visual hint of a hand pressing the "Next" button appears, encouraging inexperienced users to start the tutorial. During the tutorial, the gesture or functionality is explained with text, images and animated *visual hints*. The user is also further encouraged

to try the gesture or functionality themselves. When the tutorial is finished, the view changes over to the tracking of images and explains what needs to be done. When the images are successfully tracked, a success sound is played and a checkmark appears on the images. The fetus hologram appears to be inside the 3D printed abdomen and visualisation of ultrasound waves appear out of the 3D printed probe. Additionally, the spectrogram window appears next to the abdomen at first only showing a white line. The next menu view shows the status of the BLE connection, usually, it should have already successfully connected to Arduino in the background when the application has started, so the user can go further in the process.

When the set-up described above is complete, the user will have arrived at the measurement view and is encouraged to measure the blood velocity in the umbilical cord. By intersecting the ultrasound waves with the red part of the umbilical cord, the feedback is given to the user by moving the waves and changing colour to yellow (if the angle is over 30 degrees) or green (if the angle is under 30 degrees). The spectrogram then changes based on the parameters allowing the user to explore its effects. One is also able to change the sampling depth and PRF by moving the sliders on the menu. Lastly, one is able to test their knowledge by going to the last view - Quiz, where the user can input the blood velocity they think it is from measuring the blood velocity and check if it *is* the correct measurement.

Information on how to install the HoloUmoja application and known issues are described in Appendix section A.10.

6.2 Demonstration videos

The videos were made using HoloLens' built-in camera for easier understanding of the application. HoloUmoja v2.0 demo can be found at the following link: `https://youtu.be/NxOKFXkOOsg`. The previous version v1.0 can be found at: `https://youtu.be/siJbb0ELiis`. Words of caution are that the videos are not able to communicate the true experience because it fails to preserve depth perception as it films only the view of one of the eyes. Thus, some holograms might seem out of place. In addition, it costs a lot of resources for HoloLens to record, so the application might seem slower than it is when not recording.

6.3 Questionnaire

In the questionnaire, we have gathered demographic information about the test users. As seen in Table 6.1 in phase 1, people were between 18 - 35 years old, while the majority were older than 26. Three out of five identified themselves as male and the other two as female. In regards to their education, 60% have finished their Bachelor's degree while the rest 40% have already finished their Master's degree. The majority of the users worked or studied Information Technology. Looking at their experience, three out of five users have tried HoloLens 1 or 2 before the test and only one person has performed a Doppler Ultrasound procedure before. During phase 2, the test users were varied in their age covering all the categories with a majority of 26-35 years old. Four out of six people identified themselves as males and the rest as females. The overwhelming majority have finished their

Table 6.1: Summary of the demographic information about the test users during phases 1 (5 users) and 2 (6 users), where the majority category is **highlighted**.

Question	Phase 1	Phase 2
D1: Age	40% 18-25 60% **26-35**	16.7% 18-25 50% **26-35** 16.7% 36-44 16.7% 45+
D2: Gender	40% Female 60% **Male**	33.3% Female 66.7% **Male**
D3: Education	40% Master's Degree 60% **Bachelor's degree**	83.3% **Master's Degree** 16.7% Elementary, Junior or High School
D4: Field of work	60% **Information Technology** 40% Other	50% **Information Technology** 33.3% Medicine 16.7% Other
D5: HoloLens	60% **Yes, have tried** 40% No, haven't tried before	50% Yes, have tried 50% No, haven't tried before
D6: Doppler Ultrasound	20% Yes, have preformed before 80% **No, haven't preformed**	33.3% Yes, have preformed before 66.7% **No, haven't preformed**

master's degree and half of the people worked in the field of Information Technology. During this phase, we were able to test with two people working in medicine, specifically midwife students who have performed a Doppler ultrasound procedure before. In addition, only half of the users have tried HoloLens before the test.

The results from the SPINE questions have been aggregated into groups in Figure 6.3. To show the improvement from phase 1 to phase 2 and highlight the results from the midwife students, we have visualised average SPINE results per user in Figure 6.2. The higher the score on the y-axis, the more positively users have experienced that part of the application. In addition, two graphs were generated using data from both phases to compare the users from the Information Technology field and not; and who have tried the HoloLens prior to the test and not, that can be found in Figure 6.4. The more detailed results per each question from the SPINE questionnaire can be found in Appendix Figure A.1 for phase 1 and Figure A.2 for phase 2.
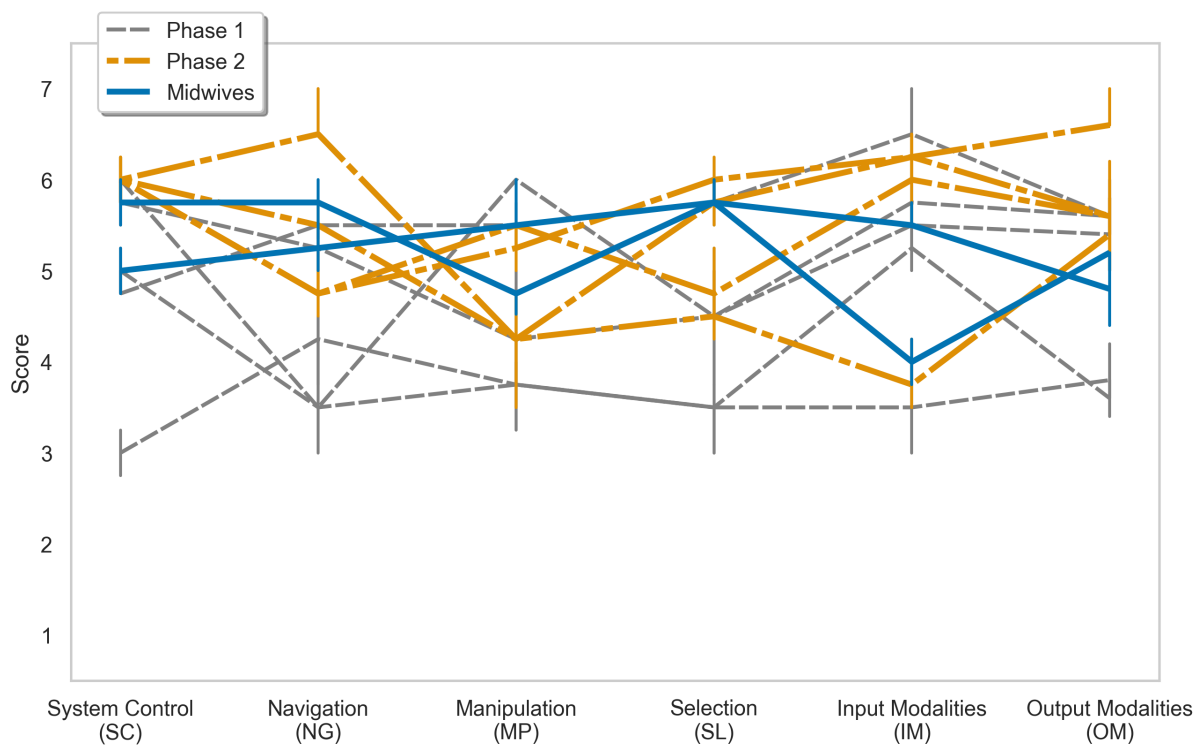
Figure 6.2: SPINE results show per user on average. They are further divided by colour and style into two phases of testing where the midwife users are highlighted with blue and solid lines. The lines across the y-axis visualise the confidence interval (it was set to 40).

