UNIVERSITAT DE BARCELONA

Final Degree Project

Biomedical Engineering Degree

"Mixed Reality system to study deformable objects: Breast Cancer application"

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Abstract

A significant amount of women who go through a breast cancer conservative surgery to treat early stage breast cancer undergo a repeat surgery due to concerns that residual tumor was left behind. To avoid this, tumor localization is needed to assist the surgeon in order to determine tumor extent and also, it is critical to account for tissue deformations. For these reasons, new navigation systems, like the one proposed on this project, are emerging to cover those needs. This project focuses on the use of a Mixed Reality system to improve the accuracy in placing the static hologram of the tumor and, to implement a dynamical hologram when deformation takes place.

In order to do so, two different molds with objects inside have been manufactured. Next, two different approaches were considered, a mathematical approach to create a 3D CAD model of the molds and a medical approach, which consisted in performing a CT and then, segment the images. The models were post-processed and imported to the HoloLens head-mounted display.

The system was tested on the molds and on a breast phantom provided by the Hospital Clinic. The results obtained were encouraging and although some things need to be improved, this exciting new use for Augmented Reality has the potential to improve the lives of many patients.

Keywords: Augmented Reality · Mixed Reality · Breast cancer · Image-guided surgery

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Glossary of terms

- WHO: World Health Organization
- BC: Breast Cancer
- BCS: Breast Conservative Surgery
- AR: Augmented Reality
- CT: Computed Tomography
- MRI: Magnetic Resonance Imaging
- IGS: Image-Guided Surgery
- OR: Operating Room
- IDC: Invasive Ductal Carcinoma
- ILC: Invasive Lobular Carcinoma
- ROLL: Radio-guided Occult Lesion Localization
- MIS: Minimally Invasive Surgeries
- BSM: Breast Surface Markers
- RTFHV: Real-Time, Fused Holographic Visualization
- ML: Machine Learning
- XR: Extended Reality
- VR: Virtual Reality
- MR: Mixed Reality
- CAD: Computer-Aided Design
- CAE: Computer-Aided Engineering
- HMD: Head-Mounted Display (HMD)
- CE: Conformité Européenne
- SDK: Software Development Kit

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1. Introduction

Cancer is the main health problem in the world. It is the second leading cause of death worldwide and it is predicted a growth of more than 30% of new cases by 2030. However, according to the WHO (World Health Organization), 30% to 50% of cancer cases could be avoided by following healthy lifestyles and implementing public health measures. Therefore, early detection and primary prevention have an important function in minimizing the impact of cancer on human lives. [1] The impact of cancer does not only have to be understood from a physical health perspective, but also from an emotional health perspective, as well as from an economic and social one. It is estimated that in total, cancer costs around 19.300 million euros to Spanish society. [2]
In Spain, Breast cancer (BC) is the most commonly diagnosed cancer in women – with 34,088 incidence cases in 2020 (shown in Figure 1.) It is predicted that 1 in 8 Spanish women will suffer from BC at some point in their lives. [2] Although the mortality from breast cancer has decreased in recent years thanks to screening programs and improved treatments, breast cancer continues to be the leading cause of death from cancer in Spain in women. In 2020, 6,606 women died of breast cancer in Spain. It is estimated that the costs of BC per patient are about 58,832€ for local BC and 210,142 for metastatic BC. [1]

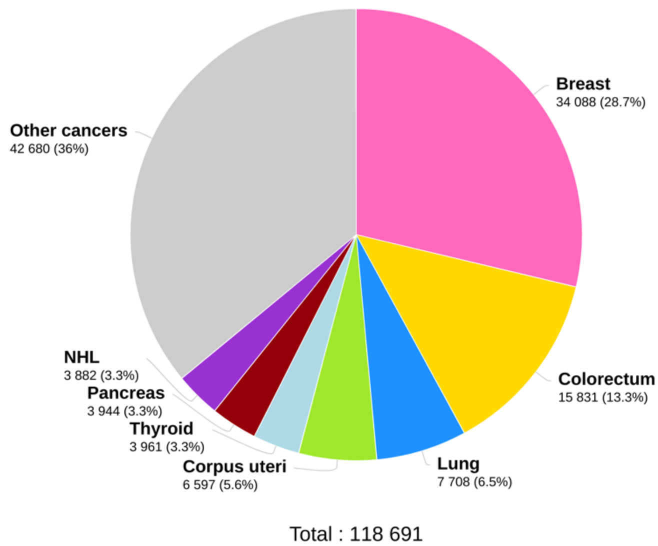


Figure 1. Estimated number of new cases of cancer in Spain, in females, in 2020 [3]

Breast cancer conservative surgery (BCS) combined with radiotherapy has become the treatment of choice for the majority of women presenting an early breast cancer. The aim of BCS is to achieve optimal long-term local control, with free margins after the tumour excision and a good cosmetic outcome. [4] Due to widespread screening, an important percentage of early breast cancers are non-palpable. As a consequence, tumor localization is needed to assist the surgeon during surgery. Innovations in 3D spatial technology and augmented reality (AR) driven by digital high-tech industrial science have accelerated exploratory research in breast cancer imaging, focusing on the acquisition of real-time information and data visualization during an ongoing surgery. [5] In AR-based surgical navigation systems, patient-specific 3D models generated from preoperative images such us computed tomography (CT) and magnetic resonance imaging (MRI) are usually superimposed on the real view of the surgical area to provide surgeons with anatomical structures and/or images. Consequently, in image-guided surgery (IGS) systems, AR technology appears as a significant development because it aims to profitably integrate surgical navigation with virtual planning contextually to the real patient's anatomy. [6]

1.1 Objectives

This project is a continuation of the Final Degree Project conducted by Teresa Puigferrat - another UB Biomedical Engineering student - in 2020. Her project consisted of the implementation of AR technology in the operating room (OR). The author was given the opportunity to proceed with her idea and bring it closer to implementing AR to improve the tumor resection and the surgery's efficiency, leading to minimized overall costs and resources and better recovery.

The **main goal** of this project is to **improve the accuracy in the location of the tumor statically and, as a first approach, implement a dynamical system when deformation takes place.** This would imply that despite all deformations that organs undergo due to manipulation, respiratory motion and interaction with the surgical instruments, the system would be able to almost instantly generate a new model that would fit with the reality. The following specific objectives were set in order to achieve those major goal:

1. **Development of molds** with objects inside to simulate "human tissue" and the tumors: this needs to be done in order to test the AR system in something that resembled the real application, since due to Covid, the project could not be implemented in real patients.
2. **3D CAD model** of the molds: a CAD software will be used to create a 3D model of the molds.
3. **Segmentation and post-processing of the molds:** A segmentation software will be used to segment the molds and the different objects inside. Also, these segmentations will be post-processed to create the virtual model for the AR application.
4. **AR application** of the **static model** on the molds: this first static approach will consist in placing a hologram of the mold over the real mold.
5. **AR application** of the **dynamic model** on the molds: the dynamic approach will consider in testing a system capable of generating a hologram that deforms the same way as the mold when a force is applied.
6. **Final assessment** in a **breast phantom**: the final testing will consider in testing the system in a breast phantom provided by the Hospital Clinic.

1.2 Methodology

The **main steps** of the methodology of the project can be structured in 2 different stages. The **pre-testing stage** and **the testing stage** with a breast phantom.

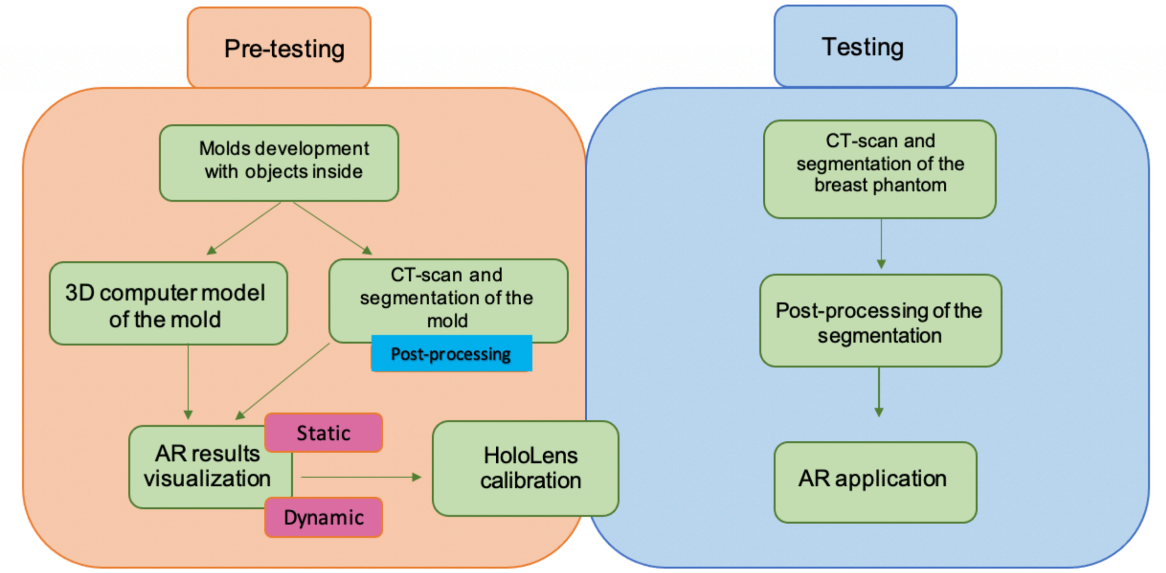


Figure 2. Scheme of the methodology of the project

The pre-testing stage consists in the **visualization of the AR results in two molds** developed by the author with objects inside. The first step is to assess the accuracy of the AR system in placing the objects in the right place when there is no deformation. The second step, the dynamic visualization with AR, consists in testing the AR system behavior when the tissue, and consequently the objects inside are deformed. The objective is that the AR hologram deforms the same way as the tissue. The testing stage consists in performing all the studied before in the molds in a **breast phantom** to be closer to the reality. The different steps performed to carry out these two stages will be explained more in detail in section 5, the detailed engineering.

1.3 Scope and limitations

The **largest limitation** has been **Covid-19 pandemic** which has forced to use molds and phantoms instead of real BC patients. The initial idea of this project was to see the application of AR in real surgeries and perform the study with real patients. With hospitals being collapsed with Covid-19 patients, the author had to adapt to the situation and find a methodology where the collaboration of a hospital was not necessary. Due to this, the study is carried out with phantoms and the evaluation of the technique could not be assessed in surgeries with real patients.
Moreover, this situation has also forced to perform almost all the project from distance. This has caused the meetings with the tutors to be online and the interaction through emails, which has drawn out the project. As this was a final project, time has been another important limitation. This project has been carried out from November 2020 to June 2021.

The **span** of this project, considering the limitations mentioned previously, is to **enhance the visualization of organ's internal anatomy during surgeries using AR**, specifically BC surgeries.

To do so, the scope of this project includes:

- Bibliographic research of possible improvements to the application of AR in BC surgeries
- Development of molds with object inside to simulate the human tissue and the tumors to assess the validity of the AR systems.
- Usage of AR technology to locate the objects precisely inside the molds.
- Assess the validity of a dynamic hologram to deform the same way the tissue does. Representing the deformation that the tissue suffers during a surgery.
- Final validity of the AR system in a breast phantom.

1.4 Location of the project

The study described has been performed in collaboration with CIMNE (International Centre for Numerical Methods in Engineering). The group is located on the first floor of building B0 at the Campus Nord of the Polytechnic University of Catalonia (UPC). Moreover, the author also had the help of the Nuclear Medicine Department at the Clinic Hospital. It has been performed majorly at distance with the help of periodic virtual meetings with Eduardo Soudah and Aida Niñerola and also some face-to-face meetings with Óscar de Coss.

2. Background

2.1 General concepts

To better understand the areas that this project will cover, this section will define some concepts. Like the **breast anatomy** and the **principal breast cancer treatments** used nowadays.

