DEVELOPMENT OF A VIRTUAL REALITY OPHTHALMOSCOPE PROTOTYPE

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Acknowledgements

Abstract

The eye examination is an important procedure that provides information about the condition of the eye by observing its fundus, thus allowing the observation and identification of abnormalities, such as blindness, diabetes, hypertension, and bleeding resulting from traumas among others. A proper eye fundus examination allows identifying conditions that may compromise the sight; however, the eye examination is challenging because it requires extensive practice to develop adequate interpretation skills that allows successfully identifying abnormalities at the back of the eye seen through an ophthalmoscope. To assist trainees in developing the eye examination skills, medical simulation devices are providing training opportunities to explore numerous eye cases in simulated, controlled, and monitored scenarios. However, advances in eye simulation have led to expensive simulators with limited access as practice remain conducted on a one trainee basis in some cases offering the instructor a view of the trainee interactions. Because of the costs associated with medical simulation, there various alternatives reported in the literature review presenting cost-effective and consumer-level approaches to maximize the effectiveness of the eye examination training. In this work, we present the development an immersive and non-immersive augmented reality application for Android mobile devices with interactions through a 3D printed controller with embedded electronic components that mimics a real ophthalmoscope. The application presents users with a virtual patient visiting the doctor for an eye examination, and requires the trainees to perform the eye fundus examination and diagnose their findings. The immersive version of the application requires the trainees to wear a mobile VR headset and hold the 3D printed ophthalmoscope, while the non-immersive version requires them to hold the marker within the field of view of the mobile device.

Keywords: Augmented reality, Eye fundus, Simulation

Resumen

El examen visual es un procedimiento importante que proporciona información acerca de la condición del fondo de ojo, permitiendo la observación e identificación de anomalías, como ceguera, diabetes, hipertensión, sangrados resultado de traumas, entre otros. Un apropiado examen permite identificar condiciones que pueden comprometer la visión, sin embargo, éste es desafiante porque requiere de una práctica extensiva para desarrollar las habilidades para una adecuada interpretación que permiten la identificación exitosa de anomalías en el fondo de ojo con un oftalmoscopio. Para ayudar a los practicantes a desarrollar sus habilidades para la examinación ocular, los dispositivos de simulación médica están ofreciendo oportunidades de entrenamiento para explorar numerosos casos del ojo en escenarios simulados, controlados y monitoreados. Sin embargo, los avances en la simulación del ojo han llevado a costosos simuladores con acceso limitado ya que la práctica se mantiene con interacciones para un aprendiz y en algunos casos, ofreciendo al entrenador la visión para la interacción del practicante. Gracias a los costos asociados a la simulación médica, hay varias alternativas reportadas en la revisión de la literatura, presentando aproximaciones efectividad-costo y nivel de consumo para maximizar la efectividad del entrenamiento para el examen de ojo. En este trabajo se presenta el desarrollo de una aplicación con realidad aumentada inmersiva y no-inmersiva, para dispositivos móviles Android con interacciones a través de un controlador impreso en 3D con componentes electrónicos embebidos que imitan a un oftalmoscopio real. La aplicación presenta a los usuarios un paciente virtual visitando al doctor para un examen ocular, y requiere que el aprendiz ejecute el examen de fondo de ojo haciendo diagnosticando sus hallazgos. La versión inmersiva de la aplicación requiere del uso de un casco de realidad virtual, además del prototipo 3D de oftalmoscopio, mientras que la no inmersiva, requiere únicamente del marcador dentro del campo de visión del dispositivo móvil.

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1 Introduction

Proper eye fundus diagnosis requires proficiency and competence in medical skills that are the result of an extensive and proper training [1]. Direct ophthalmoscopy is challenging as it requires proper interpretation of the eye fundus images visualized in two dimensions through the ophthalmoscope. Traditionally, eye examination was taught by employing images, pictures, and video, complemented with live practices with either patients or fellow trainees [2]. Furthermore, because of the eye examination nature of having a trainee looking into the eye through an ophthalmoscope, the practices are guided by the instructor who describes and cannot know where the trainee is focusing [2][3]. Currently, technological advances are providing multimedia contents through virtual reality, augmented reality, and simulation tools [3]. However, as studied by Kelly et al. [2], trainees prefer studying the eye fundus with photographs because of their higher definition, better quality, and without patient interactions or ophthalmoscope operation that can alter and increase the difficulty when conducting a real examination [2]. Since the ophthalmoscope is a general examination tool used in primary health care, it allows examiners to take a glimpse to numerous conditions that, if it is detected early, can help prevent or promptly address eyesight threatening scenarios [4]. As a result, there are developments focused creating training tools to perform direct and indirect ophthalmoscopy with the intention of approaching the students to the procedure and improving their skills performing it [5], and those kind of developments are the medicine simulators, in this case, simulators for ophthalmoscopy.

A definition of simulator is "An artificial means to model a real-world system, generally falling into two categories: physical simulator or computer simulator" [6]. The simulators are systems whose purpose is to offer a realistic experience in a specific field, being this the reason why the simulators are popular in the military industry, training procedures, structure testing, and medicine, among others fields [7]. Within simulation, virtual reality (VR) can present computer generated worlds where the user is immersed by providing sensory stimuli to its senses [8]. Currently, VR is being used in medical applications for mental health care through different devices like smart-phones, tablets, and medical devices [9]. However, due to the limitations that virtual reality presents, it is expanding itself in other areas such as the augmented and mixed reality that provides to the user new kind of interactions [10]. In particular, augmented reality is defined as a system that can augment the image of the real world with a computer-generated image providing additional information. Typically, this process is made in two phases; the first one is sensing the environment information, and the second one is the reconstruction of the environment, but user keeps feeling the presence of real

world [11]. Due that, it is possible to see currently, developments and advances in simulators applied to medical training and learning [12], it includes the direct ophthalmoscopy as it is presented in this work.

1.1 Problem

Direct ophthalmoscopy eye fundus examination is a medical procedure to determinate the condition of the eye using a direct ophthalmoscope [13]. This examination allows identifying possible risks of blindness associated with hypertension, cataracts, glaucoma, and diabetes among others [14]; nevertheless, to perform a proper eye examination, it is required of factors such as time for training and the elements used during that training. Indeed, the first factor is related to that it is required extensive training hours to perform properly the eye fundus examination[15], but in some cases like students from the Canadian Medical Curriculum, for example, are receiving no more than three hours of training which would result in insufficient experience [16]. The second one is related to the elements within the training to simulate the eye fundus examination, in this case, medical simulation devices provide the opportunity to find multiple cases with different eye conditions in multiple scenarios [17]; however, the technology for this purpose is limited in aspects such as cost, and the access. To clarify this context, access means the opportunity that the medicine student has to perform the training, and the kind of interaction that usually the simulation devices offer, so it is not possible to have training multiples medicine students in the same laboratory at the same time, and the simulation is in one way, for one trainee [18]; however, the instructor can see the trainee interactions in some simulators [19]. As consequence, due to all these limitations, the examiners are not confident using the ophthalmoscope resulting in an uncertain diagnosing, putting in risk the eye patient health [18]. In this point, the question is How the Virtual Reality can generate a complementary tool for the eye examination training to explore new ways for simulating this procedure, and evaluating the performance from a usability perspective? In this scenario, this project looks for developing a complementary training tool for the eye fundus examination using a 3D printed ophthalmoscope prototype with virtual reality, and evaluate it from a usability perspective with medicine students using the System of Usability Scale.

1.2 Rationale

The opportune diagnosis is essential for treating different diseases, and this analysis depends of doctor's skills [17] [13], therefore, it is important to offer the tools to medicine students for improving their abilities and giving them the trust in medical instruments, in this case, the direct ophthalmoscopy, thus, making feel them confident for doing a diagnosis of the eye condition.

The problem statement presents the importance of direct ophthalmoscopy and the roll that it plays to know the eye condition. The complete procedure encompasses features such as the proper ophthalmoscope handling, peripheral vision review, the ocular muscles examination, and finally, the eye fundus examination. In this point, the examiner must have the skills for identifying the physiological elements and their condition to do a diagnosis; although, due to the eye fundus is viewed through a tool in two dimensions [20], the deepness information linked with vessels inflammation is hardly detected at time and some times late, putting in risk the patient's eye health [13].