(a) Phase 1: v1.0

(b) Phase 2: v2.0

Figure 6.3: Comparison of the SPINE questionnaire results during first and second phase testing of the HoloUmoja versions 1.0 and 2.0
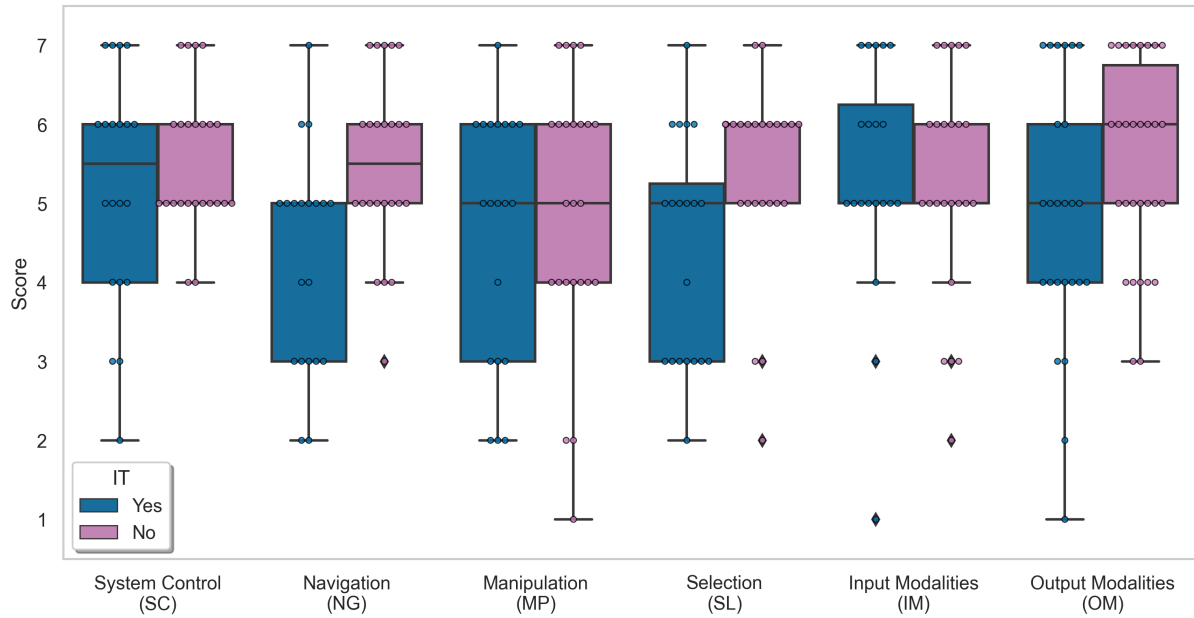
(a) Comparison of users from Information Technology to those from other fields of work.
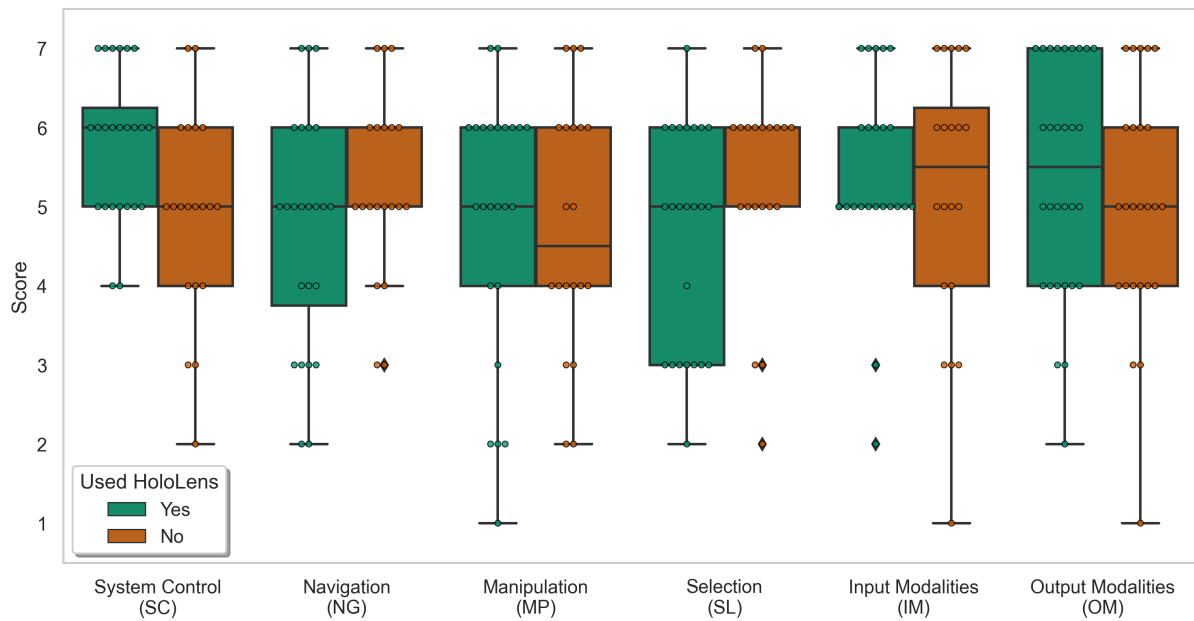
(b) Comparison of users who have tried HoloLens prior to the test and those who have not.

Figure 6.4: The data from both phases was used, so it represents the answers from 11 people in total.

6.4   Feedback and observations

We have collected feedback from the stakeholders during phase 1, it can be read in detail in the Appendix section A.7. The results were quite positive, highlighting the usefulness of visualisation for 'understanding the 3D relationship between the probe position and orientation of the umbilical cord that is to be examined'. The feedback comments on the combination of the 3D models with the hologram to be 'very beneficial since it improves the stability of the probe and allows for a more realistic scenario'. Lastly, it suggests the use of sensors for 'more accurate orientation' or for 'measuring how hard the user is pushing the probe against the abdomen [...] to mimic the real situation'.

The video of the first version of the application was also shown to two midwife professors. They were interviewed and their feedback on the application was overall positive, especially in regards to the visualisation: 'Students often struggle with finding the correct angle, I am sure it will help to see the model of the fetus and experience the situation. This application gives a good visualisation of the important concept with the angle ratio. It is important to be able to build on the basic skills the more complex understanding'. For a more detailed interview transcript refer to Appendix section A.8.

During phase 2, we have gathered qualitative results in the form of feedback from the users during testing, where two of them were midwife students and expert feedback. Overall users have mentioned that they 'enjoyed the physical connection, seeing consequences between doing something real and how it affects the spectrogram'. The users found the feedback from the application useful: 'Oh, it has turned green, so I am doing something right', where they are referring to the ultrasound waves turning green when the angle is below recommended 30 degrees.

Midwife students gave important medical feedback when they recognised the positioning of the abdomen to be wrong at first, as a midwife wants to face the patient. During positioning of the ultrasound probe and changing parameters with the other hand, midwife users said that 'ergonomy is really important in this line of work'. They also commented on the intersection part of the umbilical cord: 'the position of the intersection is illogical, I would have chosen the one that is on its way up'. In addition, they noticed the form of the 3D printed probe: 'we use another type of the ultrasound probe that is easier to rotate', meaning that they used a convex shaped instead of phased array one (Figure 2.11). Midwife students mentioned that this type of learning application would benefit to be applied to other difficult to visualise procedures. In the end, they expressed being happy that 'this is in AR, not VR as I get motion sick from VR. Also good to see the environment around'. During user tests, we have noted down observations and summarised similar experiences in Table 6.2.

Since there was a limited amount of users to test on, especially midwife students, we have also conducted unstructured interviews with the experts. First, they observed the tests with the midwife students and then, they tried the application for themselves. One of them noticed 'the importance of the angle ratio is very well shown, especially the effect of it on the measurements'. The other one agreed and added that 'moving the probe around the abdomen, learning and performing how to move is useful'. Both experts were in tandem with the suggestion to use it for the brain specifying that 'fetal brain ultrasound procedure is extremely complex as one has to hit a 10 mm point, it would be good to practice this in the same way'.

Table 6.2: Summary of the comments and observations during testing. The highlighted users and observations are from phase 2 of testing. The users marked with underline are midwife students.

ID	Observation	#001	#002	#003	#004	#005	#006	#007	#008	#009	#010	#011
OB01	Performed test with the abdomen in front	x	x									
OB02	Performed test with the abdomen to the side			x	x	x	x	x	x	x	x	x
OB03	Ignored Welcome Menu instructions	x	x	x	x	x				x		x
OB04	Did not understand when the blood velocity is measured and when it does not	x	x	x	x	x						
OB05	Lost tracking of the probe after the initial tracking to the point it was affecting the performance of the user	x	x	x	x	x				x	x	x
OB06	Had issues with Tracking Images for the first time	x	x		x	x						
OB07	Did not understand that the ray should intersect with the red part of the umbilical cord	x	x	x	x		x					
OB08	Confused the labels on the sliders		x	x	x	x						
OB09	Had issues with menu positioning		x	x	x	x	x				x	x
OB10	Noticed the effects of the parameters on the graph	x	x	x	x	x	x	x	x	x	x	
OB11	Understood how to interact with the sliders	x	x	x	x	x	x	x	x	x	x	
OB12	Struggled with pinching the sliders	-	-	-	-	-	x	x		x	x	x
OB13	The ultrasound ray was unstable	-	-	-	-	-	x		x	x		x
OB14	The 3D printed abdomen moved away	-	-	-	-	-	x		x		x	x
OB15	Finished Tutorial	-	-	-	-	-	x	x	x		x	
OB16	Insecure with the English language	-	-	-	-	-					x	x

Chapter 7

Discussion

7.1 Interpretation of the results

Looking at the evaluation goals defined in subsection 4.6.1 and the research questions in section 1.2, we can interpret the results shown in chapter 6, especially in regards to the improvements of the artefacts from phase 1 to phase 2 of the project.