2.1.1 The Breast

The **breast** is part of the female and male sexual anatomy. The breast is located on the anterior thoracic wall. It extends horizontally from the lateral edge of the sternum to the mid-axillary line. In the vertical direction, it straddles between the 2nd and 6th costal cartilage and it is located on the surface of the pectoralis major and serratus anterior muscles. [7] The visible parts of breast anatomy include the nipples and areolae.

For women, breasts are both functional (for breastfeeding) and sexual (for pleasure). [8] Male breasts have no function, during puberty, the male hormone testosterone usually prevents breasts from developing like women. Internally, their mammary ducts are underdeveloped and there is no glandular tissue. However, they can also develop BC, though it is very uncommon (just 1% of cases) [9]

In females, the breasts contain the mammary glands – an accessory gland of the female reproductive system which are the key structures involved in lactation. The mammary glands are surrounded by a connective tissue stroma. They consist of a series of ducts and secretory lobules (15-20). Each lobule is composed of many alveoli drained by a single milk duct. The connective tissue stroma is a supporting structure which surrounds the mammary glands. It has a fibrous and a fatty component. [7]

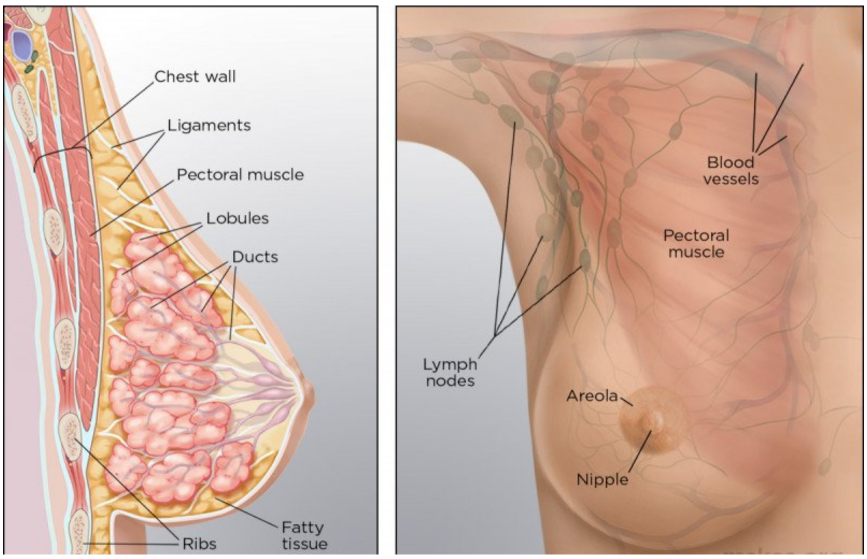


Figure 3. Scheme of the breast's anatomy [9]

2.1.2 Breast cancer

Breast cancer is a disease in which **cells in the breast grow out of control**. The kind of BC depends on which cells in the breast turn into cancer. Most BC begin in the ducts or lobules. The most common kinds of BC are:

- **Invasive ductal carcinoma (IDC):** It begins in the cells of a milk duct, then it grows through the duct walls and into the surrounding breast tissue. It can also spread to other parts of your body. Invasive ductal carcinoma (IDC) accounts for about 80% of all invasive breast cancers in women and 90% in men. [10]
- **Invasive lobular carcinoma (ILC):** Cancer cells spread from the lobules to the breast tissues that are close by. It's the second most common form of breast cancer. [11]

There are several treatments for BC. It depends on the kind of BC and how far it has spread. People often get more than one treatment. The most **typical treatments** are **chemotherapy, radiation therapy, hormonal therapy, and surgery**. There are two surgical treatment options: **breast-conserving surgery (BCS**) -also called lumpectomy or partial mastectomy- which consists of removing the tumor and some of the surrounding normal breast tissue leaving the breast intact. [12] A **mastectomy**, on the other hand, removes the entire breast. BCS can almost be considered the gold standard of early-stage invasive breast cancer treatment, allowing to achieve adequate surgical margins (SM) with an acceptable cosmetic outcome. Various randomized trials have reported this approach to be safe and effective, thus determining a decrease in the adoption of mastectomy as the treatment of choice for early invasive breast cancer [13, 14].

A requirement for successful BCS is a careful preoperative planning with proper localization of the lesion, especially in non-palpable breast lesions [15]. Wire-guided localization, radio-guided occult lesion localization (ROLL), carbon marking, intraoperative ultrasound-guided localization, cavity shave margins, and biopsy markers are traditional methods commonly used to assist the surgeon during the intervention. [16]

2.1.3 AR in surgery

AR can be regarded as a technology that integrates computer-generated objects and/or virtual content into the real world, thereby enhancing the perception of reality. This artificial information helps the user to perform tasks more efficiently. One important point of this technology is the visualization method the surgeon has when is operating. Traditionally the surgeon operates with the '**Head's up**' method, visualizing the data on the screen. The purpose of AR in surgery is to combine preoperative data, such as MRI or CT volumes, and fuse the data onto the intraoperative real-time environment. [12] AR technology allows the surgeon to 'see through' the patient's skin and appreciate the underlying anatomy without making a single incision, therefore the surgeon has the information on top of the patient without having to stop looking at the patient to look at a screen. [17]

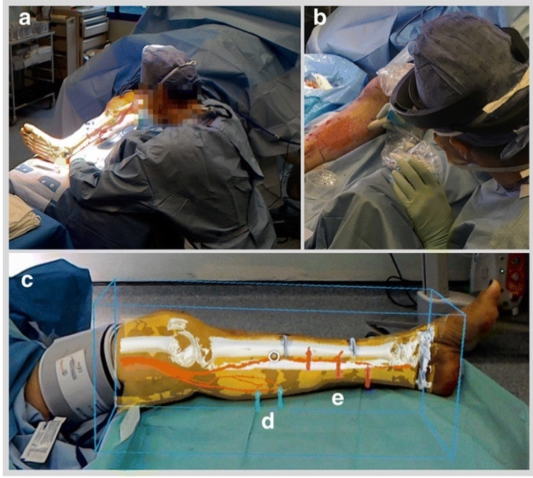


Figure 4. Augmented Reality using HoloLens. The image bellow (C) shows what the surgeon sees during the operation. [17]

2.2 State of Art

In the last years, AR-based IGS systems for minimally invasive surgeries (MIS) or little deformable tissues like maxillofacial surgery, orthopedic surgery, and neurosurgery [18] have been increasingly tested, even if mostly at research level. Many studies proposed using augmented reality in laparoscopic procedures with success [19]. However, up to date only few studies involving the use of AR in open surgery of soft tissues have been conducted. This is because in open surgery, the registration of virtual scenes and real scenes is still an open problem. Nonetheless, in open surgery, AR represents a particularly useful asset to improve the surgeon's spatial perception of the surgical field, thereby avoiding unnecessary operations or accidental damage to internal organs. [6]

The author presents a literature review aiming to describe and evaluate the studies performed up to date regarding the use of AR in open surgery, specifically in breast surgery. The author has performed a PubMed search of the available literature updated from 2017 to 2021 using the terms "**Augmented Reality**" AND **"breast surgery"**. The initial search yielded 12 articles, after reading the abstracts, 7 articles were chosen.

Reference	Organ targeted	Goal	Data source	Segmentation software	AR system display
[4] (2021)	Breast	Evaluation of an experimental digital and non-invasive intra-operative localization method with augmented reality comparing it with the standard pre-operative localization with carbon tattooing	MRI	Horos R software	Microsoft HoloLens

[5] (2019)	Breast	Development of a research prototype which enables virtual preoperative localization of nonpalpable breast lesions using MRI images	MRI	Medical Image Segmentation Tool (MIST)	Anatoreg ©.
[20] (2019)	Breast	Perform a mastectomy surgical planning prototype. Enabling the surgeons to see the shape of the implants, as 3D holograms on the patient's body.	Scan of the patient using HoloLens infrared sensors	Not applicable	Microsoft HoloLens
[21] (2018)	Breast	Development of a fiber optoacoustic guide (FOG) with augmented reality (AR) for sub-millimeter tumor localization and intuitive surgical guidance with minimal interference.	MRI and mammogram	Not mentioned	Microsoft HoloLens
[22] (2018)	Breast	Development of a framework that is capable of displaying a virtual model of the tumor on a patient's breast.	MRI	Not mentioned	Microsoft HoloLens
[23] (2017)	Breast	Pilot study in patients with palpable tumors to analyze the spatial accuracy of the HoloLens tumor renderings compared to standard localization methods.	MRI	ITK- SNAP	Microsoft HoloLens

[24] (2017)	Breast	Development of an Augmented Reality visualization framework that enables breast cancer biopsy image guidance by using X-Ray vision technique on a mobile display.	CT/MRI	3D slicer	Tablet

Table 1. Articles from 2017 to 2021 in which AR technology has been implemented in breast surgeries.

The most recent breast surgery performed with AR up to date is the one performed by the **Champalimaud Clinical Centre, in Lisbon**. [4] The group performed a **conservative breast surgery with tumor localization**. During the surgery, an experimental digital and non-invasive intra-operative localization method with AR was compared with the standard pre-operative localization with carbon tattooing. The breast surgeon wearing an augmented reality headset (HoloLens) was able to visualize the tumor location projection inside the patient's left breast in the usual supine position.

Figure 5. In action: surgeon wearing HoloLens headset at the surgical theater. [4]

The clinical case was performed in a 57-year-old post-menopausal woman presented with a screen-detected left sided BC. The breast surface markers (BSM) were applied on the patient's breast with a 10cm fiducial marker. A 3D surface scan of the patient was performed in the supine position with arms at 90 degrees, capturing the size and shape of both breasts and torso

A contrast enhanced MRI, using fish-oil capsules as markers, in the prone position was performed. The annotation, segmentation, and volume computation of the MRI tissue portions were performed using Horos R software. Breast MRI/3D scan fusion was accomplished with overlap between both modalities. A patient-specific 3D digital breast model was uploaded to an AR headset: HoloLens 1.

This tumor localization procedure using AR was compared with the standard pre-operative localization with carbon tattooing under ultrasound guidance to assess the accuracy of the AR method. The localization of the tumor was successful although the protocol needed to be adapted with patient repositioning from prone to supine during the MRI registration.

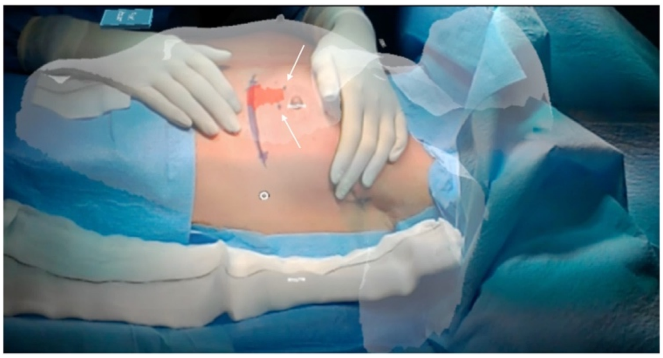


Figure 6. – Surgeon's view of the phantom model (with tumor location) synchronized with the patient through augmented reality.

Though tremendous strides have been made over the past years in the usability of AR in medical applications, specifically in the OR, there is still room for improvement. A major limitation of AR is miss-registration between the real world being viewed and the superimposed virtual object. This can occur because of "system latency, tracker error, calibration error, and optical distortion" [25]. All the articles reviewed focus in the location of the tumor statically. The authors place the tumor over the skin's patient. This project aims to take this application one step further and be able to consider the deformation of the tissues, performing a better registration with the real environment.

Remark, that this final degree project is a follow up project of two other UB final degree projects. Firstly, O.Palomares project consisted on to study the feasibility of using augmented reality in a lamb liver surgery. For this purpose, a 3D model of an animal's liver from a medical image was printed and the augmented reality system was tried on such model [60]. Secondly, M.Puigferrat project was based on creating static personalized models of liver and breast based on CT images, and combine them with augmented reality techniques [61].