On the other hand, the use of photography and theoretical preparation are the most popular components within the fundoscopy training, as well as the increasing of accessibility to information and communication technologies makes easier the enrichment of cases and educative resources for trainees [21], so the theoretical identification might have an improvement, but there is not a simulation component. Instead, the simulation component is still linked to technologies using mannequins, currently with computational components [22], among other conventional technologies. So a development employing other fields such as the virtual reality for creating a direct ophthalmoscopy simulation might have an incidence in the perception about the training for this procedure by the medicine students, even adding a level of deepness that a single photo can not provide. In summary, it is known that an incorrectly diagnosis might put in risk the patient's eye condition, so the medical skills matter for performing properly this procedure, and that is the reason for developing simulators focused to improve those medical skills using the technology available, including virtual reality [23], and linking them with the multimedia content that is currently available.

1.3 Objective

Design an ophthalmoscope prototype with virtual reality that offers to medicine students the stereoscopic view and identification of the eye and its anatomical information.

1.3.1 Specific objectives:

- Analyze and characterize the compiled information with the purpose of defining the most important properties to develop the prototype.

- Design, develop and implement each subsystem that conform the prototype in its different components.

- Validate the prototype from a usability perspective.

1.4 Methodology

To achieve the proposed objectives, the methodology compromises the following five stages: Analyzing, design, development, implementation and evaluation. The first one defines and identifies the current developments and the technologies that are available in the market currently to simulate direct fundoscopy. The second one is related to the designing of components that must be included in the simulator, the pathologies selection, and the general system components. The third stage is linked to the building the 3d models, the features that the selected game engine has for the communication and the virtual reality component, also, the prototype modelling and the assembly. For the implementation stage, the main goal is to have ready the ecosystem; it implies the bug fixing and the issues solution for the prototype. Finally, the last stage is the evaluation from a practical perspective, so the simulator is tested for taking the required measurements to evaluate its usability, as it is proposed on the general objective.

1.5 Document Summary

This document is organized as follows:

- Chapter 2 - Literature review: This chapter includes the explanation about the ophthalmoscope operation, eye fundus information, eye fundus examination, and the current technologies that are used to develop ophthalmoscopy simulators.

- Chapter 3 – Design: This section contains information how is the procedure performed and its general steps. Additionally, there are descriptions about which are the main characteristics for each pathology, the system architecture and the diagrams about how the program will work..

- Chapter 4 - Development: This chapter presents the process about all aspects inside of the development, including the different versions and states where the application was before, and the final prototype.

- Chapter 5 - Evaluation and results: This chapter presents the methods used to validate the simulator.

- Chapter 6 - Conclusion: The global conclusions are presented as well as the future work.

2 Literature Review

This chapter presents the literature review. It comprises an analysis of existing work in, and eye pathologies.

2.1 Eye Fundus

Superior rectus muscle
Sclera
Choroid
Retina
Fovea centralis
Central artery
Central vein
Optic nerve
Inferior rectus muscle
Conjunctiva
Ciliary body
Posterior chamber
Anterior chamber
Anterior cavity
Cornea
Pupil
Lens
Iris
Posterior chamber
Zonular fibers of suspensory ligament
Vitreous chamber (posterior cavity)
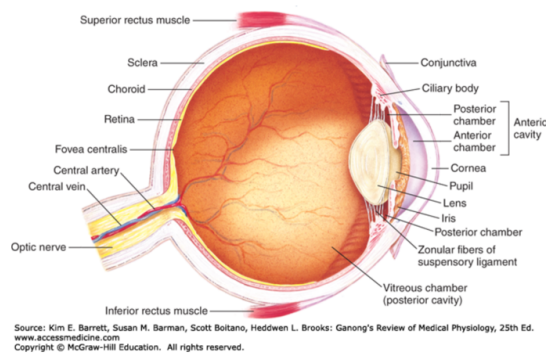
Figure 2-1: A schematic of the anatomy of the eye.
[24]

The human visual system takes information from the environment for aiding in the guidance of the normal human behaviour; it begins from the images capturing through multiple organs inside the eye such as the cornea, and retina among others [25]. Traditionally, the eye is considered as an organ-structure in charge of taking that visual information; it is surrounded and maintained by different tissues as Figure **2-1** presents. One of them is a protective layer called Sclera, the white visible element in the eye, and the component where the light can not pass. In the other hand, the cornea is the transparent element that allows the light-passing. Behind the cornea, there is a mucous and translucent membrane called Conjunctiva that is covered by the sclera, and inside of this one, there is a vascular layer to provide oxygen and nutrients to the internal structures within the eye called choroid. Finally, behind the conjunctiva, the retina is located in the posterior two-thirds of the choroid. There are other layers presented (see Figure **2-1**), but in summary, the light capturing is through the presented layers, so the light comes inside through the cornea, and it goes by the sclera until coming to the retina where the optic nerve is located [26]. Consequently, the eye fundus visualization is the summation of the different layers where the light is going

in, so the result is the image that is viewed through the direct ophthalmoscope presenting the current eye condition, nevertheless, that condition can reflex not only the sign of a local issue, it might be sign of disorders and diseases in the human body such as hypertension or even disorders in the metabolism, so the eye fundus information is certainly not isolated [27].
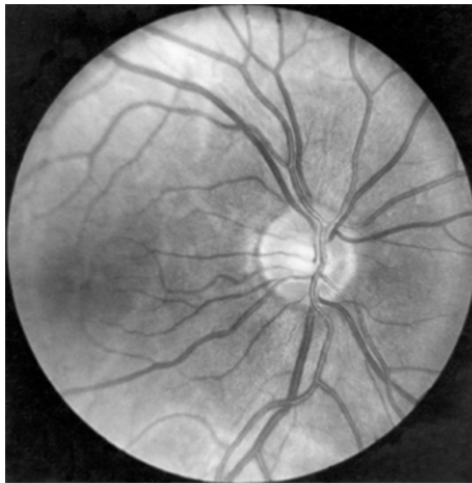
Figure 2-2: Healthy eye fundus.
[28]

Viewed through the ophthalmoscope, eye fundus is interpreted as a two dimensions' image, however, it is possible to identify it, as the area where the blood vessels born, also where the macula, fovea, and head of the optic disc are located. Looking at Figure **2-2**, it is possible to identify the optic disc that is the highlighted circumference. In this point, all the veins and arteries are growing until their respective quadrants or hemispheres, superonasal, inferonasal, superotemporal and inferotemporal, that are specific zones inside the eye like coordinates for the blood vessels [29]. Besides the blood vessels, there is an organ that connect the eye with the neuronal system, this organ is the optic nerve whose size might variate depending of the patient, however, it is not a sign of disease or anomalies in the eye condition, even sometimes there are confusions between healthy eyes and glaucoma cases whether the examiner takes as criteria the optic nerve size[30], nevertheless, it is important to keep in mind that a healthy optic disc has well-defined borders, the real criteria for diagnosing the optic disc. Finally, between the superotemporal and inferotemporal hemispheres, next to the optic disc, there is found the macular region where the fovea and macula are placed.

2.1.1 Eye Fundus Pathologies

The condition for each organ in the eye fundus is the reflex of different factors that influence over the eye such as the age, genetic conditions and clinical history [31]. This section presents the pathologies with their description including the main features that there are for each one.

2.1.2 Copper wire vessels

Hypertensive retinopathy can manifest through of different forms; one of them is generalized as the arteriolar sclerosis that resembles copper or silver wires in the eye fundus [32].
The arteries diameter is half of the veins in the eye, but in pathological cases, it is altered,
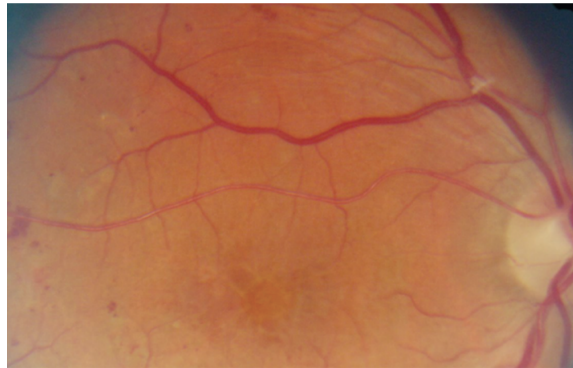
Figure 2-3: Copper and Silver Wiring.
[32]

so arteries diameter begins to decrease taking a metal brightness. In less advanced cases it is called copper wire vessels and in most advanced, the arteries try to constrict the veins and look like silver wires [33].