Looking at our Persona 4.1, and the scenario shown in Figure 4.2, she independently decides to use the HoloLens to practice. For the FR7 requirement, the application includes a step-by-step tutorial explaining the actions needed to be made. As seen in OB03, during phase 1, all users ignored the instructions, while in the second phase only two out of six ignored them. This could be taken to mean that the onboarding information presented in v2.0 is more clear. Its benefit is especially visible in OB06, where the majority of the users from phase 1 struggled tracking images for the first time, compared to no users in phase 2. For v1.0 we started testing with users going through the official HoloLens gesture tutorial if it was their first time using HoloLens and they agreed to it. For v2.0 we only used the in-built tutorial with visual hints in HoloUmoja where the majority of the users decided to go through the tutorial as seen in OB15. Looking at the overall positive results for the application seen in phase 2 (Figure 6.3b), we can assume that the tutorial with visual hints and on-boarding information was helpful.

The use of 3D printed objects constricts the user's position and orientation. The midwife students have also mentioned that ergonomy in the context of working with patients, is an important part of their profession. With that in mind, it was important to get the spatial relations comfortable for the user. One of the issues developers met was about how to place the 3D printed abdomen in regards to the user. During phase 1, in OB01 and OB02 tests were done, both with the abdomen in front and at the side. Midwife students have also commented on the abdomen position, and changed it independently to a more realistic orientation - facing the patient. This resulted in some issues with menu orientation, as seen in OB09, because the menus were placed with a specific layout in mind. The navigation (NG) and manipulation (MP) groups in SPINE (Figure 6.3) saw great improvements in phase 2. This could be because even though there were menu positioning problems, they still could be moved by the user in v2.0 to where they find it more comfortable. In addition, the user could "reset" the position of the menus if it went wrong.

Looking at the selection (SL) and output modalities (OM) groups in Figure 6.3, we see it was im-

proved in phase 2. The v1.0 of HoloUmoja struggled with following Norman's design principles (subsection 2.2.1), especially with feedback and affordance as seen in OB04 and OB07. Those issues have been resolved in v2.0 by adding sound and visual effects both to the ultrasound waves and the spectrogram. On the other hand, a better understanding of those interactions could be because the menu instructions were clearer in v2.0; or more users in phase 2 were familiar with the ultrasound procedure than in phase 1. To control the values of other parameters than the angle, users had to use sliders. In v1.0, the labels on the sliders were placed below the sliders, which led to some confusion from the users as seen in OB08, this positioning lead to wrong proximity relationships (subsection 2.2.2). To resolve the issue, in v2.0 labels were moved to the side of their respective sliders. The design of the sliders follows the Norman's consistency principle, so the users understood how to interact with them (OB11). Unfortunately, their size was too small in v2.0, which resulted in difficulties to pinch them, as seen OB12.

To control the angle parameter, users had to move the 3D printed ultrasound probe, where HoloLens tracks its position and rotation using the Image Target and gyroscope. It was essential for the application to do so, precise and fast enough, but also to be able to inform the user how to initiate the tracking. As seen in OB06, in v1.0 the users struggled to understand how to start tracking and when it succeeded. In v2.0 it was improved to the point that no users had the same issue. This is due to the clearer instructions, but also the sound feedback when tracking succeeded, and holograms overlaying the image. Another issue came up in v2.0, as seen in OB13, where the ray became unstable, because the sensor fusion between Vuforia Image Tracking and gyroscope was not accurate enough. The image tracking of 3D printed abdomen was stable throughout the tests, as long as users re-calibrated if the abdomen was moved. Sometimes it moved away involuntarily, as seen in OB14, if users pressed the probe on the abdomen. This goes against the realism of the procedure, as midwives need to press the ultrasound probe on the skin of a patient a certain amount.

Overall the improvements made in v2.0 of HoloUmoja have yielded a positive effect. Following the Figure 6.2, we see that the midwife students answered on average similar to the other users and that it has improved from phase 1 to phase 2. Even though the other users did not have the same experiences as our target group, it is beneficial to see that their opinions are in tune with each other. In the Figure 6.3, where all groups that SPINE measures have seen an improvement except for input modalities (IM) [1]. Possible reasons can be that the in-built HoloLens gestures have stayed the same from v1.0 to v2.0. As seen in Figure 6.4b, the score in input modalities (IM) of people who have tried the HoloLens before is overall higher than those who have not. Meaning that it might require practice to use gestures using HoloLens, similarly to the results from the pilot study on tangible AR in [17] as mentioned in subsection 2.1.1. On the other hand, we were concerned that users from IT field of work had more exposure to technology and thus would find it easier than users from other fields such as our target group. The Figure 6.4a showed there was little to no difference in scores between users from the IT field and other fields of work on input modalities (IM).

Following the feedback from the experts, there is a learning potential in this application. It is visible in OB10, where users noticed the effects of their actions on the spectrogram. Even though the Doppler

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[1]Definitions of the different groups of SPINE are attached to Appendix Table A.1.

spectrogram is simplified, it managed to successfully convey the message of the effects of the parameters. Both experts and midwife students suggested more use cases for this application in other areas, meaning there is further educational potential for HoloUmoja.

7.2   Requirements

The final version of HoloUmoja as seen in section 6.1 was implemented following the requirements specified in section 4.3. Its completion is discussed in Table 7.1.

Table 7.1: Requirements completion discussion

ID	Completed	Discussion
FR1	✓	The application has been tested on HoloLens 2 headset.
FR2	Partially ✓	Images are used to track the position and rotation of the 3D printed probe and abdomen. To improve tracking additionally gyroscope has been added to the probe. The tracking of the abdomen showed to be stable, unfortunately, the probe tracking did not seem to be accurate enough for the procedure for the target users.
FR3	✓	Relevant 3D holographic models such as fetus, placenta and umbilical cord are connected to the 3D printed abdomen. A visualisation of ultrasound waves is connected to the probe to provide feedback for the user.
FR4	✓	Doppler spectrogram is simulated in real-time based on four parameters: blood velocity, sampling depth, PRF and beam-to-flow angle.
FR5	✓	It is possible for users to change the input parameters using the position and rotation of the probe and sliders.
FR6	✓	The angle between the 3D printed probe and the virtual umbilical cord is derived in real-time and feedback on its value is given back to the user.
FR7	✓	The application includes a detailed tutorial and contains explanations for the needed gestures and existing functionality. User-testing has shown that the tutorial was useful.
NFR1	✓	Based on the feedback from the experts and midwife students, there is potential educational use for the application.
NFR2	Mostly ✓	The majority of the app quality criteria are met such as FPS, viewing zone, depth, spatial sound, user position and interactions. The only lacking is the hologram stability as has been seen during user-testing in OB13 holograms connected to the probe were unstable to the point it affecting the performance of the user.

7.3 Research Questions

Looking at the interpretation of the results, we will attempt to make hypothetical claims from the emergent patterns to answer our research questions (section 1.2) stated at the beginning of this project.

RQ1: How can one **simulate** and **visualise** in AR the procedure of measuring the blood flow in the umbilical cord using Doppler ultrasound?

A less realistic *simulation* of the spectrogram created from Doppler ultrasound measurements based on the four parameters (blood velocity, PRF, angle and depth) is able to communicate their relationship. The presented *simulation* and *visualisation* are robust and allow more freedom to explore the changes than static prerecorded images. Most of all, it is a feasible application to be run on a standalone HoloLens 2 headset.

RQ2: How should the **interaction** be implemented in AR to accommodate midwife students?

In the application, we tested different ways of controlling the parameters such as sliders, which showed to be understandable, and with the use 3D printed probe. The latter with the angle adjustment showed to be the most useful visualisation of the concept. Other interactions included standard HoloLens gestures which take some time to get used to but eventually accommodate users.

RQ2.1: To what degree can midwife students use the prototype without external **guidance**?

In the first version, a simple explanation showed to be demotivating and difficult for users to understand, so they had to rely on external guidance. In the second version, the step-by-step menu proved to be useful if the users decided to proceed with the tutorial. Since in phase 2 we did not use the standard HoloLens tutorial, only the one in the application in contrast to phase 1. We might claim that the tutorial in the application is at least as good or better in teaching the users. To provide further assistance in learning the gestures, the use of animated visual hints helped users as none had major issues. Midwife students still required guidance during testing, but that in part could have been caused by the language barrier.

RQ3: How can user experience be improved with the use of **3D printed objects** and **sensors**?