3. Analysis of the market

3.1 AR opportunities in healthcare

The application of augmented reality technology is opening new opportunities in the healthcare industry. The benefits that it can bring to the field of medicine are revolutionary. Therefore, with the development of this trend, more and more companies on the healthcare sector are investing in this technology. Medical applications are wide-reaching and affect every facet of medical care from learning gross anatomy and surgical technique to patient-specific pre-procedural planning and intra-operative guidance.
Breast surgery is only one example of many other applications that AR can have in the field of medicine. A research has been made to find companies that intend to be at the forefront AR surgery. [26]

Startup	Features
echopixel	· *Echopixel True 3D* is a software platform that **enables physicians to interact with virtual patient specific anatomy** without the need for a bulky VR/AR headset. · True 3D is used to assist physicians to **plan surgical and interventional procedures** to treat Congenital Heart Defects. [27]
MediView SURGICAL NAVIGATION	· MediView is developing a first-of-its-kind intraoperative Real-Time, Fused Holographic Visualization (RTFHV) for Augmented/Extended Reality head-mounted displays with **intended use in ablation and biopsy of cancerous tumors.** · The physician can use the Head Mounted Display to **see the patient's internal anatomical structures and planned path of their surgical tools** and verify location with Real-Time, Fused Holographic Visualization [28]
Augmedics	· The company has what it calls "the first augmented reality guidance system for surgery," known as *xvision*. · xvision Spine **allows surgeons to visualize their patients' 3D spinal anatomy during surgery** as if they had "x-ray vision," helping them to accurately navigate instruments and implants while looking directly at the patient, rather than a remote screen. [29]
Proprio	· This company **combines machine learning (ML) and AR to create ultra-precise 3D medical images.** · Using Proprio's multi-camera system, surgeons access all the data they need—including **pre-operative imaging, powerful magnification, virtual annotation and collaborative feedback**—directly in their field of view. [30]

SENTIAR	· SentiAR develops a **3D augmented reality platform featuring real-time holographic visualization of the patient's actual anatomy**, "floating" over the patient. · The technology converts CT, MRI, and real-time mapping/catheter location outputs into a real-time hologram in the clinician field of view using a holographic headset. [31]
ImmersiveTouch®	·Converts 2D medical images into 3D spatial models, enhancing surgical planning, training, and collaboration. ·The company's ImmersiveView Surgical Plan platform generates **3D replicas from patient scans**, allowing surgeons to study and collaborate with their team on surgical tactics. [32]

Table 2. Principal companies worldwide at the forefront of AR applications in surgery.

3.2 Future perspectives

AR is not a new concept, but over the last few years, advances in camera and sensor technology and AR-focused software research have made it practical — we're still in the early stages of the AR revolution, but we can expect to see an explosion of AR devices and applications enter the market. As health costs continue to rise, AR will play a significant role to help prevent, manage, and cure billions of people. [33]
The AR market will resemble the smartphones market, thus targeting a huge population worldwide. The future of AR will evolve in the lines mentioned before, the three big roles that AR will play are:

- **Medical education and training**: Augmented reality, by combining real and virtual images, can help the aspiring healthcare experts. It helps them to understand the human anatomy in a more precise and spectacular way. It enables the students to visualize and perceive every muscle and vein present in the human body in a three-dimensional vision. In this way, augmented reality can revolutionize medical education. [34]

- **Consumer education**: AR can help patients understand the benefits and risks of certain medications and procedures by providing visual demonstrations or consumer scanning functionalities. [35]

- **Surgical planning**: As data access technologies are already very advanced, the next step is to provide real-time, life-saving patient information to surgeons which they can use during simple or complex procedures. The applications of AR during surgery will continue to evolve. [26]

The AR ecosystem is witnessing an influx of software and hardware manufacturers and mobile data and voice businesses, with a large number of mergers and acquisitions already.
According to Statista, the global Extended Reality (XR) market is expected to be worth 31 billion U.S. dollars in 2021, rising to close to 300 billion U.S. dollars by 2024 [36].

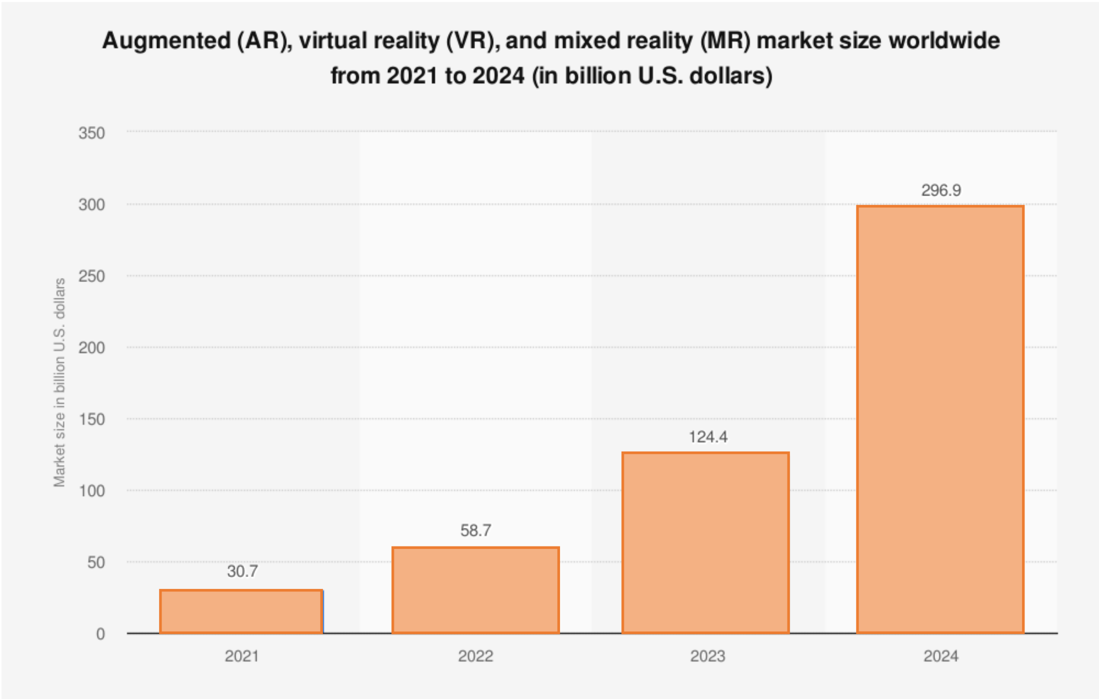


Figure 7. Evolution of the AR, VR and MR market size in billion US dollars for the incoming years. [36]

4. Conception engineering

4.1 Solutions studied

In this section different approaches have been studied in order to fulfil the tasks required to accomplish the objectives.

	Studied Solutions
Materials for the phantom development	• EcoFlex™ 00-10 • EcoFlex™ 00-20 • EcoFlex™ 00-35 • SORTA-Clear™ Series • Dragon Skin™ 10
CAD software	• SOLIDWORKS • AutoCAD
Segmentation software	• Syngo (Siemens) • 3D slicer
Optimization of the mesh	• Meshlab • Gmsh
Post-processing	• GiD • Meshlab
Display AR	• HoloLens • HoloLens2

Table 3. Proposed solutions for each step of the project.

4.1.1 Mold development

Different materials were considered to build our mold. The author needed to develop a mold, simulating human tissue with objects inside, simulating tumors. Different materials were considered to develop the mold. The **main requirement** for the material was that it had to be **soft**, to resemble human tissue as much as possible. Transparency was a plus to verify the positions of the tumors with the AR system, but not mandatory.

Materials considered	Shore Hardness	Color	Price
EcoFlex™ 00-10	00-10	Translucent	38.3€/kg
EcoFlex™ 00-20	00-20	Translucent	38.3€/kg

EcoFlex™ 00-35	00-35	Translucent	36.65€/kg
SORTA-Clear™ Series	A-18	Transparent	46.75€/kg
Dragon Skin™ 10	A-10	Translucent	38.3€/kg

Table 4. Different materials considered with its relevant properties [37]

In order to choose the most suitable material for this project, each material has been carefully analyzed.

Ecoflex™ rubbers are **platinum-catalyzed silicones** that are versatile and easy to use. It has low viscosity and cures to a **very soft but very strong and stretchy rubber**. It can be found in different hardness **Shore 00**. The Shore 00 Hardness Scale measures rubbers and gels that are extra soft. [38] Ecoflex products are suitable for a variety of applications including making prosthetic appliances, cushioning for orthotics and special effects applications. [39]

Three different types of EcoFlex products were considered**. EcoFlex 00-10** is the softest type, with a cure time of 4 hours and a pot life of 30 minutes. **EcoFlex-20** is very similar, with the same cure and pot times**. EcoFlex 00-35** is the hardest one of these three and is a fast cure silicone. Its pot life is about 2.5 minutes and rubber cures in about 5 minutes at room temperature with negligible shrinkage.

SORTA-Clear™ Series are **near-clear translucent silicone rubbers** which cure at room temperature with negligible shrinkage and feature high tensile and tear strength. They are catalogued as **Shore A**, which is used for measuring the hardness of flexible mold rubbers. These can range in hardness from very soft and flexible, to medium and somewhat flexible to hard with almost no flexibility at all. A-18 is considered soft. [38] They are commonly used for making prototypes, jewelry or other molds where model visibility is important. [40]

Dragon Skin Series are **very strong and flexible rubbers**. They stretch many times its original size without tearing and will rebound to its original form without distortion. They are classified as **Shore A**. The Dragon Skin™ 10 has a pot life of 8 minutes and a cure time of 75 minutes. They are very used in creating skin effects and other movie special effects. [41]

To represent the "tumors" inside the mold, different objects were considered to put inside:

Objects considered
Marbles
Styrofoam ball
Clay ball
Plastic straw

Table 5. Different materials considered to put inside the mold.

4.1.2 CAD software

SOLIDWORKS is a solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) computer program published by Dassault Systèmes, that runs primarily on Microsoft Windows. It is used for modeling 3D pieces and assemblies and 2D drawings. With SOLIDWORKS one can create, design, simulate, manufacture, publish and manage the data of the design process. A license is required to use the program; however, the university has this license. [42]

AutoCAD is a commercial computer-aided design (CAD) and drafting software. Developed and marketed by Autodesk. It allows you to draw and edit digital 2D and 3D designs more quickly and easily than you could by hand. [43] It can be used on Microsoft Windows or macOS and it requires a license too, which the university has.

4.1.3 Segmentation software

Syngo.via is a software developed by **Siemen**s to segment medical images in 3D structures. *syngo*.via offers multi-modality reading, including CT and MRI and fast 3D results to speed up daily routine. [44] It is **intended for clinical use** and, although is a closed software, the Nuclear Medicine Department of the Clinic Hospital has at its disposals the license.

3D slicer is a free, open-source and multi-platform software package widely used for medical, biomedical, and related imaging research. [45] It is used to segment medical images and since it is an open-source software, the user is allowed to export the segmentations created. The only problem is it is **not intended for clinical use**, hence, nor a diagnosis nor a procedure can be based in the results obtained.

4.1.4 Mesh optimization and post-processing software's

Gmsh is an open-source 3D finite element mesh generator with a built-in CAD engine and post-processor. Its design goal is to provide a fast, light, and user-friendly meshing tool with parametric input and advanced visualization capabilities. [46]
Meshlab is an open-source system for processing and editing 3D triangular meshes. It provides a set of tools for editing, cleaning, healing, inspecting, rendering, texturing and converting meshes. [47]
GiD is an open-source software that provides an interactive graphical interface used for the pre-processing and post-processing for numerical simulations developed by CIMNE. It offers a complete set of tools that allow quick geometry definition and edition. [48]

4.1.5 AR display

HoloLens is a head-mounted display (HMD), a pair of mixed reality smart glasses, that runs on Windows Mixed Reality operating system created by Microsoft. Microsoft has developed two series of HoloLens. In order to compare accurately both models, a table has been made.