2.1.3 Cotton wool spots.

Cotton wool spots are a non-specific signal of a singular disease because they can appear in different cases involving the retinal vascular system [34]. Cotton wool spots are usually lipids, fat and other fluids that come out from the vessels (Figure **2-4**). However, it is an asymptomatic retinal sign, even sometimes, it is the first sign of a systematic disease, or in some cases, the reflex of a serious vascular damage [36]. Usually, it resembles like cotton spots in the eye fundus, and sometimes it can be classified as hard or soft exudates (any fluid filters from the circulatory system) depending of its shape. This pathology is presented in diseases like hypertensive retinopathy, diabetic retinopathy, dengue fever, malaria retinopathy metastatic carcinoma, among others [37].

Figure 2-4: Cotton wool spots.
[35]

2.1.4 Papilledema

Papilledema is a disease discovered by first time in 1853. Essentially, it is the sign of high intracranial pressure reflected in the optic disc condition[38].

Figure 2-5: Papilledema from increased intracranial pressure.
[39]

Papilledema refers to an optic disc inflammation related to the increasing of intracranial pressure. It is visible around the head of optic nerve as its edges become blurred (see Figure **2-5**). This pathology is common in obese women, and usually, it presents headaches, visual disturbances, and in some cases, whooshes sounds. Approximately two-thirds papilledema patients present visual impairment, the majority these patients improve their condition [40],

but one study reveal that 9% of them get permanent visual loss [41].

Neovascularization

Neovascularization is one of the Retinopathy signs, but there are different types of retinopathy including Non-Proliferative Diabetic Retinopathy and Proliferative Diabetic Retinopathy, and the neovascularization is the key to differentiate one of them (Figure **2-6**) [42]. Retinal neovascular complexes are irregular wires of fine blood vessels that grow in eye fun-
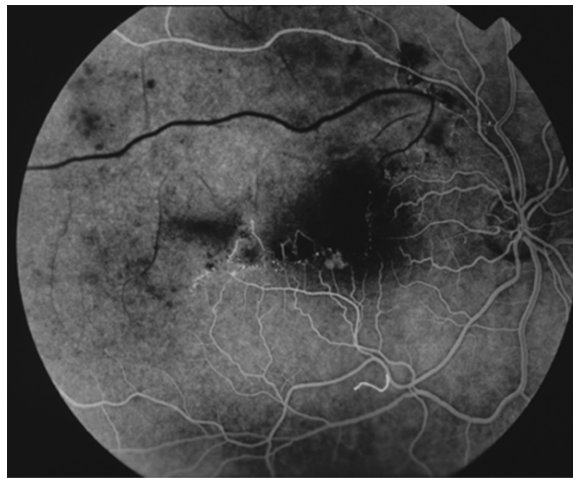
Figure 2-6: Fundus fluorescent angiogram of superotemporal branch retinal vein occlusion with extensive retinal ischemia
[43].

dus related to severe retinal ischemia or chronic inflammation. Neovascularization causes high risk of hemorrhaging, often causing visual loss, so it is possible to see not only one sign, it is possible to see also exudates (cotton wool spots) among other symptoms [44].

2.2 Ophthalmoscope

The ophthalmoscope is a hand-held optical instrument used to inspect the eye fundus. Usually, the view provided by this instrument is monocular, non-stereoscopic, narrow field, and the view is magnified about 15 times [45]. The Figure **2-7** presents the ophthalmoscope working, where it is possible to see that the process begins from the light emission in the bulb, until the patient's eye through to an aperture wheel, lenses and mirror until the patient's eye where the light is reflected and it goes to the examiner through the compensation lenses for adjusting the error of view between the doctor and the patient's eye.
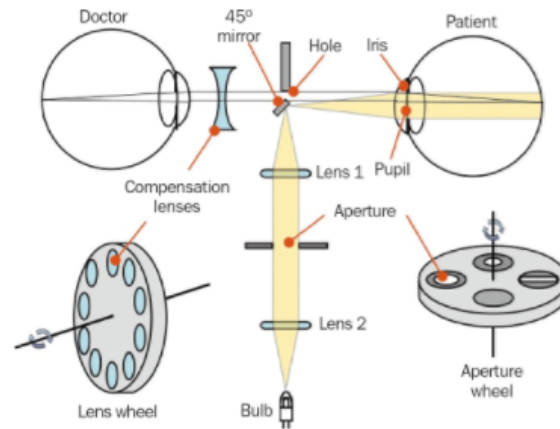
Figure 2-7: Ophthalmoscope elements and operation.
[45]

2.3 Traditional Training.

The current training for the eye fundus examination does not enough for improving the skills in trainees in respecting of the current needs [46], that is why, it is necessary to know the learning process for this procedure.Also, it is important to recognize some features included in traditional training because this kind of training might not be the same for all countries; however, there are steps and key points to follow to perform the training. As first step, student of medicine takes theoretical lessons where are included elements such as eye semiology, and introduction to some pathologies that are related with visual affectation, among others. The second step is the training in itself, where the student or participant uses photographs or in some cases, they make the practice with their companions. Use of photography is commonly the way where the participants must identify with different cases the elements that are present inside the eye fundus, even in some emergency departments, the use of digital images improves the examination and diagnosis with the ophthalmoscope [47], especially nowadays because it is possible the access to many digital photographs through internet and online data bases [47]. Finally, medical schools make emphasis on using ophthalmoscope in ophthalmologic clinics, but that is not the case for general medicine programs, so students do not feel confident using the ophthalmoscope, even when usually, it is needed to use it more than 10 times to make feel the students feel fearless [13].

2.4 Current and New Technologies.

Currently, the industry and academic fields are working to develop different solutions for the medical learning and training requirements, so it is possible to find diversity in technologies that born linked with all these needs, including in some cases, ways for collecting and processing symptoms data [48], or creating solutions for precision medicine with computational

solutions [49]. Before to show some technological advances, it is important to identify the terms such as Virtual Reality, Augmented Reality and Mixed Reality.

2.4.1 Virtual and augmented reality

Currently, these terms are popular in the world. It is possible to see an increase of using for different developments using these kind of technology in a variety of applications, such as fashion world, art, cinema, television, among other fields [50], but, What is the difference among them?

Virtual Reality

Virtual reality is a system composed of an interactive computer simulation where user gets a sense of being immersed in a virtual world, and at the same time, this system sense user's state and replaces or augments sensory feedback to one or more user senses [8]. Currently, it is possible to use this technology in fields such as medicine for mental health care through different devices like smart-phones, tablets and medical devices [9].

Augmented Reality.

Augmented reality is defined as a system that can augment the image of real world with a computer-generated image providing additional information. Typically, this process is made in two phases; the first one is sensing the environment information, and the second one is the reconstruction of the environment, but user keeps feeling the presence of real world [11].

2.4.2 Eye Fundus Simulation

The traditional method of training is thought the use of digital photographs with different cases because the use of simulators is restricted to the use in some cases to mannequins or elements with human shape whose interior houses eye fundus images [2]. Bellow, there are listed some developments for ophthalmoscopy training and a brief description and analysis for each one.

3D Virtual Reality Trainer

The 3D Virtual Reality Ophthalmoscopy trainer is and android step-by-step guide developed in Unity Engine that requires a configuration to operate using the Google Cardboard Version 1 or RITHECH II. This guide has included images provided by Sandwell and West Birmingham, also, the simulator includes audios and visual cues to accompany the text instructions.
The simulator comprises five levels. The first one is the tutorial where the user gets the instructions to learn how to use the app moving their head to locate some elements to
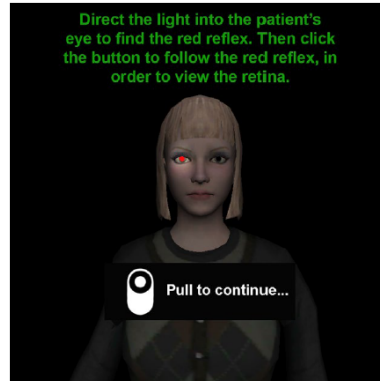
Figure 2-8: Screen of 3D Virtual Reality Trainer
[51]

interact with in the VR scenario using the headset. The second level is related with the red reflex location, so the user is taught about how to orientate the light for getting the red reflex and zoom it, simulating the approaching process.