Ergonomy and realism should be the vital parts of development for this target group. In our case, tangible AR with the use of *3D printed objects* lead to a stronger connection between the physical and augmented world, providing context and affordances to the user. As we have seen in the EWK continuum [14], AR application depends on its understanding of reality. Tracking of those 3D printed objects using Vuforia Tracking Images, to create that understanding, is suitable for static objects, in our case, the abdomen. But it did not seem sufficient for stable tracking of the ultrasound probe due to the HoloLens losing the visibility of the image when moving it. The additional *sensor*, gyroscope, for rotational tracking allowed for more precise control for the user, but it was affected by the jitter of the ultrasound waves hologram. Meaning that the use of a sensor has improved the user experience, but not yet to the point of being stable enough for further use.

7.4   Comparison to related work

Table 7.2: Comparison of the related work and this project.

Paper	Hardware	3D Objects	Data	Tracking
Palmer *et al.* [9]	Mobile phone, ultrasound machine	-/-	Real	Image
Yeo *et al.* [1]	Web-camera, laptop	Scanning pad, probe	Real	Image
Intelligent Ultrasound Simulation [2]	ScanTrainer	-/-	Real	Motion tracker
Hirji *et al.* [38]	Computer, FOB transmitter	Probe	Simulated	Motion tracker
Mahmood *et al.* [8]	HoloLens 1, computer	Probe, mannequin	Simulated	Anchors
HoloUmoja	HoloLens 2	Probe, abdomen	Simulated	Image, gyroscope

Looking at the Table 7.2, we can see that our application has some similar artefacts as in the related works. We will go through the differences and similarities and explain how they might benefit or constrain it.

In comparison to ScanTrainer [2] our solution is lightweight; easy to transform and to add new use-cases since no real data is used. As this application uses HoloLens 2, it avoids the unnecessary considerations of where to place the monitor and the camera such as in the case of Palmer *et al.* [9]. Since our application does not use real ultrasound data, it also avoids the issue of finding RCTL for fetal ultrasound as Palmer *et al.* [9] have mentioned. The same applies to Yeo *et al.* [1] where they used real data that they have interpolated, but then they were constrained by existing datasets, while in our case we are not limited by that. Their solution allowed the user to move a probe in six degrees of freedom while in HoloUmoja, the user is able to move in 9 degrees of freedom, which is more realistic. Yeo *et al.* [1] have not used any AR technology, so whilst they were able to train the users in hand-to-eye coordination, expert feedback entails that by showing a 3D model of a fetus we help the trainee to have an easier volumetric understanding of the internal structure as mentioned by Mahmood *et al.* [8]. They were the only paper in our related works that used a HoloLens headset (an older version than the one used in this project) with a mannequin. Even though their method with calibration allows the application to be used with a variety of different mannequins, our constant image tracking of 3D printed objects might lead to quicker onboarding.

7.5   Contributions

Seeing the comparison of this project to the related work, we are able to state this project's contributions in the list below.

1. **First working proof of concept Doppler ultrasound simulator in AR on HoloLens 2 for measuring blood velocity in an umbilical cord.**

   At the time of writing, there is no existing application falling under that description. During this project, we were able to develop and test the HoloUmoja application, including the way of simulating the Doppler ultrasound and visualisation methods of the procedure.

2. **Feedback from experts regarding the use of AR for training on the Doppler ultrasound procedure.**

   We have gathered valuable feedback from experts in the field during two evaluation phases, where they suggested improvements, important aspects when developing such applications and other use cases.

3. **Supported interaction using 3D printed objects.**

   There are several examples of using mannequins and real ultrasound probes for training as seen in Table 7.2. In our application, we showed how 3D printed objects can successfully be used in this area to connect the physical and augmented worlds.

4. **Image tracking combined with gyroscope tracking between HoloLens 2 and Arduino over BLE connection.**

   Building on top of the open-source work done by adabru [2], we have developed and provided an open-source example [3] on how to connect Arduino Nano 33 BLE to HoloLens 2 over BLE using Unity Engine. In the HoloUmoja application, we further show how to combine rotational data from Vuforia image tracking with the information from the gyroscope.

7.6 Limitations

The number of user tests was quite low to get any statistically significant results: five people in phase 1 and six people in phase 2 with only two people from the target user group (midwife students). So the results were mostly based on people not from the target group. This limitation with the test users was due to the pandemic restrictions and the strict time constraints of the medical professionals.

During the testing of the two last users, the developers noticed that midwife students were not as comfortable with the English language as those who are from the IT field. So, some of the user interfaces had to be translated or explained during the test. In addition, some users found the questionnaire to be too technical, so some parameters had to be explained orally. This could have affected the interpretation of the statements and the experience itself. The users were tested in different environments with various levels of noise which could have affected their concentration. In addition, image tracking quality could have also been affected by the lighting conditions. Lastly, the observational results were limited by the testers' concentration. Some observations could have been overlooked or interpreted wrongly leading to biased results.

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[2] https://github.com/adabru/BleWinrtDll
[3] https://github.com/marianylund/BleWinrtDll

Chapter 8

Conclusion

8.1 Summary

Following the need for an effective training tool for the widely used procedure, PW Doppler ultrasound, and the great promise of AR in medical education, we explored a possible solution. We decided to focus on (RQ1) the ways to **simulate** and **visualise** the said procedure; (RQ2) how users, especially midwife students, should **interact** in AR; (RQ2.1) **guide** the interactions in the application; and (RQ3) improvement possibilities using **3D printed** objects and **sensors**.

By using Unity Engine with Vuforia image tracking and gyroscope for tracking of 3D printed ultrasound probe and abdomen, we implemented the first working proof of concept Doppler ultrasound simulator in AR on HoloLens 2 for measuring blood velocity in an umbilical cord. Where users can control sampling depth, PRF and beam-to-flow angle parameters in real-time. The implementation and evaluation consisted of two phases of user testing with 5 users and then 6 users (2 midwife students) and expert feedback.

The results presented that the application was especially successful in showing the importance of beam-to-flow angle, where a user controls it with the 3D printed ultrasound probe. The visualisation of the procedure showed potential use for other similar cases as well. In addition, 3D printed objects provided great tactile feedback and helped to connect the physical world with the augmented. Lastly, the image tracking of the abdomen showed to be sufficient, while the tracking of the probe was not, even with the added value of the gyroscope to accommodate midwife students. Overall, both experts and users found the application to be positive and have educational potential in ultrasound training.

The application that was created during this project had midwife students in Norway as its target users. Nevertheless, we hope that the findings here and the developed prototype will be used for further research, with the main focus on improving obstetric ultrasound training in LMICs as in the original UMOJA project.

8.2 Future Work

- **Improving tracking of the 3D printed ultrasound probe.**
  Tracking of the abdomen proved to be stable, in contrast to tracking of the ultrasound probe. Even though gyroscope improved rotational stability, it was still one of the biggest issues when testing. It would greatly improve the application if the ultrasound probe tracking was not dependent on the visibility of the image.

- **Changing the form of the 3D printed ultrasound probe.**
  Following the expert feedback, the 3D printed form of the ultrasound probe should be changed from its current to convex probe seen in the 2.11.

- **Improving ergonomy for the users.**
  As mentioned by the midwife students ergonomy is important in this line of work, there are ways to improve this application for example: adding a freeze button to stop the angle from changing, allowing the users to explore other parameters. Thus avoiding the need for the users to keep one of their hands still while they are changing other variables.

- **Adding more spatial interactions.**
  The control of the angle was the most successful one according to the feedback from the experts. This could partially be explained by the fact that the change was connected to the 3D actions made by the user. The other parameters were controlled through sliders, but they could also be converted into 3D spatial actions. For example, controlling spatial depth could be done by moving a spatial window on the ultrasound waves until it is hitting the desired target.

- **Making the whole umbilical cord "interactible"**
  Midwife students commented on the illogical place of measurement, it was chosen for the sake of simplicity, but in future work, it would benefit if the whole cord could be measured. Then the blood velocity could change depending on where on the cord the measurement has taken place. For example, the blood velocity could be higher closer to the placenta [35], thus making the training application more realistic.

- **Closer collaboration with medical professionals.**
  To avoid medical inaccuracies (e.g. patient orientation to a midwife), more input early in the development from people in the field is needed.

- **Exploring the educational potential.**
  This project did not have as its goal to test the educational benefit of this application due to limited collaboration with the medical professionals. So far, it has only been confirmed by the experts that this application has educational potential. Further evaluation of educational benefits would be highly relevant.

- **Peer to peer learning**
  As we have seen in the 4.2.1 section about persona, midwifes find learning together an important aspect. Adding a multiplayer functionality to the HoloUmoja application could possibly improve learning potential, similarly to "Augmented reality and ultrasound education: initial experience" [8].