	HoloLens1	HoloLens2
Release year	2016	2019
Display resolution	1280x720px (per eye)	2048x1080 px (per eye)
Field of view	34 °	52 °
Hand tracking	One hand	Both hands
Operating system	Windows Mixed Reality	Windows Mixed Reality
Price	3,000$	3,500$
Gestures: Press, grab, direct manipulation, touch interaction	no	yes

Table 6. Comparative table between the two models of HoloLens [49].

4.2 Solutions proposed

Considering all things mentioned, the table below was elaborated with the aim of presenting the solution taken for the development of this project.

	Solutions proposed
Materials for the phantom development	• EcoFlex™ 00-20
CAD software	• SOLIDWORKS
Segmentation software	• 3D Slicer
Optimization of the mesh	• Meshlab
Post-processing	• GiD
Display AR	• HoloLens2

Table 7. The final solutions proposed to develop each step of the project.

For the **materials selection**, the SORTA-Clear and the Dragon skin were discarded. Although SORTA-Clear was the only transparent material considered, the softness of the material takes precedence over the transparency. Regarding that, the final decision was taken considering the three different types of EcoFlex. The EcoFlex™ 00-35 was discarded because it is a fast cure silicone, and the pot time is just 2.5 minutes. Since it was the first time of the author using this type of silicones, more pot time was preferable in order to avoid mistakes and the waste of the product. Finally, since EcoFlex™ 00-20 and EcoFlex™ 00-10 were very similar, the author decided to take the **EcoFlex™ 00-20** since the 00-10 was not available in the store and had to be ordered.

Regarding the objects to put inside the mold, since the EcoFlex 00-20 was chosen as the material to create the mold. It had to be considered that addition-cure silicone rubber may be inhibited by certain contaminants resulting in the total lack of cure. Latex, tin-cure silicone, sulfur clays, certain wood surfaces, newly cast polyester, epoxy or urethane rubber may cause inhibition. Considering that, the clay ball was discarded since it contained sulfur. To develop both molds, different objects from table 5 were used for each mold, this will be explained in more detail in the next section (5. Detail Engineering).

Regarding the **CAD software**, both possibilities were very similar and more or less offered the same features. Therefore, the author felt more comfortable using **SOLIDWORKS.**

To do the **optimization and post-processing**, after gathering information and watching some tutorials, the easiest and best programs to perform those steps were **Meshlab and GiD**. Therefore, those were the selected programs.

Finally, as **AR display.** Since CIMNE – the centre of investigation of the research team- had both systems, HoloLens 1 and HoloLens2 and the last ones were newer and had better features, **HoloLens 2** were the selected device.

5. Detail Engineering

5.1 Mold development

The **first step** of the project is to **develop the molds** with objects inside in order to assess the pre-testing stage of the project and visualize the AR results, the idea is that the HoloLens project a hologram of the mold with the objects inside.

As a first mold, the author decided to develop a square, since it was an easy geometric form to develop and to create the mathematical model. To develop the mold, the materials shown in figure 8 were used.

EcoflexTM rubbers are mixed 1A:1B by weight or volume and cured at room temperature.

In order to know the positions of the different objects introduced inside the mold and its dimensions, the mold was developed in different layers.

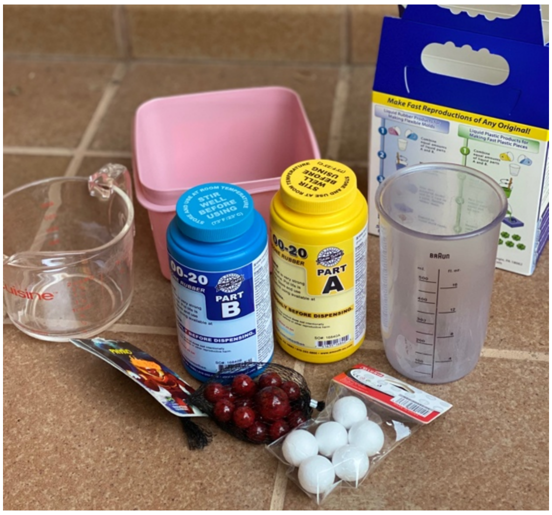


Figure 8. Materials used to develop the mold.

1. First, a first layer of the mix was poured inside a tupperware. After 4 hours, it was solidified.
2. Secondly, on the top of this layer (measuring 1,5 cm of height) two marbles and one styrofoam ball were place. Measuring the distances from the sides of the tupperware to know the exact positions of the balls. The marbles measured 16mm of diameter and the Styrofoam measured 23mm. More mix was poured to cover the balls.
3. Once the mix had solidified for one hour, it was still viscous but with some consistency. The author decided to put woolen threads attached to a piece of plastic inside the mold (shown in figure 9). This was done in order to be able to deform the mold tearing from the thread and see how the materials inside behaved. The plastic pieces were put to act as a barrier, since the thread alone would break the silicone.
4. After 4 hours, it was perfectly cured. The Styrofoam ball was removed, leaving a hole in the silicone.

   This hole was filled with the same EcoFlex 00-20 mix colored with red alimentary colorant.

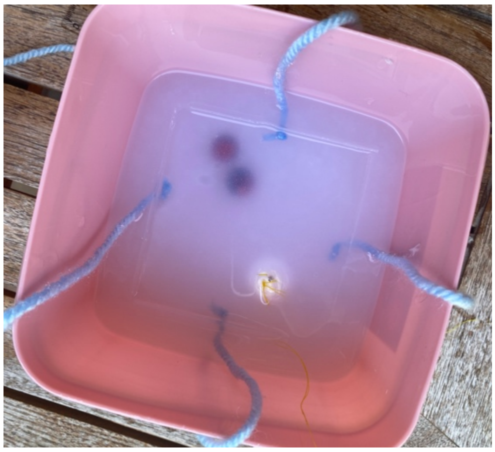


Figure 9. Picture while the mold was being developed.

5. After pouring the red mix, some more normal mix (not colored) was poured. In this step there was a mistake, the red mix hadn't cure completely and when the author poured more normal mix over the red one, it spread.
6. The final step was to let it cure completely and demould it from the tupperware. The final result can be seen in figure 10.

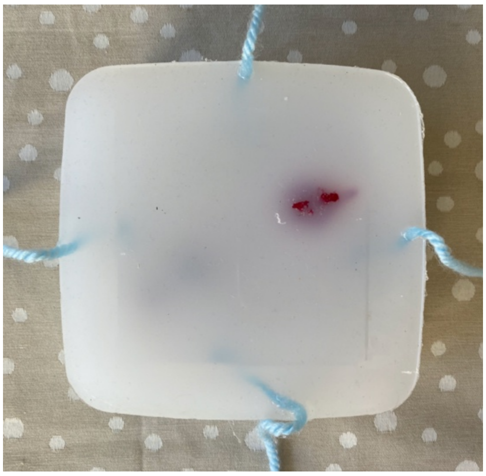


Figure 10. Final result of the mold.

In order to adjust better to reality, a **second and more complex mold was developed.** It is worth mentioning that the development of this second mold was after the segmentation and post-processing of the square mold, where the author realized some mistakes that needed to be solved. With this second mold, the author tried to solve those problems, which will be explained as they occurred. Since the steps followed for segmentation and post-processing are common, it has been explained together for both molds.

The author decided to develop this second mold with the same material (EcoFlex 00-20) as the first mold, since it gave good results, and it was easy to use. This time, the author decided to do a semispherical mold to be closer to the form of a real breast and also, the author decided to put more objects inside with different forms.

In order to do so, the following materials shown in Figure 11 were needed. This time, since we wanted to achieve a hemispherical mold, the methacrylate dome shown in Figure 11 was used. Also, different objects were introduced inside. Using the marbles in the first mold, when this was deformed, just the displacement of the marbles could be seen. Therefore, the author decided to try different objects to produce internal deformations: a straw, a marble, and a different type of silicone with different density. Since the same type of EcoFlex 00-20 was used, the procedure to use this silicone was the same and it was also developed in different layers.

Figure 11. Materials used to develop the second mold.

1. To be able to deform the mold, a cross made with plastic and attached to a woolen thread was introduced in a hole previously made to the methacrylate dome. This time, the cross was made with a single piece of plastic, since the author saw in the square mold that putting four separates plastic pieces can affect the deformation in the mathematical model since their separate behavior can't be known.
2. Once the cross was introduced through the hole and it was in the center of the dome, some mix of EcoFlex was poured.
3. Once this was solidified, a marble measuring 16mm of diameter and a 2cm long straw with modeling clay inside were placed. More mix was poured to cover them.
4. After four hours, the mix was perfectly solid and another marble and a straw with the form of an L (Shown in Figure 13), to be able to study different deformations) were placed. Again, some more mix was poured to cover them.
5. Once the mix was solidified, the marble was removed, and the hole was filled with slime (the pink sphere shown in Figure 14).

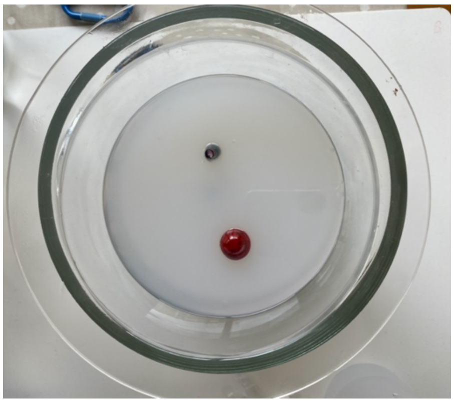


Figure 12. Placement of the first marble and the straw.

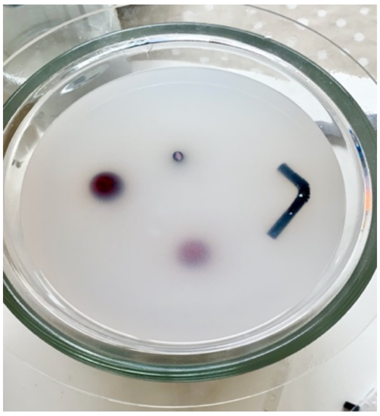


Figure 13. Placement of the second marble and the straw.

Figure 14. Replacement of the marble for pink slime.

6. To finish, some more mix was poured. Moreover, a mark was made to the mold to be used as a reference to place the marker for the AR always in the same place, something that was not done in the square mold. After 4 hours the mix was solidified, and the mold was demolded. The result is shown in Figure 15.

Figure 15. Final result of the mold.

5.2 3D computer model

All the measures of the molds were obtained while they were manufactured.

The first mold measured 13,5x13,5x4,5 cm. The positions of the objects inside were known too. Knowing that, a 3D computer model of the mold using SOLIDWORKS was made. During this time, some tutorial about the use of SOLIDWORKS were watched.

A 3D croquis of a half-circumference was created for each ball. Always taking into consideration the position of the center of each sphere in the final figure and placing them in the right coordinates. After that, using the revolution tool, the spheres were created. To finish, another croquis with a square form was drawn. Using the extrusion tool, the final volume was created surrounding the spheres.

After creating the 3D model, it didn't match exactly the reality. Since it was made inside a tupperware, the mold had the form of the tupperware and it was not a perfect square as the 3D model. Moreover, since it was created using SOLIDWORDS, there were some problems exporting the model to MeshLab and GiD to do the post-processing. Therefore, the author decided to perform a TC to the mold to have a better approximation of the reality. Also, since the development of this 3D computer model was time consuming and didn't give the expected results, the author decided to not create the CAD model for the spheric mold and follow directly with the TC.