The third one is the retinal navigation, so the user is taught about the retinal examination sequence, then, the user is guided to locate the four quadrants in the retina and the optic disc. The fourth level is related with the pathologies where the app shows a presentation with audio-visual commentaries providing an explanation about the most common pathologies in the eye such as cotton wool spots, hemorrhages and papilledema.

Finally, the fifth one presents a quiz for the user where are shown randomly eight images and the participant has to identify which case is presents in. To clarify, among the eight cases, there are healthy eyes, wool spots, papilledema and hemorrhages.

Results.

To evaluate the application, it was required of 15 volunteers (fourth-year undergraduate medical students) whose perception about the app was surveyed in Birmingham City Hospital (UK),and as result, there were two different surveys:

The first one is related with the usefulness perception, and the Table **2-1** presents the quantified opinion of all the participants around the understanding of use, the landmarks recognition, the abnormalities identification and the confidence to perform the procedure.

Related to the improvement of understanding and landmarks identification in the eye, the general perception is in favour, 14 of the 15 students are agree and only one of them had a neutral position on those statements. Related to the perception about whether the application improves the abnormalities recognition within the eye, the total of the participants are agree, nevertheless, corresponding with the perception about whether the app gives them the confidence to perform the ophthalmoscopy in the future, one of them is completely disagree, two of them have a neutral perception, and 12 of them consider the simulator provides them that confidence.

Table 2-1: Usefulness Perception Results.
[51]

	Completely Agree	Agree	Neutral	Disagree	Completely Disagree
The app improves my understanding of the process involved in ophthalmoscopy	7	7	1	0	0
The app improves my ability to identify the main landmarks in the eye	8	6	1	0	0
The app improves my ability to recognize abnormalities within the eye	9	6	0	0	0
The app will give me the confidence to perform this task on a person in future	7	5	2	0	1

Table 2-2: Easiness of Use Perception
[51]

	Completely Agree	Agree	Neutral	Disagree	Completely Disagree
Learning to use the app would be easy for me	11	3	1	0	0
I would find it easy to control the app so it will do what I want it to	8	5	2	0	0
I would find it easy to understand how to use the app in the future	9	6	0	0	0
Overall I find it easy to use the app	9	6	0	0	0

On the other hand, there is a survey for getting the easiness to use perception for the application (see Table **2-2**) where in general terms, the simulator has a good perception, and the interviewed medicine students perceived the application as an easy tool to use. Evaluating the learning process to use the app, 14 of the 15 participants considered easy to learn how to use it, however, about the app control, two pf them have neutral position. Finally in overall terms, all the students are agree with the easiness of use on this application [51].

Discussion
The 3D Virtual Reality Ophthalmoscopy is a training tool tested in 15 medicine students presenting a good perception in terms of usefulness and easiness of use. Also, the simulator requires of smartphone and the headset (Google Cardboard or RITHECH II), so it is not expensive and it is possible to have training multiple students in the same place; however, the application emulates the ophthalmoscopy without the ophthalmoscope emulation, so it does not include the features related with the ophthalmoscope itself. Also, the identification does not include the macula and fovea region.

Eyesi® Direct Ophthalmoscope

Figure 2-9: VR Magic training station
[52]

VR Magic is currently, the enterprise that develops medical simulators based in virtual reality. One of them is the Eyesi® Direct Ophthalmoscope, a simulator to enhance the teaching of the diagnostic skill of direct ophthalmoscopy [53]. This simulator is a training station composed by a monitor, a head with sensors, a ophthalmoscope device and the computer. Between the head and the ophthalmoscope device there is located the tracking system, so the student can perform the fundoscopy (Figure **2-9**), and the monitor displays what the trainee is looking at, so the educator can supervise the student process while during the simulation.

The simulator has features related with the training experience, the independent practice, the competency-based assessment, the pattern recognition, and the Online tools for teaching and management. Related with the training experience, Eyesi Direct Ophthalmoscope Simulator uses virtual reality and real ophthalmoscope components to make an immersive training experience, also, it requires that medicine students identify the pathological findings and the eye components using properly the ophthalmoscopy techniques. Additionally, the simulator includes patient's features like blinking, spontaneous venous pulsation,and real time neurophysiologic model of pupil response to light, among others [52].

Another feature presents is the ability to provide unlimited practice time, so whether a medicine student has access to the simulator, it provides all its contents each time. The Competency-Based Assessment is another feature included in the simulator, so the trainee has an objective during the training and immediately, they have a feedback after the visual exam, so the medicine students can systematically improve their skills according to what they are identifying on, and the assessment designated. Also, the simulator provides to the educators tools such as access students' training data through the web portal, so they can follow the students progress.

Another feature is the Pattern Recognition of Retinal Pathologies. In this point, the simulator offers a variety of different cases to explore such as optic disc edema, diabetic and hypertensive retinopathy or vascular occlusions in different stages and varying their severity and conditions.

Finally, the last feature is stated as "Complete Teaching Solution with VRmNet" which is a group of online features to help the teaching to large groups of students, so the platform provides online educative resources and web administration tools for the designed educators[52]. Discussion.

Indeed, Eyesi® Direct Ophthalmoscope Simulator is an ophthalmoscopy training tool that includes features focused in the training course, teaching and progress supervision, taking advantage of technologies that currently it uses such as virtual reality and Information Technologies. However, it is a high cost tool, so it is not possible to have training multiple medicine students at the same time.

FAK-I

The FAK-I is a low-cost prototype for ophthalmoscopy training. It was designed to approximate several anatomic properties of the human eye using low-cost materials. The simulator is comprised of an opaque bottle cap of 24 mm in depth to replicate the anterior-posterior dimension of the human eye, and it is covered by black card stock. Also, it has high-resolution digital retinal images printed in matte paper to minimize glare; these images are within the bottle caps that are located in a Styrofoam head (Figure **2-10**).

To evaluate the simulator, the test was designed with the following elements: Previous hands-on direct ophthalmoscopy training session, and the randomly definition of two groups with 6
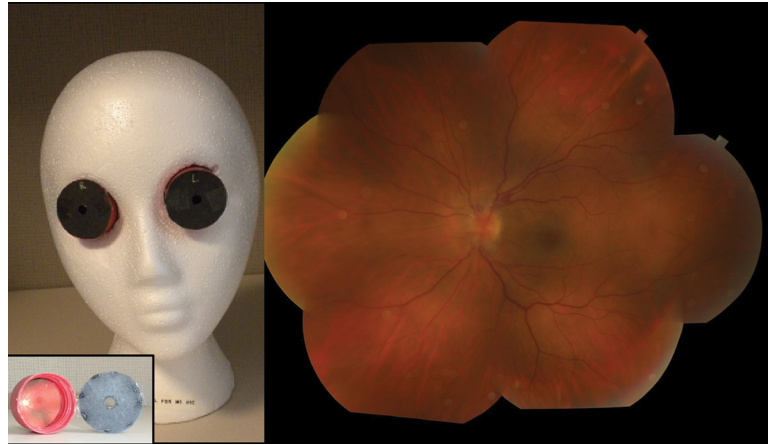
Figure 2-10: FAK-I prototype and high-resolution eye fundus image
[54]

first-year medicine students for each one. The first group (control arm) did not receive FAK-I model intervention and the second one (study arm) received FAK-1 model intervention. For the study arm, they received a FAK-I set consisting of one Styrofoam head and five FAK-I models with different posterior pole findings, however, they received the information about where there were direct ophthalmoscopes available on campus, not the devices them self. All the participants during 45 days were instructed to attend an ophthalmic practical skills session, consisting of two hours of lectures and practice of eye examinations. After those 45 days the investigators evaluated the clinical direct ophthalmoscopy skills.

As result, the study arm had a higher percentage of correct responses (44%) than the control group (40%). Also, more students in the study group reported independently training of the direct ophthalmoscope than the control group [54].