- **Adding language support to HoloUmoja in the native language of the target users.**
  Seeing in OB16 that midwife students were insecure in the English language, the application should have had more suitable language choices.

- **Improving the surface of the 3D printed abdomen.**
  The surface of the abdomen is unpleasant and does not resemble the skin, it would help to apply some material on top of it for easier movement. In addition, seeing the OB14, the abdomen was prone to movement once the user has pushed on the abdomen, some restriction on the bottom to stop it from moving on the table would improve the experience and stabilise tracking.

- **Adding other use cases.**
  As mentioned by the experts and midwife students, it could be beneficial to use a similar approach in other areas such as fetus's heart or brain.

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Appendix A

A.1 Published abstract with NFUD

HoloUmoja: augmented reality training application for obstetric Doppler ultrasound
Maria Emine Nylund, Gabriel Hanssen Kiss, Ekaterina Prasolova-Førland
Department of Informatics (IDI), Norwegian University of Science and Technology (NTNU), Trondheim

Pulsed-Wave (PW) Doppler ultrasound is a well-established and widely used technique to monitor pregnancies and time-delivery. Its use is becoming more widespread as the ultrasound machines are becoming hand-held and more countries are entering the developing stage where education and health opportunities emerge. In addition to the ultrasound hardware, it takes several years to become ultrasound proficient and requires resources such as the presence of a professional, ultrasound equipment, and a volunteering patient. In this study, we proposed the use of an augmented reality (AR) application to facilitate the understanding of parameters used in PW-Doppler ultrasound when acquiring a spectrogram of the umbilical artery and to develop the skills required for this task. Doppler spectrograms are simulated by parsing a synthetic sinus curve through a Fourier transform, while the user has the possibility of adjusting various parameters (e.g., pulse repetition frequency (PRF), sampling depth, wall/clutter filter, probe position with regards to a virtual fetus model). The AR application was implemented in C# using Unity Engine for HoloLens 2 headset combined with a 3D-printed abdomen and ultrasound probe, tracked using Vuforia. The technical feasibility of such an application as well as the merging of AR elements and physical 3D printed objects was tested. The results of the first version of the HoloUmoja application were collected through observations during user-testing, SPINE questionnaire, and feedback from experts. The application as seen in the figure above was proven to be technically feasible, both the procedure and the change of the parameters could be simulated. The next version of HoloUmoja will be evaluated by midwife experts and students in the spring, after clinically relevant PW-Doppler curves will be added. Overall, the application promises to be a useful teaching tool for obstetric Doppler ultrasound.

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Mahmood F., Mahmood E., Dorfman R. G., Mitchell J., Mahmood F.-U., Jones S. B., and Matyal R., "Augmented reality and ultrasound education: Initial experience," Journal of cardio-thoracic and vascular anesthesia, vol. 32, no. 3, pp. 1363–1367, 2018

Hammer M., DopplerSim, 2014, Last accessed on: 22.03.2022, [Online]. Available: www.xrayphysics.com/doppler.html

A.2   Consent Form

Are you interested in taking part in the research project "HoloUmoja"?

This is an inquiry about participation in a research project where the main purpose is to create an educational application about measuring the blood in an umbilical cord. In this letter, we will give you information about the purpose of the project and what your participation will involve.

Purpose of the project

This project is a master's thesis with the goal to create an educational application for midwife students. Specifically to train and explore the Doppler ultrasound procedure done to measure the blood velocity in an umbilical cord.

Who is responsible for the research project?

NTNU, Department of Computer Science and Department of Education and Lifelong Learning are the institutions responsible for the project.

Why are you being asked to participate?

You are asked to participate because you are a potential user of the educational application developed as a part of this project. Your feedback is important for developing innovative learning methods and tools.

What does participation involve for you?

You will be asked to test an immersive application for learning and training purposes and give feedback in the form of questionnaires and interviews.

Participation is voluntary

Participation in the project is voluntary. If you chose to participate, you can withdraw your consent at any time without giving a reason. All information about you will then be made anonymous. There will be no negative consequences for you if you chose not to participate or later decide to withdraw. This will not affect your relationship with the student on this project.

Your personal privacy – how we will store and use your personal data

We will only use your personal data for the purpose(s) specified in this information letter. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Any data that can be traced to individual participants will be kept confidential and anonymized before being used for research purposes. Parts of the sound recordings will be transcribed (written down) and stored electronically. All source data will be handled and stored in accordance with the existing regulations by NTNU as the responsible institution and only persons associated with the project (master student and supervisors) will have access to them.

What will happen to your personal data at the end of the research project?

The project is scheduled to end 15.06.2022. All data will be anonymized at the end of the project, e.g. audio and video will be deleted when transcripts and analysis of data are completed, except for selected video and photo material to be used for research purposes. These and anonymized recordings from the inside of the virtual environments may be used for demonstrations in a research context

in such a way that no information will be linked to individuals. Scientific reports and presentations from this study might contain recordings from the AR sessions, questionnaire results, anonymized photos/videos from the sessions and anonymized citations from the interviews.

Your rights

So long as you can be identified in the collected data, you have the right to:

- access the personal data that is being processed about you
- request that your personal data is deleted
- request that incorrect personal data about you is corrected/rectified
- receive a copy of your personal data (data portability), and
- send a complaint to the Data Protection Officer or The Norwegian Data Protection Authority regarding the processing of your personal data

What gives us the right to process your personal data?

We will process your personal data based on your consent. Based on an agreement with NTNU, NSD - The Norwegian Centre for Research Data AS has assessed that the processing of personal data in this project is in accordance with data protection legislation.

Where can I find out more?

If you have questions about the project, or want to exercise your rights, contact:

- Gabriel Kiss (Department of Computer Science, NTNU), email: gabriel.kiss@ntnu.no
- Ekaterina Praslove-Førland (Department of Education and Lifelong Learning, NTNU), email: ekaterip@ntnu.no
- Maria Emine Nylund (Department of Computer Science, NTNU), email: mariaiva@stud.ntnu.no
- NSD - The Norwegian Centre for Research Data AS, email: (personverntjenester@nsd.no) or by telephone: +47 55 58 21 17.

Yours sincerely,

_____   _____

Student   Date

Consent form

I have received and understood information about the project HoloUmoja and have been given the opportunity to ask questions. I hereby declare my consent that my data in relation to HoloUmoja may be stored, documented and used for research and educational purposes as described above. I give consent for my personal data to be processed until the end date of the project, approx. 15.06.2022.

_____   _____

Participant   Date

A.3   Task scenarios for phase 1 of the evaluation

You are interested in exploring how to measure blood velocity in an umbilical cord using Doppler ultrasound and how the four parameters such as beam-to-flow angle, PRF, blood velocity and sampling depth affect the measurement.

A: On-boarding

You are at University and want to explore the HoloUmoja application. In front of you, you see 3D printed models of an ultrasound probe and abdomen with images connected to them. You want to start the application and see if you are able to see a visualisation of a fetus inside the abdomen and a ray coming out of the probe.

1. Open the HoloLens menu and click on the HoloUmoja application
2. Notice the "Welcome" menu explaining the situation
3. Navigate the HoloLens camera towards the images until the 3D objects are visible

B: Spectrograms

Now that you see the fetus, you notice the umbilical cord, you want to measure the blood velocity using the ray coming out of the probe and see the spectrograms.

1. Point the ray coming out of the probe towards the orange part of the umbilical cord
2. Turn towards the "Ultrasound" menu and see the changes to the black square having a spectrogram

C: Angle 90

In addition, to the spectrograms, you want to see what angle you have now between the ray and the blood direction and say it out loud. Once you find it, you want to change that value closer to 90 and see how the spectrogram has changed.

1. Notice the angle value on the corner and read it out loud
2. Change the probe orientation until the value is closer to 90
3. See the spectrograms become flatter

D: Angle 30

You want to change the angle to closer to 30 and see how the spectrogram has changed

1. Change the probe orientation until the value is closer to 30
2. See the spectrograms become higher

E: Values

You want to explore the effects of other values such as depth, PRF and Blood velocity on the spectrograms

1. Change the slider values
2. See their effect on the spectrograms

A.4 SPINE

The changes from the original SPINE application are marked in *italic*. We have removed the original questions about gaze (**IM1** and **IM11**) and voice commands (**IM3** and **IM33**) because the application did not have those. Instead we asked (*IM01* and *IM03*) if the user thought it would have been useful with such commands. In addition, we have substituted the word "controller" with "3D printed objects" to be more specific in the questions (**IM4** and **IM44**).