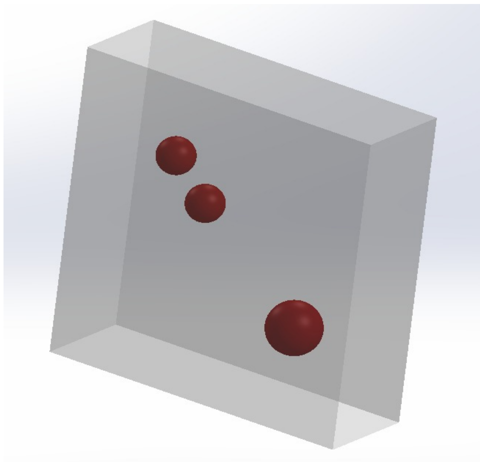


Figure 16. 3D computer model of the mold.

5.3 TC and segmentation

The TC was performed to both molds in the Hospital Clinic. It was performed in a hybrid PET-TC, Biograph mCT model from Siemens, the machine consists in a spiral Somatom Definition model TC with 32 crowns. and the DICOM files were imported to 3D slicer. The problem doing the CT to the first mold, as it can be seen in Figure 17, was that the big ball made of the same material (EcoFlex 00-20) couldn't be seen. Moreover, since the TC was done in a stretcher with a curve form, the mold took this form. Those problems were not found in the spherical mold, since the soft material (the slime) had different density to the silicone and a wooden board was placed under the mold to make sure it didn't deform. Moreover, when performing the TC to the second mold, 4 markers were placed (as shown in Figure 20) to have a reference to place the markers needed to perform the dynamical model with AR. The markers used in the CT were 4 pieces of cork. The DICOM files opened with 3D slicer are shown in the following figures,

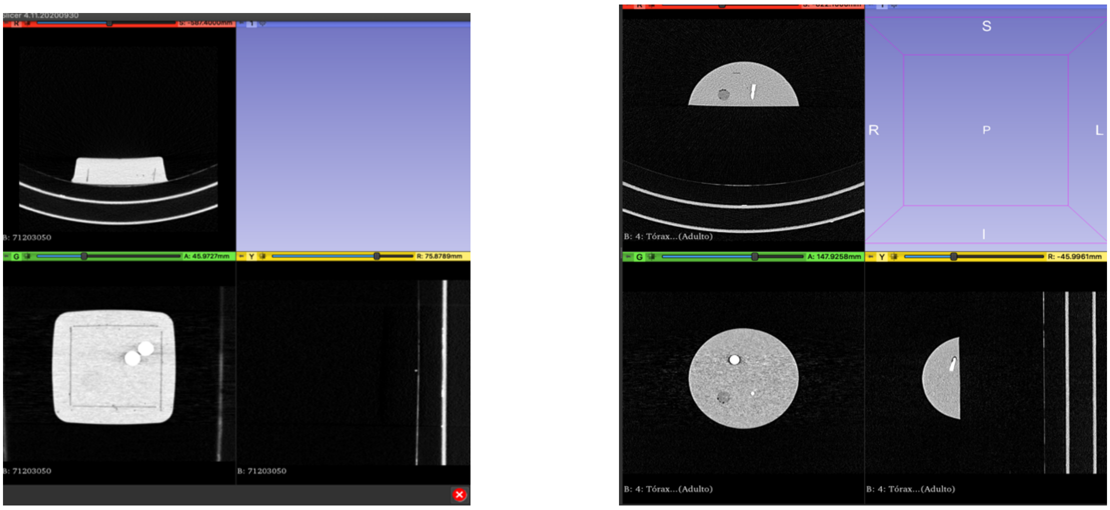


Figure 17. CT scan DICOM images opened with 3D Slicer. The squared mold is on the left while the spherical mold is on the right.

In order to do the segmentation, several works [58] [59] and tutorials were analyzed/watched to learn the better way to do the segmentation. Before starting with the segmentation process as such, the extension Segmentation Editor Extra Effects was downloaded in order to have more effects available to segment. The steps followed to do the segmentation are exactly the same for the squared and the spherical mold.

1. Threshold

In the first mold, there were two different parts to segment, the silicone, and the marbles. After performing some tests, the best and fastest way to perform the segmentation was using the threshold tool form the Segmentation Editor. The threshold range for the balls was from 2419.88 hu to 3071.00 hu (Figure 13) while the threshold range for the silicone was 20.20 hu to 769.60 hu (Figure 14).

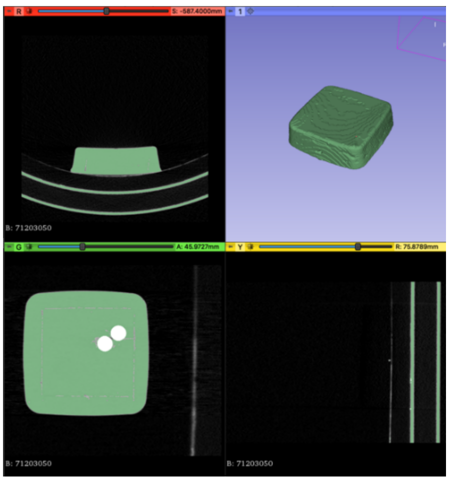


Figure 18. Threshold to segment the squared mold.

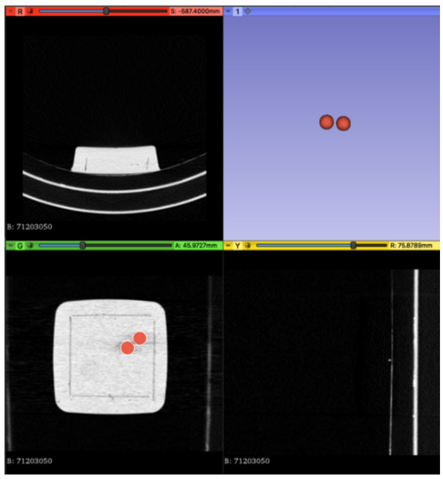


Figure 19. Threshold to segment the objects inside the mold.

The same procedure was done in the second mold, the only difference was that it had more objects inside and the markers. Therefore, more threshold ranges had to be used.

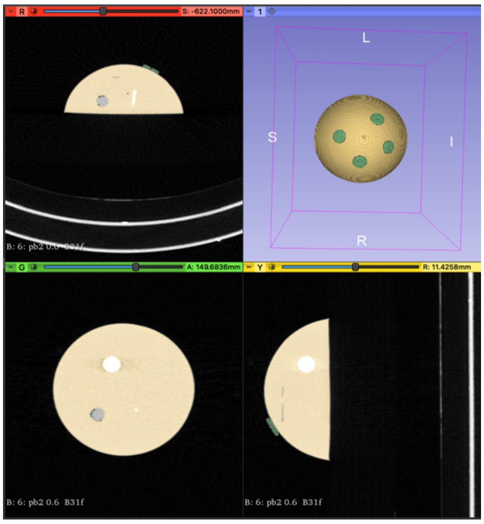


Figure 20. Using the threshold tool to segment the spheric mold.

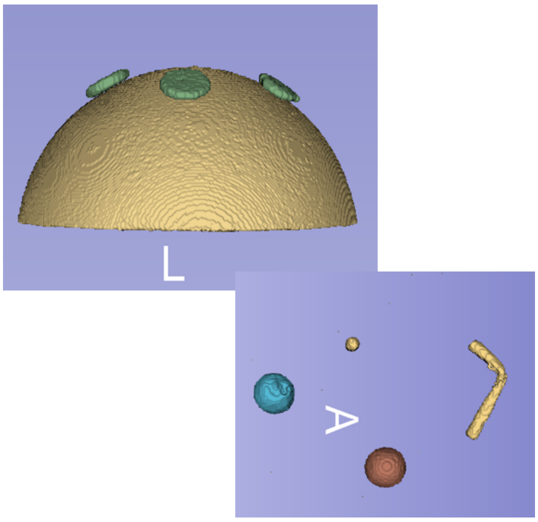


Figure 21. Final segmentations of the spheric mold.

2. Scissors

The scissors tool was used to polish the segmentation manually, to remove several extrusions that were not interesting to create the mathematical model.

3. Smoothing

In the smoothing tool there are some methods that can be used to polish the segmentation automatically. "Median" and "Gaussian" method fills holes and remove extrusions to make surfaces smoother. "Opening" method only removes material (flattens the surface), "Closing" method only adds material (fills holes and gaps).

After the segmentation was properly done, in order to proceed with the post-processing step, one must export the files generated in a STL file format.

5.4 Optimization of the mesh

The post-processing consists in slightly modifying the models created in order to enable the proper implementation of AR application. By using Meshlab, some filters were applied to the models. Moreover, finite element meshes of the models were generated by tessellating its geometry. One of the important aspects of a mesh generator is to preserve the geometrical features of the input model, specifically the sharp edges (ridges) and corners. To explain the optimization process, since the steps followed were the same for both molds, mainly the images from the square mold will be supporting the explanation. Exactly the same can be applied to the spherical mold.

1. Importing and reading the STL files into Meshlab.

When importing the STL to Meshlab, one can see that the model still has some roughness and noise that needs to be removed. Moreover, there are too many elements in the model, as it can be seen in Figure 15.

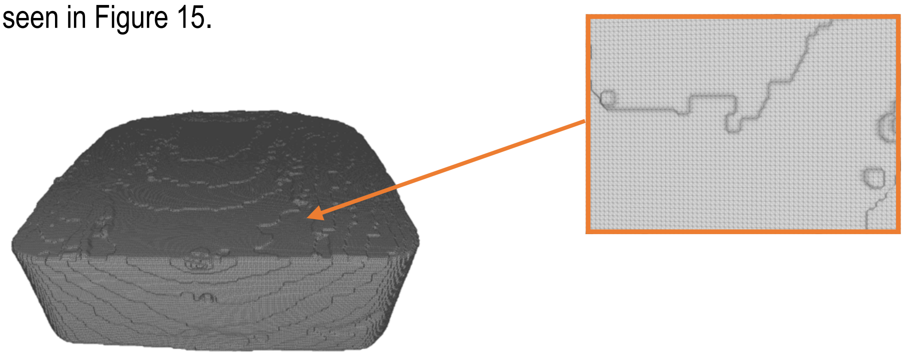


Figure 22. First mesh created before processing it. On the right a zoom is performed to show the triangles forming the mesh.

2. Applying filters

In order to polish the model and remove the undesired extrusions. Different filters were applied. First, a Laplacian smooth and then a Taubin smooth. Once those filters have been applied, the surface of the model is smoother.

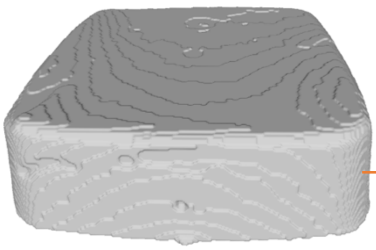


Figure 23. Mold before applying the filters.

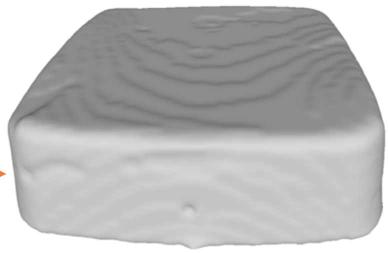


Figure 24. Mold after applying the filters.

3. Collapsing elements

This large number of surface elements is too much to handle in terms of computation time, therefore a collapse of the elements must be performed in order to reduce the number without losing precision. Selecting the module "simplification: quadratic edge collapse decimation", the surface elements can be reduced. The number of desired vertices is introduced, and the total number of triangles is reduced. The function "preserve boundaries of the mesh" is activated in order to preserve the limits as they were and decimate only inside the area of the mesh. Moreover,

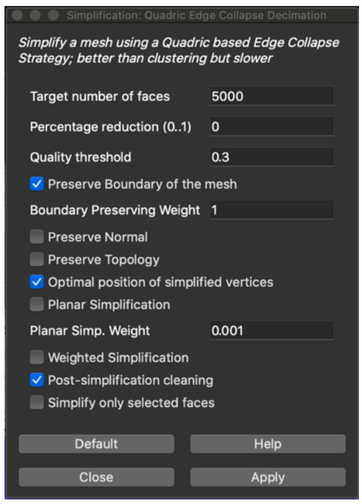


Figure 25. Panel of the function simplification: quadratic edge collapse

the function "merge close vertices" is also applied. This function merges together all the vertices that are nearer than a specified threshold.