Discussion

The FAK-I simulator is a low-cost alternative to the ophthalmoscopy training that includes high-resolution images and cheap elements to build it, allowing the easy replication, so it is possible to have multiple medicine students performing the eye examination training using at the same time a real direct ophthalmoscope; however, during the practice the instructor cannot know what is the trainee looking at, and there is not an immediate feedback to the student along the training.

Nasco Digital Eye Examination/Retinopathy Trainer

Digital Eye Examination/Retinopathy Trainer is a simulator that comprises mainly two elements, a mannequin head, and a direct ophthalmoscope. The head has included an internal high resolution digital display, so the trainee see through the eyes the content that the simulator provides. Also in the top, there is a control where the instructor can set up the pathology they want the trainee looks at; moreover, the simulator allows to set different

Figure 2-11: Digital Eye Examination/Retinopathy Trainer – Light version
[55]

pathologies for each eye. The simulator offers 36 different cases of eye condition that provides a variety in the content classified in three main groups: Diabetic retinopathy, common retinal conditions, and important less common retinal conditions.

- Diabetic retinopathy: Background Diabetic Retinopathy, Maculopathy, Pre-Proliferative Diabetic Retinopathy, Proliferative Diabetic Retinopathy, New Vessels Disc, Laser, Photocoagulation,and Ungradable.

- Retinal Conditions: Normal, Glaucoma, Papilloedema, Optic Atrophy, Age-Related Macular Degeneration (Dry), Hypertensive Retinopathy, Central Retinal Vein Occlusion, Central Retinal Artery Occlusion, Drusen, Retinitis Pigmentosa, Medulated Nerve Fibres, High Myopia, and Branch Retinal Vein Occlusion.

- Important and Less Common Retinal Conditions: Pre-Retinal Vein Occlusion, Multiple Retinal Haemorrhages, Retinal Detachment, Angioid Streaks, Benign Disc Neavus, Malignant Melanoma, Macular Hamorrhage, Choroidal Naevus, Macular Scar (Toxoplasma), Cytomegalovirus Retinitis, Lipaemia Retinalis, Medusa Head, Myopic Crescent - Normal Choroidal Vessels, Sub Hyaloid Haemorrhage Resolving, and Macular Burn.

Discussion
Nasco Digital Eye Examination/Retinopathy Trainer provides 36 different eye condition cases related to diabetes, and all of them are visualized through a high-resolution display. This simulator allows the trainee to perform the eye examination using a direct ophthalmoscope; however, the cost for each one is $1,485.95 USD [55]. Also, the trainee has not a feedback from the simulator during the training.
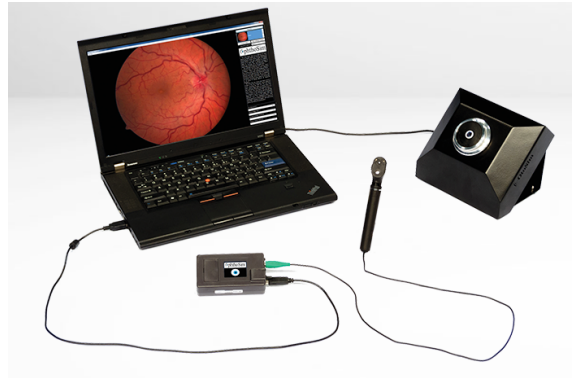
Figure 2-12: Digital Eye Examination/Retinopathy Trainer – Light version.
[55]

OphthoSim™ Ophthalmoscopy Training & Simulation System

OphthoSim™ Ophthalmoscopy Training & Simulation System is the product that OtoSim offers for eye examination training. This simulator comprises the display unit, a direct ophthalmoscope with a tracking mechanism, the sensor box (it works only with the OphthoSim ophthalmoscope) and the USB containing the software to install on Windows or Mac. This simulator provides to the trainees a database of 200 high resolution images, some of them with pre-annotated text for landmarks and pathological features. Also, the software allows the highlighting specific areas in the model from the computer, it enhances the student-instruction interaction [55].

Investigators from the University of Toronto made an investigation to evaluate the simulator to teach funduscopy skills to pediatric residents in the Hospital for Sick Children. For this purpose, they selected 17 pediatric residents (postgraduated years 1-30), and created two groups randomly. The first one with 8 participants (control group) and the other one with 9 (intervention group). They were asked in a pre-test where both groups presented a similar statistical performance with 51% for the control group and 49.45% for the intervention one of correct responses. Then, the intervention group had a training session with OphthoSim™ Ophthalmoscopy Training & Simulation System, then, a new test was performed and the intervention group presented an important improvement, getting a 95%, but the control one did not. The main conclusion of this study was that a single session with the ophthalmoscope simulator can improve diagnostic accuracy in postgraduate pediatric trainees [56].

Discussion

OphthoSim™ Ophthalmoscopy Training & Simulation System has features that allows the improvement in the diagnostic accuracy skills in postgraduate pediatric trainees with a single session, it offers tools to inprove the interaction between instructor and trainee through the computer and eye display, also it provides a database with 200 images, however, it is a simulator whose price is $10000 USD [55], so it is not possible to have multiple trainees

performing the eye examination training with the simulator at the same time.

2.5 Serious Games and Simulators.

Videogames certainly are defined such as "an electronic game with video feedback where user input has consequences that affect the game environment" [57]; however, it matters to know that inside of videogames there are Games for Entertaining and Serious games, and in some cases, there is a difference between serious games and simulators; these differences are explained bellow.

Serious Games.

It is necessary to clarify that games are unconsciously to videogames, but it might be any activity whose purpose is to have fun following a structure, sequence or rules; however, this document makes emphasis on platforms with a kind of computing level. Usually, games are made to make people feels good and entertained, so serious games have the same features than entertaining games, but the main goal is related with learning [58], healthcare training [59], among others, so this is the most relevant difference. Understanding the difference between Entertainment games and Serious Games, it is important to highlight the possibility for a third component. Serious games may be divided in two types. As well it is presented, message
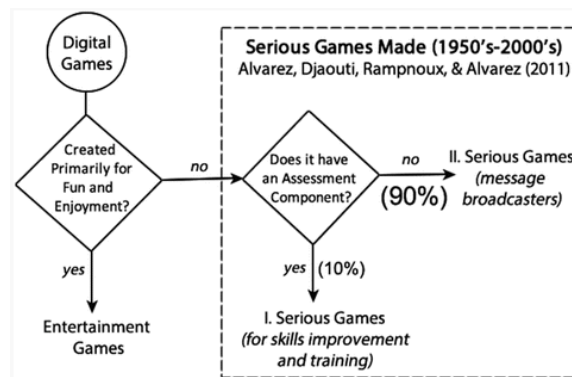
Figure 2-13: Difference between Entertaining Games and Serious Games
[60]

broadcasters are not serious games, so it means that not all games with not entertaining purposes are serious games and, as its name says, they just send information in one-way, they are educational, if it is their purpose, but are not serious games.[61]

Simulators.

A definition of simulator is "An artificial means to model a real-world system, generally falling into two categories: physical simulator or computer simulator" [6]. The simulators

are systems whose purpose is to offer a realistic experience in a specific field, being this the reason why the simulators are popular in the military industry, training procedures, structure testing, and medicine, among others fields [7]. Within simulation, virtual reality (VR) can present computer generated worlds where the user is immersed by providing sensory stimuli to its senses [8].

Figure 2-14: Advanced task trainer for bronchoscopy. This one presents the characteristics of computer simulators, using physical references, on this case, a mannequin. [62]

2.5.1 Literature Review Summary.

A proper ophthalmology allows to identify the current eye condition, for this reason there are different developments around of ophthalmoscopy simulation, looking for the improvement of the diagnosis skills. Currently, these simulators encompass different fields of technology and resources such as virtual reality, mannequins, photography and software developments; however, many of them have high cost, taking off the possibility to have multiple students performing the training at the same time. The others do not offer a feedback to the trainees or they do not include the intrinsic features that commonly the direct ophthalmoscope has in. Finally, the other simulators do not offer stereoscopic vision to provide new interactions with the user.

3 Design.

This chapter presents the elements for designing the direct ophthalmoscope simulator, including the characterization of eye fundus examination, the selection of pathologies, system architecture, and the requirements for the physical prototype, among others.