- **SC1**: It was easy to control the application.
- **SC2**: The user interface elements clearly represented their functions.
- **SC3**: I was able to understand where I am in the system.
- **SC4**: The user interface blends together with the real world.
- **NG1**: It was easy to find the target with the navigational pointers provided.
- **NG2**: The navigation through the environment helped me to avoid obstacles.
- **NG3**: I had difficulties to identify in which direction I need to face.
- **NG4**: It was clear how I need to position myself to have the best experience.
- **MP1**: I was able to go back in the system and redo my actions.
- **MP2**: The user interface interrupted my real-world task performance.
- **MP3**: The interface blocked my interaction with the real world.
- **MP4**: The instruction from the system was not clear.
- **SL1**: The size of the user interface elements was sufficient to select.
- **SL2**: I understood the functionality I used.
- **SL3**: The system provides timely feedback about the processes happening.
- **SL4**: The system provided a clear confirmation of the actions I performed.
- ***IM01****: Using gaze to trigger system functionality would be suitable for this application.*
- **IM2**: The gesture commands were easy to use.
- **IM22**: I knew where to position my hands for the system to recognise my gesture commands.
- ***IM03****: I would have found it useful if I could use voice commands to control the application.*
- **IM4**: The *3D printed objects* allows me to be flexible with interaction.
- **IM44**: Using the *3D printed objects* was simple.
- **OM1**: Audio cues were understandable and loud enough.
- **OM2**: Text instructions were successful in delivering their meaning.
- **OM3**: Holograms helped me to use the system.
- **OM4**: The spatial arrangement of the content was consistent.
- **OM5**: Haptic feedback complimented my experience with the system.

Table A.1: SPINE constructs as described by Ravagnolo, Helin, Musso, *et al.* [51]

Group	Constructs	Summary
System control (SC)	Ease of use Metaphors Status Realism	Measures general usability of the system and overall control of the application. It helps to determine whether the user understands what is happening at a particular moment and ensures that the spatial interface is seamlessly integrated
Navigation (NG)	Location Obstacles Orientation Wayfinding	Measures one of the primary tasks in AR — movement through space. This group is designed to solve problems with navigation that the user might encounter while moving from one location to another in a physical space
Manipulation (MP)	Progress Accuracy Precision Understanding	Measures how well users understand directions from the application. These constructs also look at the balance between spatial interface and real-world view, helping to estimate amount of "augmentation" of the content
Selection (SL)	Size Instruction Feedback Confirmation	Measures the combination of important elements in a feedback loop, providing sufficient information about users' understanding of the actions within the system. It also helps to find out whether functions and their representation within the application is clear
Input modalities (IM)	Gaze Gesture Voice Controller	Measures a selection of the most common input methods: gaze (head position), gestures (using hands), voice (different predefined voice commands) and controller (in case of the HoloLens it is a clicker, i.e. remote controller).
Output modalities (OM)	Sound Text Visuals Space Haptic	Measures a selection of the most common output methods: sound (voice instructions, music), text (written instructions in a form of note or annotation), visuals (3D holograms, 2D images, video files, glyphs etc.), space (container for all AR content that can act as a medium itself) and haptic (tactile feedback).

A.5   Questionnaire

HoloUmoja: Demographics + SPINE

Thank you for agreeing to participate in this user test. Here you will be asked some demographic questions and questions developed to measure usability of the augmented reality application.

* Required

D1: What is you age? *

Mark only one oval.

◯ 18-25

◯ 26-35

◯ 36-44

◯ 45+

D2: What gender do you identify as? *

Mark only one oval.

◯ Female

◯ Male

◯ Prefer not to say

◯ Other: _____

D3: What is the highest degree or level of education you have completed? *

Mark only one oval.

◯ Elementary, Junior or High School

◯ Bachelor's Degree

◯ Master's Degree

◯ Ph.D. or higher

◯ Prefer not to say

4.   D4: Which field do you study/work in? *

Check all that apply.

☐ Information Technology
☐ Medicine
☐ Other: _____

5.   D5: Have ever you used HoloLens or HoloLens 2 Augmented Reality headset before the test? *

Mark only one oval.

◯ Yes
◯ No
◯ Maybe
◯ Other: _____

6.   D6: Have you ever preformed Doppler Ultrasound examination? *

Mark only one oval.

◯ Yes
◯ No
◯ Maybe
◯ Other: _____

Skip to question 7

SPINE   In this section you are asked to fill out how much you agree and disagree with each statement. The scale is from 1 (Strongly disagree) to 7 (Strongly agree), where 4 indicates "Neither".

7.   SC1: It was easy to control the application. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

8. SC2: The user interface elements clearly represented their functions. *

   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

9. SC3: I was able to understand where I am in the system. *

   Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

10. SC4: The user interface blends together with the real world. *

    Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

11. NG1: It was easy to find the target with the navigational pointers provided. *

    Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

12. NG2: The navigation through the environment helped me to avoid obstacles. *

    Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

13.   NG3: I had difficulties to identify in which direction I need to face. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

14.   NG4: It was clear how I need to position myself to have the best experience. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

15.   MP1: I was able to go back in the system and redo my actions. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

16.   MP2: The user interface interrupted my real-world task performance. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

17.   MP3: The interface blocked my interaction with the real world. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

18. MP4: The instruction from the system was not clear. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

19. SL1: The size of the user interface elements was sufficient to select. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

20. SL2: I understood the functionality I used. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

21. SL3: The system provides timely feedback about the processes happening. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

22. SL4: The system provided a clear confirmation of the actions I performed. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

23.   IM01: Using gaze to trigger system functionality would be suitable for this application. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

24.   IM2: The gesture commands were easy to use. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

25.   IM22: I knew where to position my hands for the system to recognise my gesture commands. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

26.   IM03: I would have found it useful if I could use voice commands to control the application. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

27.   IM4: The 3D-printed objects allows me to be flexible with interaction. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

28.   IM44: Using the 3D-printed objects was simple. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

29.   OM1: Audio cues were understandable and loud enough. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

30.   OM2: Text instructions were successful in delivering their meaning. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

31.   OM3: Holograms helped me to use the system. *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagree	◯	◯	◯	◯	◯	◯	◯	Strongly agree