Finally, the little surface triangles join into bigger triangles, it can be seen comparing Figure 15 to Figure 19.

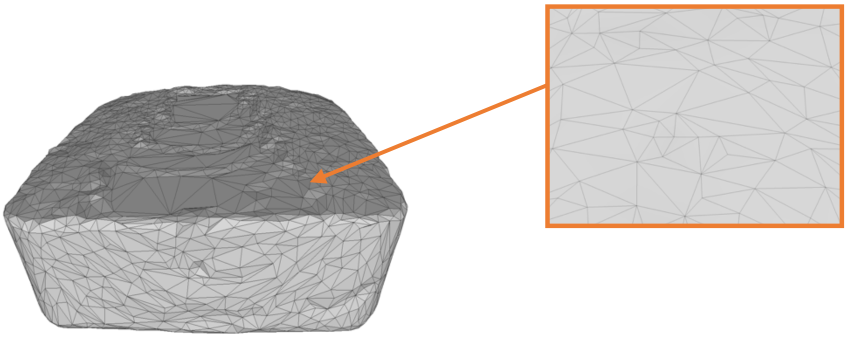


Figure 26. Final optimized mesh. On the right a zoom is performed to show the bigger triangles forming the mesh.

The same procedure is done with the segmentation of the marbles, and with the second mold and its objects inside. The final mesh for the second mold is shown in Figure 27.

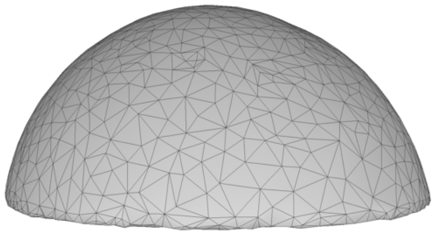


Figure 27. Final surface mesh of the spherical mold.

5.5 Post-processing of the mesh

Using Meshlab, the surface mesh is created. In order to test the dynamic system, a volumetric mesh needs to be created. To create the volumetric mesh, the optimized STL file is imported to GiD, with GiD the final volumetric mesh is created. (Figure 20) This one is composed of tetrahedral elements of four nodes.

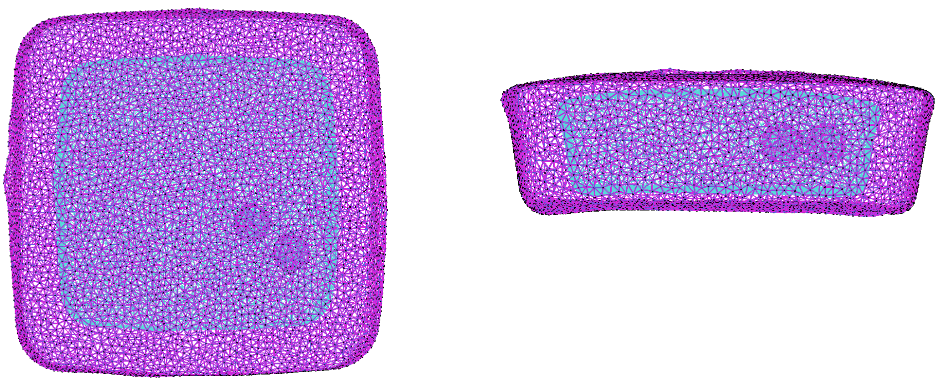


Figure 28. Final volumetric mesh of the squared mold in different views.

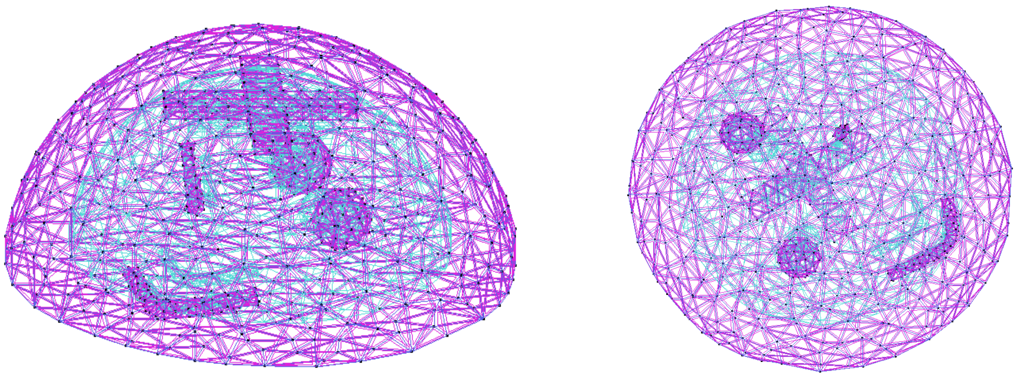


Figure 29. Final volumetric mesh of the spheric mold in different views.

5.6 AR application

5.6.1 Static

The **static assessment** consists in placing the hologram of the mold and the objects inside superposed to the real mold. To assess the static hologram, the surface mesh generated with Meshlab is imported to Unity3D. For the AR application with HoloLens display device, it is required the use of Unity3D which is an open-source game engine developed by Microsoft that provides a framework for AR development. [50] Specifically, Vuforia is needed which is a SDK (software development kit) that is added to Unity3D in order to visualize the holograms. Vuforia uses technology to recognize and track 3D objects in real time. This ability allows us to place and orient virtual objects, such as 3D models, in relation to real-world objects. [51] In order to do so, Vuforia works with a system based on markers. When your device's camera recognizes the marker in the real world, this triggers the display of virtual content over the world position of the marker in the camera view. [52] Therefore, the marker shown in Figure 30 was created for this project. Not everything is valid to be used as a marker, first you need to train the marker, Vuforia calculates the number of minutiae and rates the marker between 0 and 5 stars depending on the complexity. It is important to create a marker with a lot of elements, so it is easier for Vuforia to recognize it. The marker placed in the virtual model and in real life must be of the same measure.

Figure 30. Marker created for the position of the hologram.

5.6.2 Dynamic

The **dynamic assessment** consists in creating a hologram that is able to deform in real time and the same way as the mold does when a force is applied to the mold in the reality. This process is performed using GiD CAD system with Kratos Multiphysics, which is a framework for building multi-disciplinary finite element programs written in C++. It provides several tools for fast implementation of finite element applications. [53] Once the final volumetric mesh is generated with GiD, (explained in 5.5) two different json files are created. "project parameters.json" (which contains the parameters of the mesh), "structuralmaterials.json" (which contains the young modulus of the material, in our case, EcoFlex 00-20 has a young modulus of 55 kPa, the density and the poisson ratio) and native file "Mdpa" (which contains the form, the nodes and the boundary conditions of the mesh). Those files are created also for every object inside the mold. Also, the constitutive law that the deformation would follow is indicated, in our case an Hyperelastic NeoHookean. These are the initial conditions for our system of 9000 elements. To track the deformation, a Kinect, and some markers (stickers) are needed. The Kinect recognizes the markers placed on the surface of the molds and sends the position of those markers to Kratos. Those positions are updated in real time; therefore, the boundary conditions (the Mdpa file) change in real time and the system updates the hologram.

6. Results

6.1 Pre-testing results

The author tested the AR system in both molds at the offices of CIMNE. First, the static hologram was tested. In order to do so, the marker designed for this project (Shown in Figure 30) had to be printed and placed in the same place as in the virtual model in Unity3D. The spherical mold had a mark previously done while manufacturing the mold to place the marker always in the same place, while the squared mold did not have a mark and the placement of the marker was not as accurate. The virtual models developed in Unity3D are shown in the next figures.

Figure 31. Virtual model from Unity3D of the spherical mold.

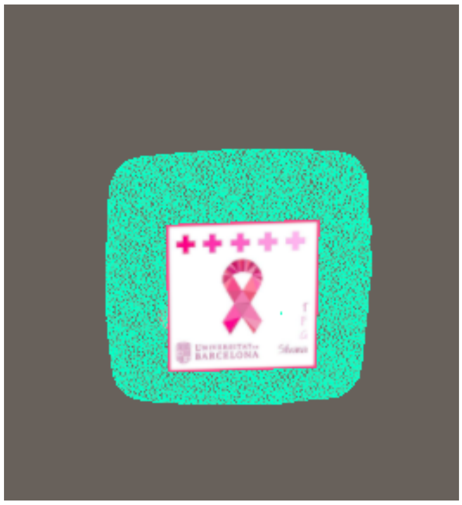


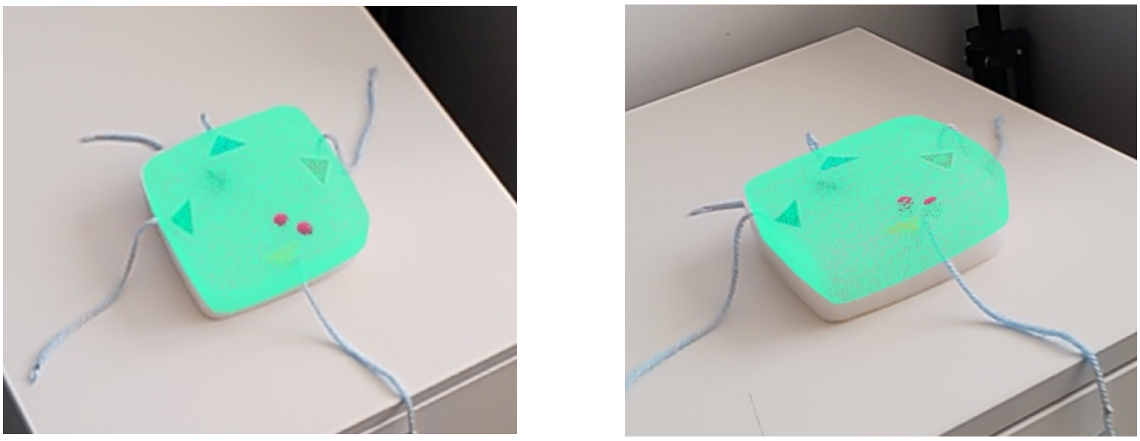
Figure 32. Virtual model from Unity3D of the squared mold

Using the HoloLens2, the hologram of the mold was properly superimposed on the real view of the mold. The hologram of the spherical mold is shown in Figure 34.

Figure 33. The author using the HoloLens in the offices of CIMNE

Figure 34. Hologram seen using the HoloLens superimposed to the real spherical mold.

It can be seen that the hologram matched accurately with the reality. The marker was placed at the beginning and once the HoloLens had detected it, it was removed.



Figures 35 and 36. Hologram seen with the HoloLens superimposed to the real squared mold. On the figure on the right a delay can be appreciated.

Regarding the squared mold, the placement of the hologram was not as accurate as with the spherical mold since there was not any mark for the marker and it had to be placed approximately but without any reference. Moreover, since the TC was performed in a stretcher and the mold deformed a little bit adopting a curved form, the form of the model was not exact to the reality. However, it was also quite accurate.

Once the static part was tested, the author proceeded to test the dynamic assessment. In order to do that, apart from the HoloLens, the Kinect was also needed, and the markers captured by the Kinect were placed on the molds. A test to see how the Kinect recognized the markers was performed. As the mold was deformed and consequently, the markers were displaced, the Kinect recognized these displacements and they were shown on the screen.