3.1 Analysis and characterization of eye fundus examination

Doing a properly fundoscopy, the examiner can detect signs present in the eye fundus of diseases and pathologies like Diabetic Retinopathy. However, to detect them, it is necessary to follow a sequence looking at the landmarks within the eye and regarding their condition [25].

3.1.1 The procedure

To perform the eye fundus examination, it is necessary to follow the sequence that is explained below:

- **Previous patient condition:**It is important to know the previous patient condition such as their age, clinic history, and allergies to myadrics (substances for pupil dilation), among others [63].

- **Locate the patient:** The first step is to locate the patient in a dark room, so the pupil can dilate itself thanks to its natural reflex in the darkness [64].

- **Pupil Dilation:** The nurse applies the mydriatic to the patient, usually phenylephrine hydrochloride 10%, one drop for each eye, every ten minutes, three times [65].

- **Red reflex location:** The examiner must be at 30 cm from patient's eye, looking for the red reflex using the ophthalmoscope. To do that, the examiner needs to be looking since 15 degrees over the horizontal to the pupil. It is important to know the examiner must handle the direct ophthalmoscope with the same hand that patient's eye they are looking at.

- **Approaching:** The examiner makes an approaching until to be at 3 or 5 centimetres from patient's eye (Figure **3-1**), and looking for the optic disc, the reference landmark.

- **Landmarks identification:** The examiner moves the looking along the blood vessels for each quadrant or hemisphere inside the eye, and then, they look for the macula and fovea. Doing this procedure, the examiner can see the eye fundus, and its internal elements, including their condition methodically [66][67].
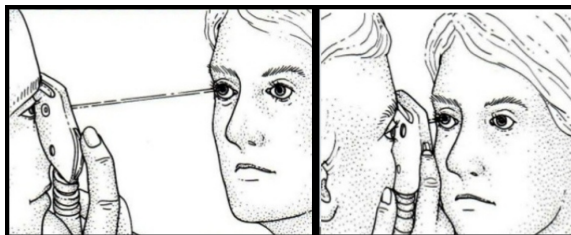
Figure 3-1: Basic sequence to handle the ophthalmoscope and approaching to patient's eye. [68]

3.1.2 Pathologies.

The criteria to select the pathologies that will be included in the application is related to which is the most commonly found disease in the world, the obesity [69]. In U.S.A. more than 70% of the population has obesity [70]. As consequence, there are other diseases and disorders related to the obesity such as hypertension and diabetes. These diseases have an impact on the eye condition that is reflexed in the following most commonly found eye diseases related to diabetes, obesity, and hypertension [25]:

- Optic disc edema.

- Cotton wool spots.

- Copper wire vessels.

- Neovascularization.

Next, there are the pathologies and their most important characteristics for each one, and landmarks to be included them in the application:

Optic Disc Edema.

Figure **3-2** presents a case with Optic Disc Edema, where it is identified due to the burred edges around the optic disc, the main characteristic of this disease, so the application may to guide the user to explore the close organs regions to the optic disc such as the macular area, the nasal quadrants, and the optic disc.
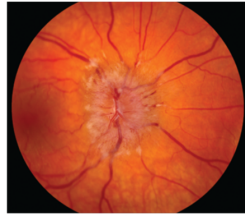
Figure 3-2: Papilledema.
[71]

Figure 3-3: Eye fundus with exudates.
[72].

Cotton Wool Spots.

Cotton wool spots is the manifestation of exudates (any fluid coming out from the circulatory system [73]) in the eye fundus. They resemble highlighted spots (see Figure **3-3**), and they are located close to the blood vessels and the macular area, so if the user explores the superotemporal arcades and macula, they can see the spots, and they can identify this eye condition, as consequence.

Copper Wire Vessels.

Copper Wire Vessels is the eye condition where the arteries decrease their diameter, and as consequence, the light reflex over these arteries resembles like copper wires, and in the severe cases, they resemble like silver wires. Figure **3-4** presents an eye fundus with Copper Wire Vessels and Cotton Wool Spots, also. The application might guide the user by the blood arcades in the eye to make them detect the anomalies in the arteries and help them
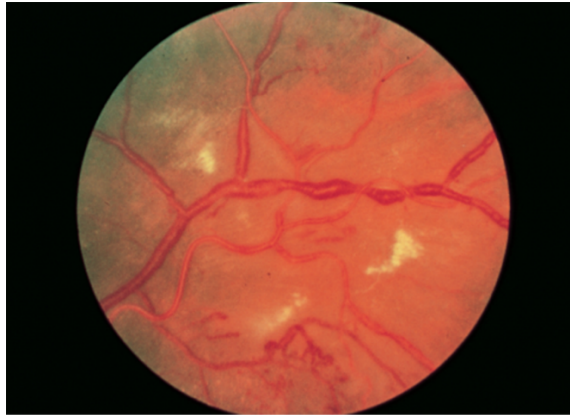
Figure 3-4: Eye fundus with Copper Wire Vessels and Cotton Wool Spots
[74].

to identify the current eye condition, in this case, Copper Wire Vessels.

Neovascularization.

Neovascularization. Neovascularization is the manifestation of new blood vessels in the eye
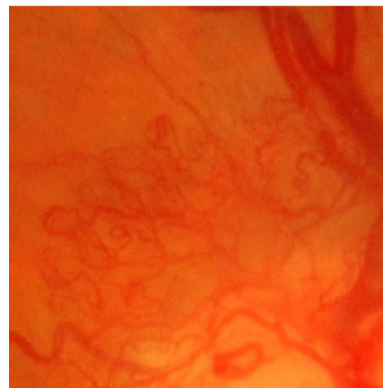
Figure 3-5: Eye fundus with microaneurism.
[75].

fundus, usually with irregular shapes. This eye condition is considered a type of retinal
hemorrhage , and it is the sign of glaucoma [43], also. To identify this condition, it is
necessary to look at the macular region carefully, so in this case, the application might focus
for guiding the user around this area.

3.2 System Architecture
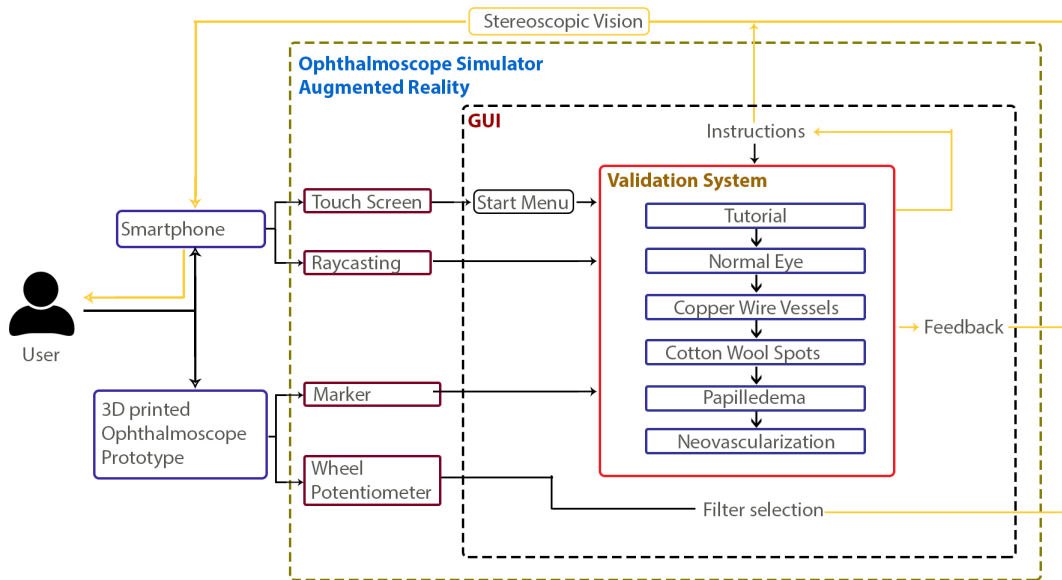
Figure 3-6: System Architecture for the project.

The System Architecture (see Figure **3-6**) has defined the inputs and outputs that are the components the application will interact with. Also, the diagram includes the validation system and the elements that the Ophthalmoscope Simulator comprises.