A.6 SPINE Results per question

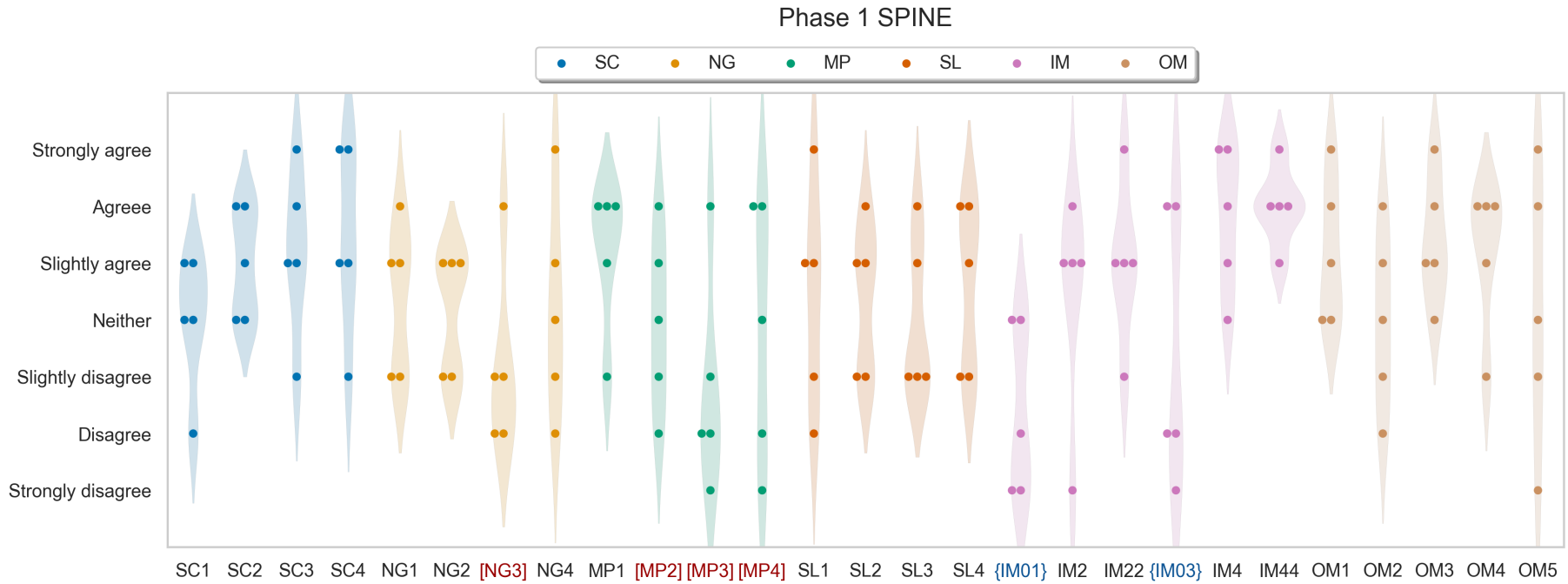Figure A.1: The results of all questions in the Spine questionnaire from phase 1 testing. The ones marked red in "[]" brackets are negatively structured questions, the blue ones in "" are would be questions.
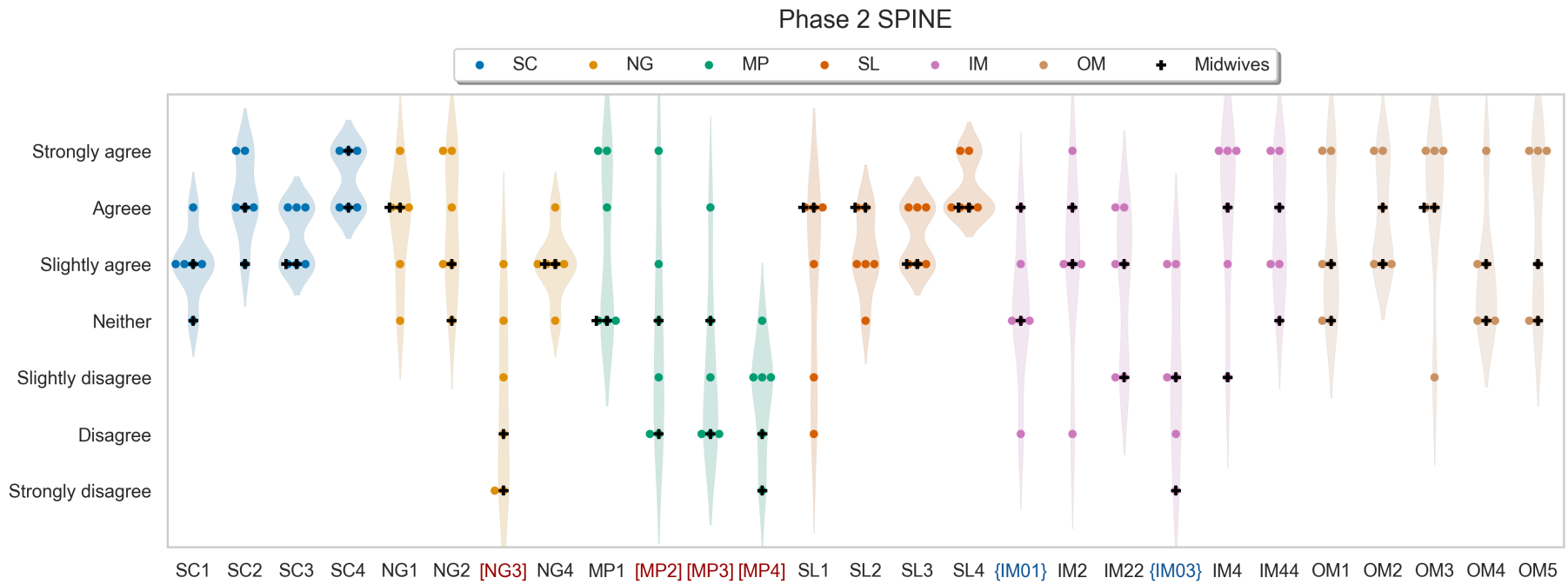
Figure A.2: The results of all questions in the Spine questionnaire from phase 2 testing. The ones marked red in "[]" brackets are negatively structured questions, the blue ones in "" are would be questions. The midwives' answers are highlighted with black "x".

A.7 Stakeholder feedback v1.0

The prototype aims to present a highly detailed geometric model of the fetus and is intended for users that are learning Doppler acquisitions in the context of fetal ultrasound. In my opinion, the current prototype is very useful for understanding the 3D relationship between the probe position and orientation of the umbilical cord that is to be examined. Furthermore, the prototype can automatically determine the relative angle between the probe and umbilical cord which is very important for proper Doppler spectrum generation. The accuracy of the frame marker-based tracking seems to be sufficient for the current application. The angle measurements are consistent and do not flicker too much.

All the relevant Doppler parameters are included in the user interface. By implementing the Doppler spectrum generation on the HoloLens device, no extra hardware is needed for the simulator. This is very useful for usability purposes. However, it will be very useful to generate more realistic Doppler spectrograms that are more representative of the umbilical cord flow, both normal and diseased.

Combining the AR model with a 3D printed abdomen is very beneficial since it improves the stability of the probe and allows for a more realistic scenario (as opposed to a probe in the air or against a flat surface). This will also allow adding more sensors to the prototype to increase its realism. For example, an orientation sensor can give more accurate orientation information as opposed to the visual tracker, once the probe is placed in a given position on the abdomen. Additionally, a force sensor measuring how hard the user is pushing the probe against the abdomen will be beneficial to mimic the real situation.

A.8 Expert interview v1.0

The interview happened on the 10th of March 2022 over Zoom due to the pandemic. Student, one of the supervisors and two professors of midwifery from NTNU attended the meeting. The interview consisted of a presentation of the motivation for the project, background, current state (HoloUmoja 1.0) and the future ideas for improvement. The last slide included the main questions to the experts after which the conversation flowed naturally and was unstructured.

Here I present the questions to the experts and their main points for answers.

When and who studies the Doppler ultrasound at NTNU?

UL6003 - Doppler Ultrasound in Obstetrics is a higher degree level subject for students in the Postgraduate Ultrasound Education for Midwives (MDULTRALYD) program. So the students have the basic training and education in obstetric ultrasound [55]. Gynaecologists can also perform this procedure, although they are not as well trained, according to the experts. Some of the medical study students also take the UL6003[55] subject.

How and for how long?

This is a one year program Master in midwifery is a two-year program, to be admitted to the program you have to have at least two years of professional practice Bachelor in the nursery is a three-year program During the course, the students are lectured on the theory of the Doppler ultrasound procedure, then it is followed by two weeks of practice. After that, students continue their practice at their respective workplaces and finish a project where they need to analyse the images. Sometimes an application called ScanTrainer is used, there is a fair amount of recording that students can watch.

What do they struggle the most with understanding?

The overall goal during the UL6003[55] subject is to learn to optimise the image given the situation. The most challenging aspect of the obstetric ultrasound is getting the overall picture of the situation. For example, the heart frequency of the fetus can be higher than the average, which in turn can affect the measurements and give wrong information. It is all about avoiding sources of error. The big challenge is that one has to optimise the image in three different modes and take the framerate in consideration as well. In addition, the fetus and the patient is moving.

What would be useful/not in such application?

Usually, one set in the correct PRF value in the colour Doppler phase and then moves on to Doppler. It may be counter-intuitive to learn to set it for the spectrograms. There are different velocities of the blood depending on which artery it is in the umbilical cord also how close or far it is to the placenta and how the cord is wrapped. The students learn the physics and mathematics behind the ultrasound, so it definitely useful to have visualised in the application as well to understand the parameters. 'Students often struggle with finding the correct angle, I am sure it will help to see the model of the fetus and experience the situation. This application gives a good visualisation of the important concept with the angle ratio. It is important to be able to build on the basic skills the more complex understanding.' Consider adding a baseline and a wall motion filter (usually the value should be under 50 or sometimes even 30) as those are the parameters being used often as well.

How do you think you could use it?