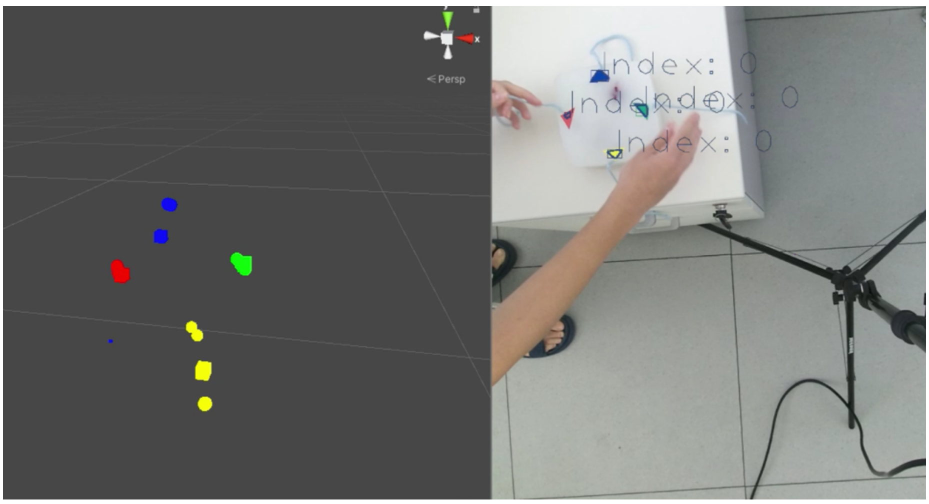


Figure 37. The left part of the image shows the displacement of the markers followed by the Kinect, the part on the right shows the mold, with the markers being deformed.

After the test with the Kinect was performed, the dynamic hologram was tested. There were some problems displaying the objects inside the mold, therefore the deformation was tested just for the mold (without objects inside) and the cross.

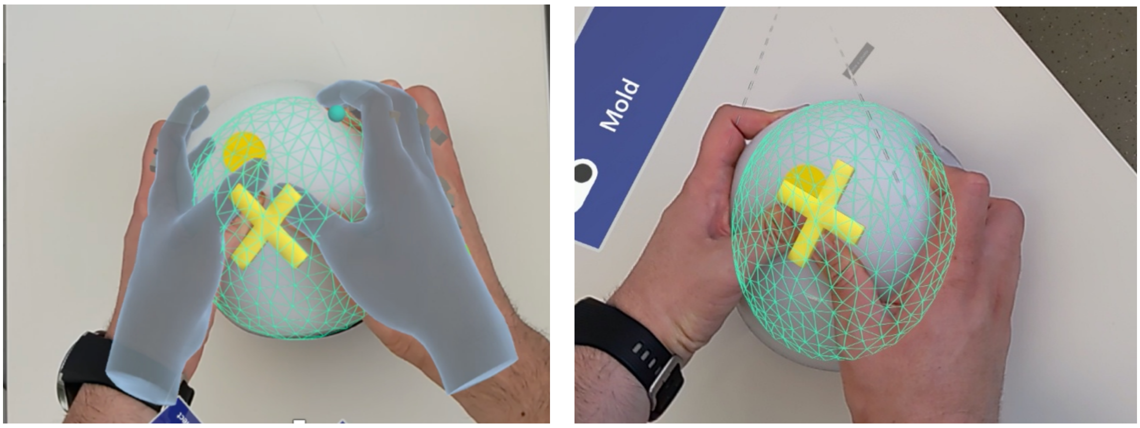


Figure 38 and 39. Results of the dynamic hologram. On the figure on the left the hands deforming the hologram are shown, while on the figure on the right the deformation of the hologram can be appreciated.

The hologram deformed the same way as the mold, however it had some delay. Moreover, the deformation of the mold was not really noticeable since a significant amount of force needed to be applied to deform it, therefore the deformation of the hologram was also very subtle.

6.2 Testing results with a breast phantom

The last step of the project was to test the AR system in a breast phantom provided by the Nuclear Medicine department of the Clinic Hospital from Barcelona. This phantom is used to perform some SPECT and PET tests

Figure 40. Breast phantom to perform the final test.

Previous to the AR application, the same procedure made with the molds was done with the breast phantom. A CT was done by Aida Niñerola at the beginning of the project, the author made the segmentation and post-processing of the breast phantom as explained in section 5 for the molds. The final result of the segmentation and post-processing are shown in next figures.

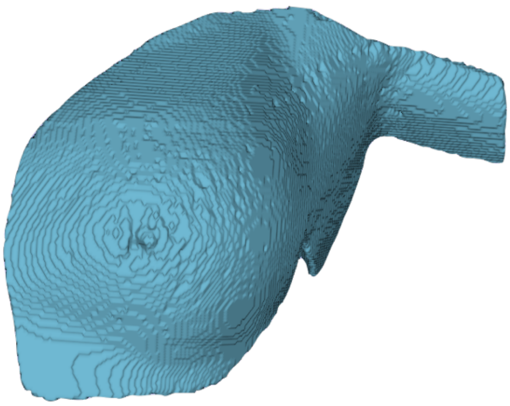


Figure 41. Final segmentation of the breast phantom.

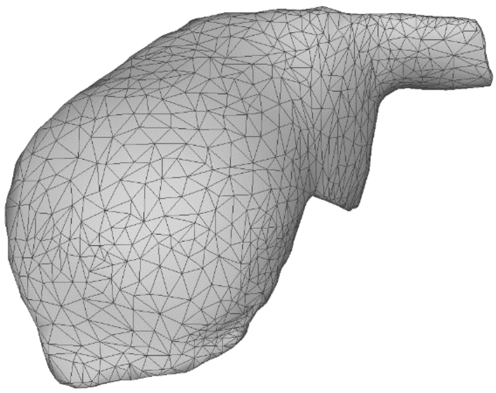


Figure 42. Final surface mesh of the breast phantom

In order to test the AR system in the breast phantom, the author and her two directors went to Hospital Clinic with all the equipment: HoloLens device and trained marker. However, the phantom, made from resin and silicone was hard and non-deformable. Therefore, the author and her directors decided to perform just the static assessment, since the dynamic assessment could not be implemented because the phantom could not be deformed.

The final placement of the static hologram is shown in Figure 43.

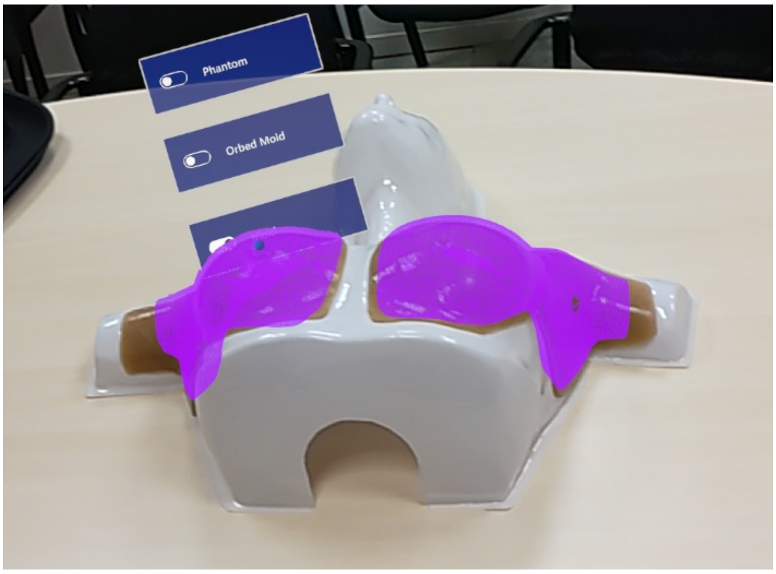


Figure 43. The breast hologram superposed to the phantom

The static placement of the hologram is accurate and fits with the reality. However, it can be that due to the post-processing, since the mesh is smoothed and polished, the model can be smaller than the real phantom and some places are not perfectly covered.

7. Discussion and future improvements

7.1 Discussion

In this subsection the degree of fulfilment of each objective set at the beginning of the project (section 1.2) will be analyzed.

The first objective, which was the **development of molds** to assess the AR system, was properly fulfilled. It is important to mention that a considerable amount of time was invested in searching and considering different materials to develop those molds. Moreover, the planning, and the different objects to put inside were also carefully thought and designed. The squared mold, which was the first one to manufacture, had some mistakes from which the author learnt and were improved on the second mold. First of all, the materials introduced inside the mold had to be different from the EcoFlex 00-20 to be seen on the TC. Moreover, the plastic bars introduced inside to deform the mold had to be made of just one piece of plastic to predict the deformation in the mathematical model. In addition, it was important to make a small mark on the mold to be the reference point to place the marker for the AR visualization. The final result of the molds was successful but it is important to mention that for the dynamic assessment, an even softer material would have been better. Although the material was shore 00, a considerable amount of force had to be applied to deform the mold. Therefore, the result was not the optimal.

Once the molds were developed, in order to create the finite elements mesh for the further AR application, two different approaches were considered. The **mathematical approach**, which consisted in generating a CAD model of the molds with Solidworks, was not successful. It was implemented in the squared mold, and the author realized that it was really time consuming, and the results were not accurate. It was difficult to take the exact positions of the objects while the mold was being manufactured, since the mix was liquid and the objects displaced some millimeters while the mix was solidifying. Moreover, since the mold was manufactured inside a tupperware, the form was not a perfect square as designed in the 3D model. For all these reasons mentioned before, the CAD model of the spherical mold was not done and the author decided to proceed with the **medical approach**, which consisted in performing a CT to the molds. The CT was done for both of them, in the squared mold, the curved form of the stretcher was not considered and the mold adjusted to the form of the stretcher. When the CT of the second mold was done, this previous mistake was considered, and a wooden board was placed as the base for the mold. Moreover, 4 round markers (made of cork) were placed over the mold to be the reference to place the stickers recognized by the Kinect during the dynamic assessment.

The following objective was to **segment and post-process** the images of the molds. It is worth mentioning that a great deal of the project depended on whether or not the segmentation was carried out correctly and whether or not the model was generated properly. In the end, the resulting segmentations were quite accurate. Also, the finite element mesh was performed well.

The **static model** of the molds was generated correctly, the virtual mold and the objects inside were properly placed over the real mold. The spherical mold hologram was placed more precisely than the squared mold for the marker reason explained above.

The **dynamic model** was more difficult to achieve. The Kinect was able to follow the markers placed over the molds and detect their displacement. However, to deform the molds, a considerable amount of force needed to be applied and therefore, it did not match exactly the behavior of a real breast.

The **final assessment with a breast phantom** was done just for the static part, which was performed successfully.

To sum up, the major goals of the project which were to improve the accuracy in the location of the tumor statically and implement a dynamical system when deformation takes place, were achieved. However, there were some things that will be discussed on the following subsection (7.2 Future Research) that need to be enhanced or modified to stablish the AR as the mainstream navigation tool in the future.

7.2 Future improvements

It is worth mentioning that in order to keep working on the implementation of augmented and mixed reality in the operating room, it would be interesting to perform the study with real patients instead of molds. Although for a first approach and as proof of concept the molds were a really good alternative. The material selected to develop the molds was EcoFlex 00-20, however for the future, it would be interesting to talk to a material's expert in order to find a softer and more deformable material to develop a more realistic mold. Actually, it would be interesting to develop a more complex mold with different parts, mixing different materials.

The static part is completely valid and is ready to be used in an OR. However, the dynamic part needs some improvements. In order to be assessed in a real breast, some kind of markers, for example vitamin A as references, need to be placed on the breast when the TC is performed to be the reference to place the markers traced by the Kinect. Moreover, the model needs to be optimized from a computational point of view, increasing the calculus speed.

It would also be interesting to use a more sophisticated segmentation software, ideally, it would have to segment the images more automatically by implementing artificial intelligence and also, it needs to be considered a medical device to base a diagnosis or a procedure on the results obtained.

Moreover, the meshes created to perform this project were really big, in a future it would be interesting to use a reduced order model in order to be more precise.