1. **Inputs:**   The system has four main inputs. The touch screen, the raycasting system, the marker, and the Prototype wheel.

   - Touch Screen: It is the medium where the user will interact with the Start menu, mainly.

   - Raycasting: It is the method where there is a ray projected from a defined element with a specific length and orientation. This ray detects the properties of all elements it is colliding with, allowing the taking of decisions depending on what is the element the ray is pointing to. For this application, the ray is projected from the camera to where the user is looking at.

   - Marker: The marker is a printed image of reference the application gets the position and orientation from, using the camera and image processing, integrated into Augmented Reality system.

   - Prototype Wheel: It is the wheel located in the ophthalmoscope prototype where the user selects the filter they will work with, to perform the eye fundus exami-

nation. In this application, a potentiometer will be used to track wheel's radial position, as a reference sensor.

2. **Validation System:** The validation system guides the user if they are wrong or not with their choice. It comprises a defined instruction presented through the Graphical User Interface (GUI), that instruction ask to the user for pointing an specific organ or area in the 3D model. If the user is or not wrong they will know it, and the instruction will not change until the user point the correct region.

3. **Outputs:** To the user, all the outputs are through the phone screen stereoscopically.

   - Feedback: The signs that indicate to the user if they made the correct or wrong choice; "Nice!" for correct choices and "X" for the wrong one. The feedback es result of the validation system. It also includes the instructions the user will follow.

   - Filter: The filter is the visual restriction the user will have depending on wheel's angular position, and it is based on the real direct ophthalmoscope filters. The filter is also displayed stereoscopically and its election does not depend on the validation system results.

Additionally, the "Ophthalmoscope Simulator Augmented Reality" comprises a Bluetooth connection between the smartphone, and the 3D printed prototype to transfer wheel's angular position.

3.3 Use Cases.

Figure **3-7** presents the global use cases the user will have to interact with. There are mainly two ways to interact with the scenes and instructions in the application. The first one is the pointing, so the user has to lead a point of reference in the screen (a cursor), moving their head to the tasked element. This use case is implemented in the tutorial, and all the eye conditions included in the application. The second one is the filter selection using the wheel in the prototype, but this task is not a condition or requirement within the validation system.

3.4 Software Design

Figure **3-8** presents the diagram of the general sequence the application will have. Bellow, there is the explanation of how the program will flow.
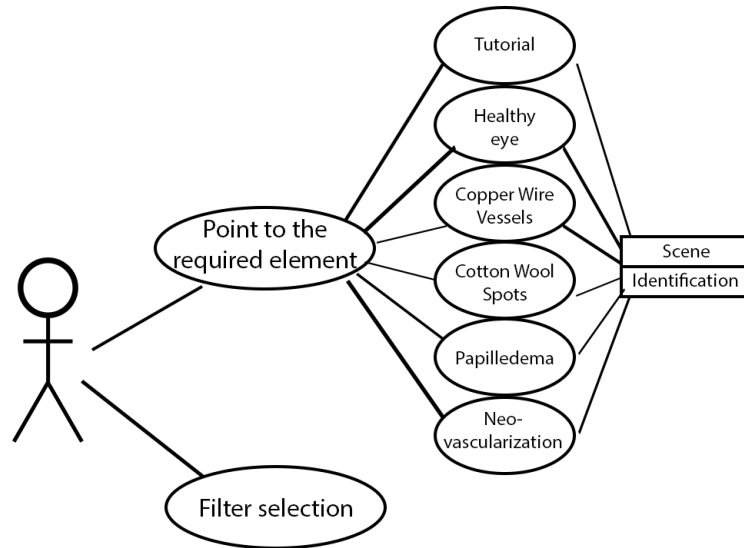
Figure 3-7: Use Cases.

3.4.1 Start Menu

The application starts with a "Start Menu" as welcome window, and there, the user access to the virtual trainer. Internally, the program looks for the Bluetooth device, if it is found, the application enables the filters and the stereoscopic vision as well, if that is not the case, the user can trains without the device (but it still requires the marker), so the application does not enable the filters, but it enables the stereoscopic vision.

3.4.2 Healthy Eye

The normal eye condition is the first case the user finds. Here the trainee will stay twice, the first time all the organs have their respective sign, so the user can identify easily which is the organ the application is asking to, meanwhile the second time, the application just will show the half of all the signs available; however, the application asks for all the organs and regions, so the user needs to use their memory to find them. From this point, all the following cases the user will interact with them once.
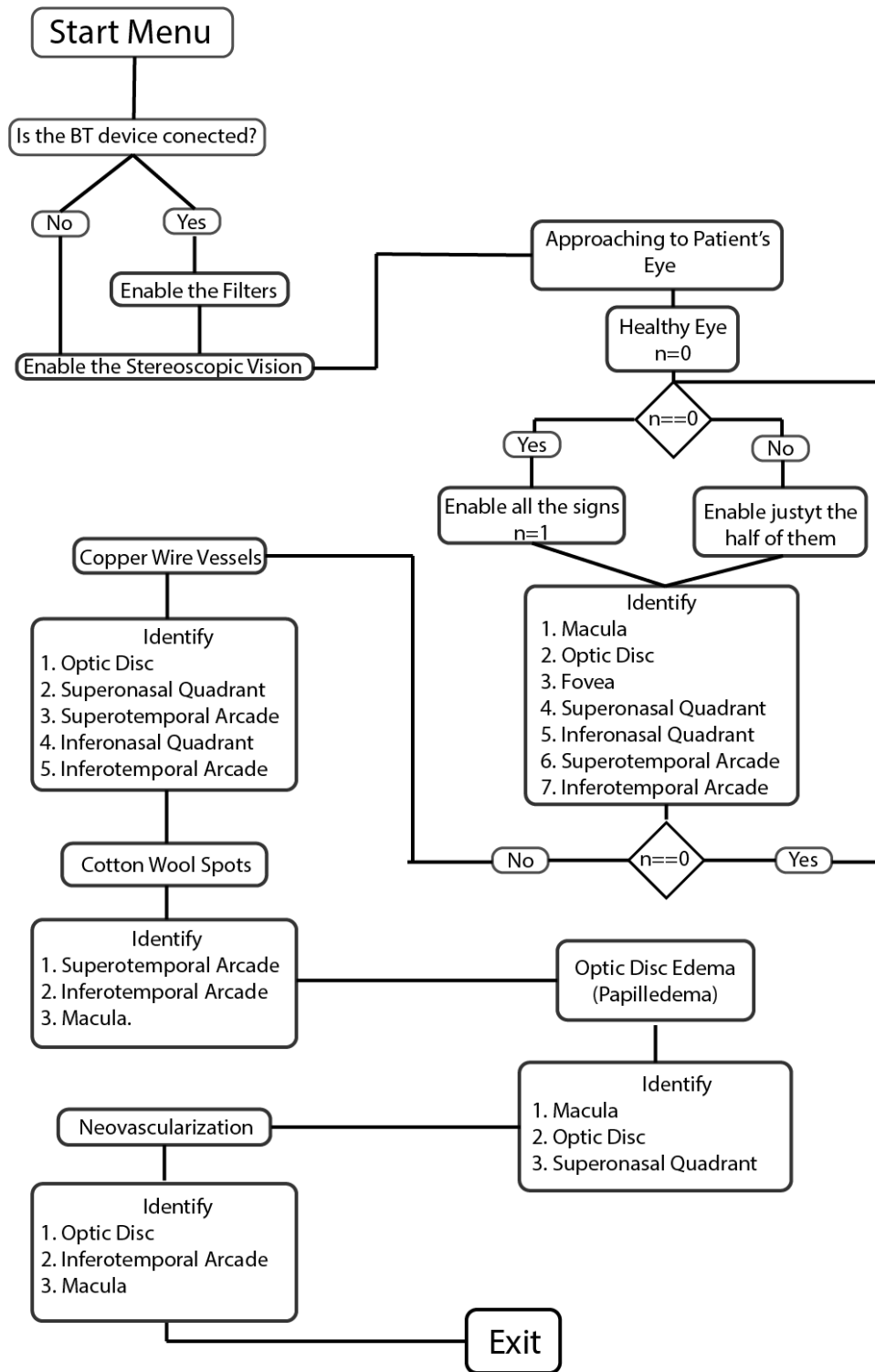
Figure 3-8: General Diagram of Software Design.