'During the theory lectures to explain and later the students can use it in their own time for training'.

```cpp
void eulerToQuat(float x, float y, float z, float* quat) {
    float yaw = x; float pitch = y; float roll = z; // Expects RADIANS

    float yawOver2 = yaw * 0.5f;
    float cosYawOver2 = cos(yawOver2);
    float sinYawOver2 = sin(yawOver2);
    float pitchOver2 = pitch * 0.5f;
    float cosPitchOver2 = cos(pitchOver2);
    float sinPitchOver2 = sin(pitchOver2);
    float rollOver2 = roll * 0.5f;
    float cosRollOver2 = cos(rollOver2);
    float sinRollOver2 = sin(rollOver2);

    quat[0] = sinYawOver2 * cosPitchOver2 * cosRollOver2 +
              cosYawOver2 * sinPitchOver2 * sinRollOver2;   // x
    quat[1] = cosYawOver2 * sinPitchOver2 * cosRollOver2 -
              sinYawOver2 * cosPitchOver2 * sinRollOver2;   // y
    quat[2] = cosYawOver2 * cosPitchOver2 * sinRollOver2 -
              sinYawOver2 * sinPitchOver2 * cosRollOver2;   // z
    quat[3] = cosYawOver2 * cosPitchOver2 * cosRollOver2 +
              sinYawOver2 * sinPitchOver2 * sinRollOver2;   // w
}
```

Listing 3: Conversion from Euler rotation to quaternion written in C++

```csharp
RaycastHit hit;
if (Physics.Raycast(transform.position, transform.TransformDirection(Vector3.forward),
                    out hit, Mathf.Infinity, layerMask)) {
    float angle = Vector3.Angle(transform.forward, hit.transform.forward);
    float cosAngle = Mathf.Abs(Mathf.Cos(angle * Mathf.Deg2Rad));
    previousAngle = Mathf.RoundToInt(CurrentAngle);
    CurrentAngle = (Mathf.Acos(cosAngle) * Mathf.Rad2Deg);

    int currentAngleRounded = Mathf.RoundToInt(CurrentAngle);
    if (currentAngleRounded != previousAngle) {
        SampleUtil.AssignStringToTextComponent(AngleTextObject ? AngleTextObject :
                                  gameObject, "Angle:\n" + currentAngleRounded);
        valueUpdate?.Invoke(currentAngleRounded);
    }
}
```

Listing 4: Calculating angle between the ray coming out of the ultrasound probe model and the umbilical cord collider.

A.9 Additional user interface views in v2.0
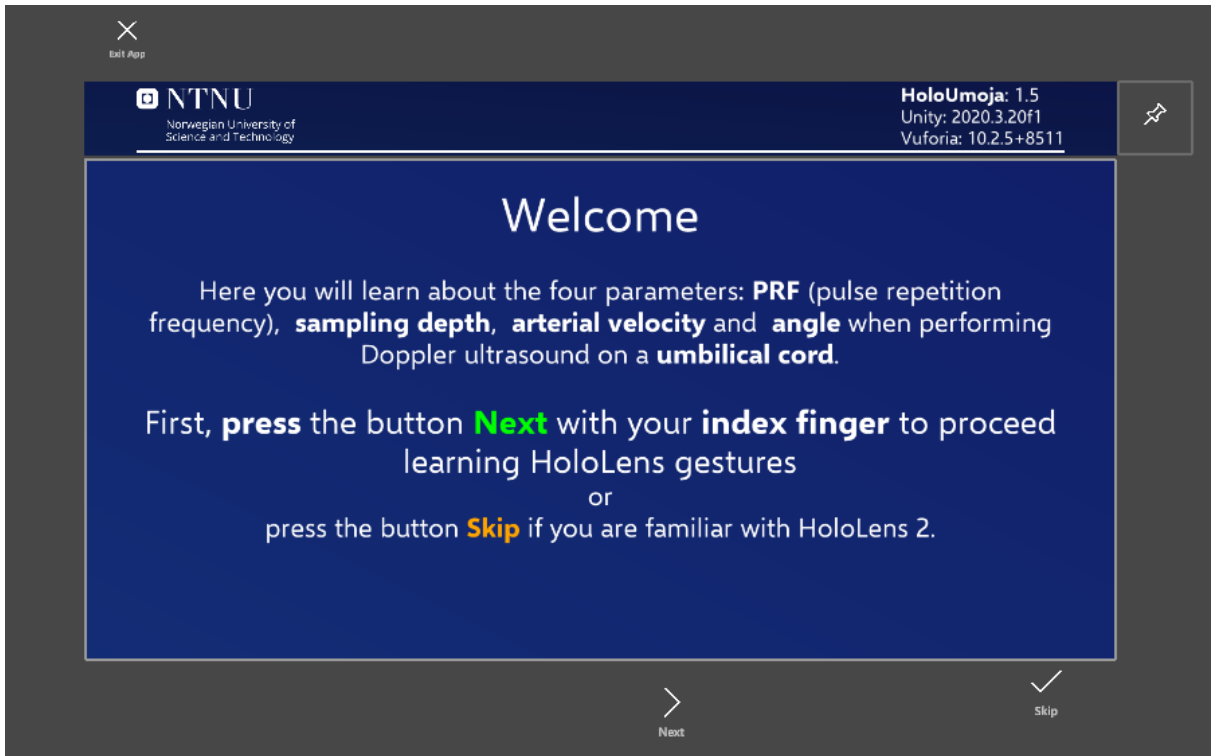

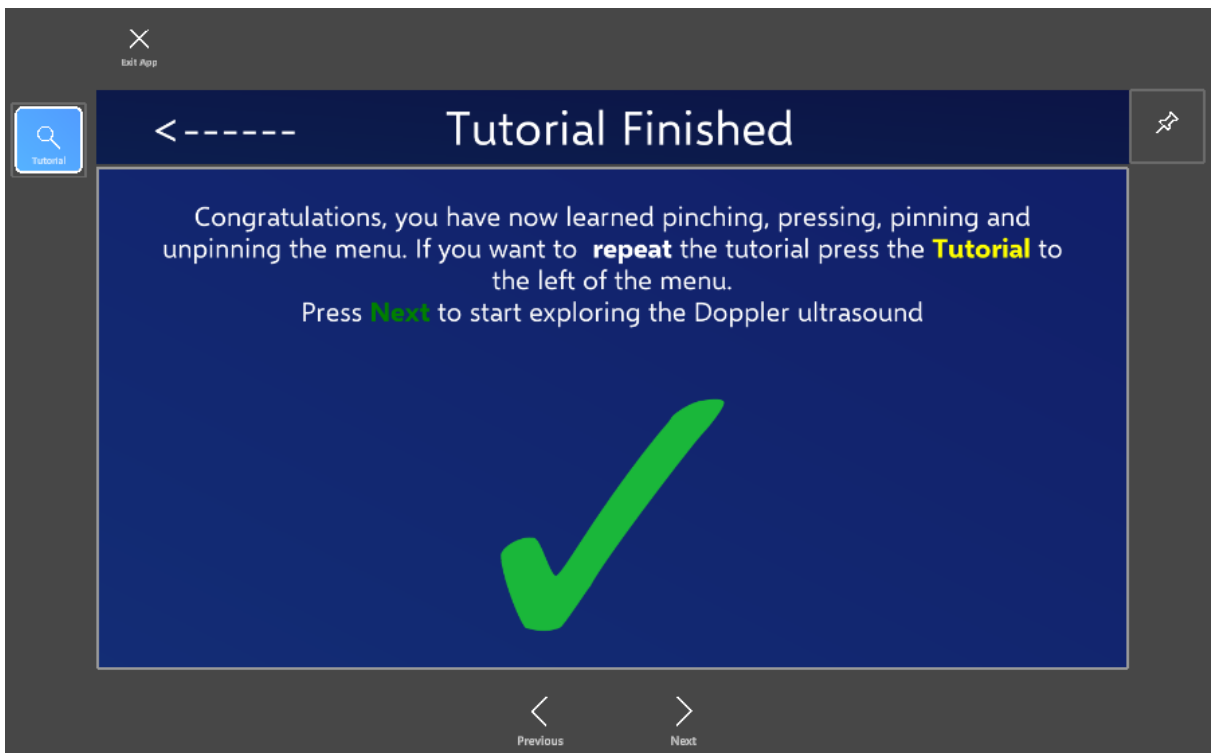Figure A.3: Welcome Menu

Figure A.4: Tutorial finished menu

A.10   Deployment

Here it is assumed that one first gets access to the private repository. For more information contact the author or supervisors of this thesis.

Installation of HoloUmoja

1. Go to the release page: <https://github.com/marianylund/holoumoja/releases/tag/2.0>

2. Download the latest release (v2.0)

3. Unzip the packages

4. Follow the guide by Microsoft [1] to install the HoloUmoja application on the HoloLens

5. Follow the guide by Arduino[2] to build the Arduino code on their respective Arduino board.

Known issues

Some issues were observed when developing the application that probably lies within the hardware itself. We attempt to provide the solutions we have used to solve the issues:

- If the user gives the headset with the application open to another person, the image recognition stops working. The same might happen if the eyes are calibrated after the application has been opened. ⟶ The possible solution is to manually *close* (not only *minimize*) the application and open again. It is best to *close* the application when changing users, perform eye calibration and *then* open the application.

- When the application is freshly installed on HoloLens, even though the user clicks that they allow the application to use the camera image tracking does not work. ⟶ Possible solution is to manually go to Settings → Application Permissions and set camera permission for the application to allowed.

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[1]<https://docs.microsoft.com/en-us/windows/mixed-reality/develop/advanced-concepts/using-the-windows-device-portal>
[2]<https://docs.arduino.cc/software/ide-v1/tutorials/arduino-ide-v1-basics#sketch>

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