8. Technical feasibility

In this section a **SWOT analysis** has been conducted. It is going to be assessed the **internal factors** (strengths and weaknesses) and the **external factors** (opportunities and threats) that affected our project.

STRENGHTS	**WEAKNESSES**
Internal	Internal
• Continuation project • Innovative method to make surgeries less invasive • Allows intra-operative visualization • The project was developed in collaboration with CIMNE and Hospital Clinic • The technique was assessed in two different molds and a breast phantom.	• Non real tissue was used to perform this project, meaning that it does not simulate exactly the reality. • Due to Covid-19 the AR system could not be assessed in real surgeries • The system was not tested by surgeons, therefore their feeling when using this technology could not be assessed.
OPPORTUNITIES	**THREATS**
External	External
• Need of new navigation systems to improve surgeries. • Hospitals and universities will be interested in AR technology as a very visual instrument to study anatomy and surgical procedures.	• There is an increasing number of companies in healthcare sector competing in the field of augmented reality • High price of the technology

Table 8. SWOT analysis of the project

8.1 Strengths

As this was a continuation project, one strength of the project was that a lot of paths and programs were already considered and tested by my predecessor, Teresa Puigferrat. This accelerated some aspects of the project, like the segmentation and the post-processing. The approach created in this project aims to improve the use of an innovative technology to make surgeries less invasive, to help surgeons increase the accuracy and to decrease the time of surgery. Specifically, this project aims to take this intra-operative visualization method one step further and be able to take the deformation of tissues into account when performing the surgery. To do so, two different molds were developed. After the technique was tested in those two different molds, it was also tested on a breast phantom provided by the Hospital Clinic. Moreover, AR is a novel method to teach anatomy and surgical procedures to medicine students. Finally, the fact that this project was developed in collaboration with CIMNE and, the author could have access to all the Hospital Clinic's installations, like the CT scans, provided the author with a lot of useful resources as well as with the help of experts of the field.

8.2 Weaknesses

The main weakness of the project is that due to Covid-19, the techniques could not be assessed with real patients in surgeries. Due to that, the author had to find another way to test the AR system, the solution to that was the manufacturing of two molds that tried to simulate the human tissue. Those two molds were made with a type of silicone that resembled the softness of the human tissue, although the result was quite accurate, it does not simulate exactly the reality. Moreover, any doctor or surgeon could test the technique.

8.3 Opportunities

With the continuing expansion of cutting-edge technology, new and enhanced navigation systems are being implemented around hospitals. Therefore, new techniques like the one proposed in this project are demanded and since we're still in the early stages of the AR revolution, all the advances regarding this technology can be revolutionary. Moreover, since AR is a very visual instrument to study anatomy and surgical procedures, universities are potential investors too.

8.4 Threats

As we previously studied, the Extended Reality market is growing so fast, more and more companies of the field are emerging. Therefore, a considerable amount of competition is increasing. Moreover, the cost of the technology can be a cause of rejecting the implementation of this technology to hospitals and universities.

9. Economical feasibility

In this section, it is going to be described the theoretical costs of completing this project. In order to do so, the costs will be divided by type of cost.

The types of cost that this project has generated are **human resources** (Table 9), **hardware** (Table 10), **software** (Table 11) and **materials** (Table 12). The total costs of the project are summarized in table 13.

	Human resources		
	Cost (€/hour)	Hours	TOTAL
Biomedical engineering student	10	370	3,700
Research engineer	20	30	600
Expert advisor in AR	35	10	350
Expert advisor in imaging techniques	35	10	350
			5,000€

Table 9. Human resources needed to develop the project with the hypothetical cost.

	Hardware
	Cost (€)
MacBook pro computer	1,600
HoloLens2	3,094.2
Kinect	117
Kinect's cable	38,99
	4,850.19€

Table 10. Hardware's cost.

	Software
	Cost (€)
3D slicer	Free source
SOLIDWORKS	License
MeshLab	Free source
GiD	Free source
Unity	Free source
	0€

Table 11. Software's cost.

The materials mentioned in the following table (table X) were for the development of the molds.

	Materials	
	Units	Cost (€)
Ecoflex 00-20	2 packs	45x2=90
Marbles	1 pack	1,95
Tupperware	1	1,60
Woolen threads	1	1
Styrophoam balls	1 pack	0,65
Alimentary colorant	1 pack	3
Slime	1 pack	2,60
Plastic semi sphere	1	12,50
Breast phantom	1	0 (provided by the Hospital Clinic)
		113,3€

Table 12. Summary of the materials used and their price.

The total cost of the project is summarized below (table X) it can be highlighted that the **main cost** of the project is due **to human resources and the hardware**. As it can be seen in figure X, the cost of the materials symbolizes just 1% of the total costs.

	TOTAL COST (€)
Human resources	5,000
Hardware	4,850.19
Software	0
Materials	113,3
	9,963.49€

Table 13. Overall costs of the project.

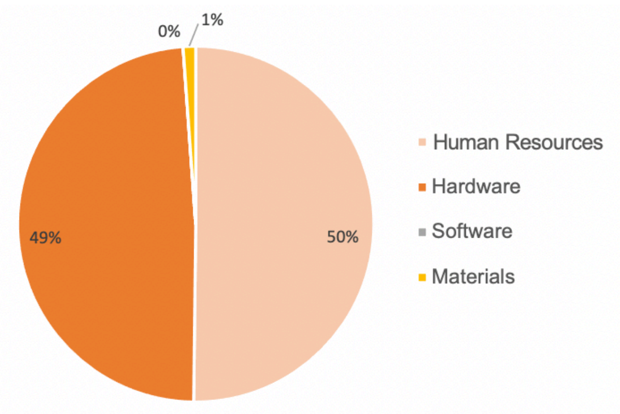


Figure 44. Graphic representation of the total costs.

10. Project implementation Schedule

In the following section, it is going to be described in detail the tasks that were completed and its temporal organization, in order to accomplish all the objectives of this project. To organise the implantation schedule, the project was divided into different objectives to be fulfilled. We also performed a GANTT diagram shown in Fig

To have a general idea, this study was divided into three stages: educational stage, developmental stage and editing stage.

The **educational stage** consisted in a bibliographic research to understand the basis of the clinic and the technology that needed to be beard in mind and understood to proceed with the research. Also, a review of the state-of-art of the technology and an analysis of the market were performed to study the current use of AR in the clinical practice. This stage was the first, it started in November until the end of January. The **developmental stage** included the design and manufacturing of the different molds that were performed to assess the accuracy of the AR system to reproduce the reality. Also, this stage included the installation and familiarization with the segmentation and post-processing software. This stage started from February with several meetings with Eduardo Soudah and Óscar de Coss, until the end of the project in June. The **editing stage** is dedicated to writing the present report and preparing the final oral presentation and it was done alongside with the developmental stage. The task of writing everything down was performed gradually as the project moved forward.

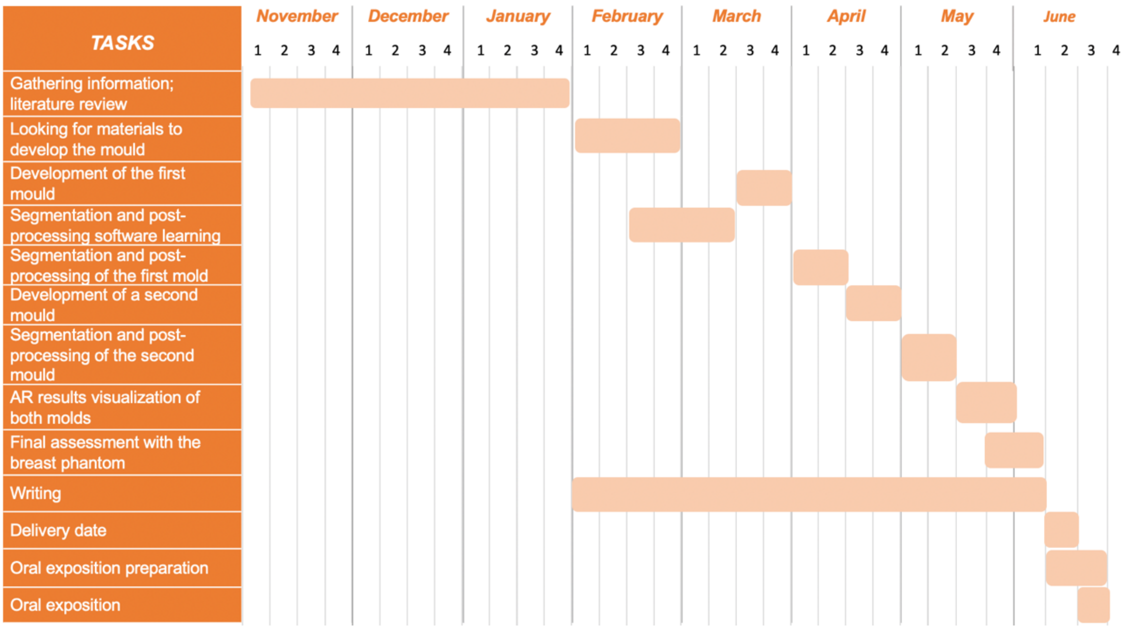


Figure 45. GANTT diagram of the Project.

11. Normative and legal aspects

This project has been fully developed in Spain, hence the legal requirements that have been considered are based on the Spanish legislation. Specifically, this project will be under the regulations established by Universitat de Barcelona *"Normes generals reguladores dels treballs de fi de grau de la Universitat de Barcelona".* [54] More precisely *"Normes reguladores dels treballs de fi de grau del grau d'enginyeria biomédica"* [55], which corresponds to specific regulations of the degree in Biomedical Engineering at Universitat de Barcelona.

An important point to consider is that neither the molds used to develop the project, nor the software used (3D Slicer, Meshlab, GiD, Unity, nor the hardware (HoloLens and Kinect) can be considered to be medical devices since they do not follow the Conformité Européenne (CE) definition: "*any instrument, apparatus, appliance, software, implant, reagent, material or other article intended by the manufacturer to be used, alone or in combination, for human beings for one or more of the following specific medical purposes: diagnosis, prevention, monitoring, treatment, prediction, alleviation of, or compensation for, an injury or disability, prognosis, investigation, replacement or modification of the anatomy or of a physiological or pathological process or state, devices for the control or support of conception"* [56]. As they cannot be considered to be medical devices, nor a diagnosis nor a procedure have been based in this project on the results provided by these devices.

Due to Covid-19, the author could not develop this project using data from real patients, therefore there is no need to follow the *Ley Orgánica 3/2018, de Protección de Datos y Garantía de los Derechos Digitales.* [57].

12. Conclusions

In conclusion, this project highlighted the potential of Mixed Reality and Augmented Reality as a new navigation system during surgery. It was proved that as a first static assessment to place the virtual tumor over the real one, this system is completely valid. This was tested using two molds developed by the author that had different objects inside and the results were successful, the holograms of the molds were placed properly over the real mold. Therefore, it is worth mentioning this technique is ready to be used for preoperative planning, surgical training and educational purposes, not only for BCS, but for almost all surgical branches from the medicine field.

In order to apply this methodology as the reference intraoperative navigation system and use the dynamic holograms with deformable tissues, more work and improvements need to be done. The testing of the system should be done with softer molds that allow more deformation and also it has to be improved from a computational point of view, increasing the calculus speed. Moreover, in order to be implemented with real patients, some kind of markers need to be placed over the breast when the TC is performed and work as a reference points to put the markers recognized by the Kinect.

Hence, one can say that the application of Augmented Reality technology is opening new opportunities in the healthcare industry since it is a non-invasive approach that can potentially overcome the limitations that traditional image-guiding systems such as CT or MRI displayed on 2D flat screens present. As a result, more and more companies on the healthcare sector are investing in this technology.

Finally, although some things need to be improved and polished (mentioned in section 6) it seems this approach is going on the right direction and appears as a versatile and reliable tool in the operating room.

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