3.4.3 Copper Wire Vessels

In the Copper Wire Vessels case, the user is asked for finding the optic disc, the Superonasal Quadrant, Superonasal Arcade, Inferonasal Quadrant and the Inferotemporal Arcade. This

section is focused in the blood vessels exploration, so the user can see their appearance.

3.4.4 Cotton Wool Spots.

For the Cotton Wool Spots case, the user is asked for finding the elements around the macular area, so they can see the exudates and to determinate the current eye condition, also.

3.4.5 Papilledema

To identify the papilledema it is necessary to look at the optic disc edges seeing their blurred shape, so the application guides the user along this region, asking for finding the colliding elements such as the Macula, Optic Disc, and the Superonasal Quadrant as well.

3.4.6 Neovascularization.

The latest eye condition presents in the application is Neovascularization. For this eye condition, it is important to look at the macular area to find the new irregular blood vessels, so the program guides the user along of one of the main arcades, the optic disc, and the macular area, too.

3.5 Operating System Selection.
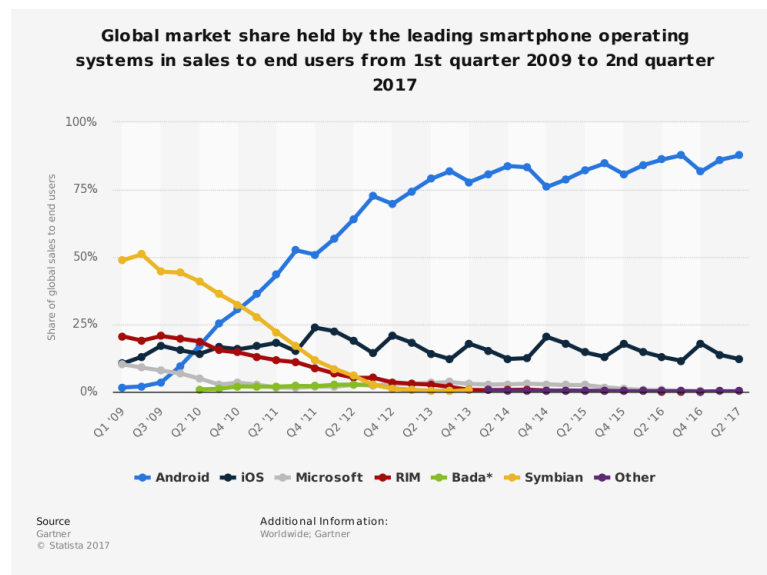
Figure 3-9: Global market share held by the leading smartphone operating systems in sales to end users from 1st quarter 2009 to 2nd quarter 2017 [76].

For this purpose, it is required of an operative system presents in the majority of smartphones in the world, that allows the replication of this project in other countries and devices without compatibility conflicts. Figure **3-9** presents the trending according to how many devices in the world are using determined operative systems. For this reason, Android is the OS we choose.

4 Development

This chapter presents the development of the application and the 3D printed ophthalmoscope prototype. It includes the visual components of the application, the electronic circuit design, and the 3D prototype model, to conclude with the general assembly.

4.1 Game Engines and 3D Programming Platforms.

The development of this application requires a game engine or 3D Programming platform to have the following characteristics:

- Developed documentation: A consolidated documentation to solve questions and issues with the platform.

- Compatibility with Android.

- Compatibility with Arduino.

- Stereoscopic Vision.

- Augmented Reality support.

- Support for Bluetooth connection and data transfer.

Due to these required elements, the choose Game Engine is Unity 3D.

4.2 Electronic Components

The selection of electronic components is thought to solve the prototype needs such as portability, Bluetooth connection and a sensor of angular position. To establish the connection between the sensor and the smartphone, the chosen system is composed by a Bluetooth unit and a processor to take and transform the analog information into a readable string in Unity 3D. Following, there is the chosen electronic components list.

- Arduino Nano: Arduino is a family of open-source computer hardware made for prototyping. It has friendly programming and a variety of educative content resources that allows people to work with it. Also, the Nano reference is the smallest version that includes a USB plug. Additionally, Arduino Nano works with a power source between 7 and 12 volts.

- Potenciometer: The potentiometer is the analog sensor to take Wheel's angular position. It might be of 1 Kilo ohms or more.

- Battery 9V: It is a standard commercial battery.

- Bluetooth module HC-05.

Due to Arduino Nano allows to be powered between 7 and 12V, it is not necessary to design or buy an external DC voltage regulator.

Figure **4-1** presents the schematic circuit of the prototype. There, the potentiometer is
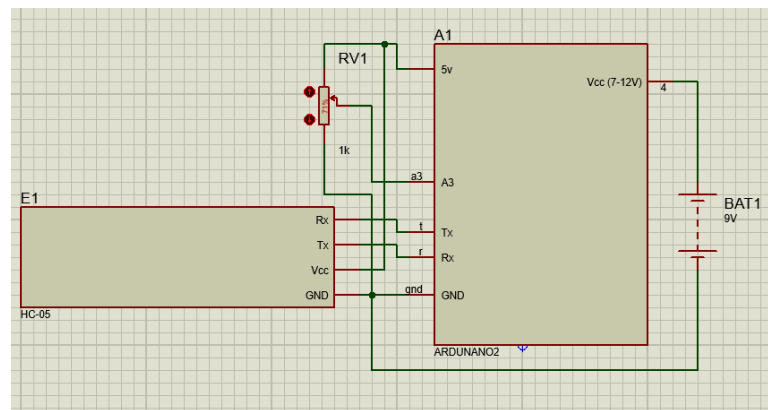
Figure 4-1: General electronic schematic.

powered to 5 V and it is connected to one of the Arduino analog pins, the Bluetooth unit is connected to Arduino's Transfer and Reception pins. The data-sheet of HC-05 module suggests to use an arrow of resistors, however, the device works fine without them. Finally, the Arduino Nano is powered by the battery.

CAD Modelling.

CAD Model defines the dimensional parameters the Direct Ophthalmoscope case has. As a reference, the 3.5V STANDARD OPHTHALMOSCOPE Welch Allyn is the base for the 3D Model. Following, there are the dimensions of the real direct ophthalmoscope.

- Height: 5.1 cm.

- Width: 8.6 cm.

- Depth: 4.5 cm.

- Radius: 1 cm.

However, it is important to know the dimension of all the electronic components to adjust them, so the handling is not influenced by them.
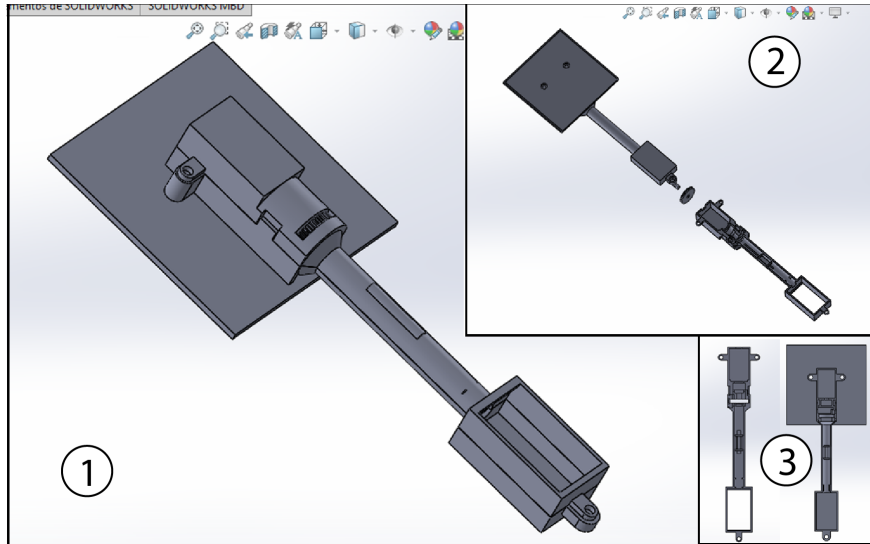
Figure 4-2: General 3D Assembly.

Figure **4-2** presents the prototype 3D model in isometric view (1), exploded view (2), and the front-back cases view (3).
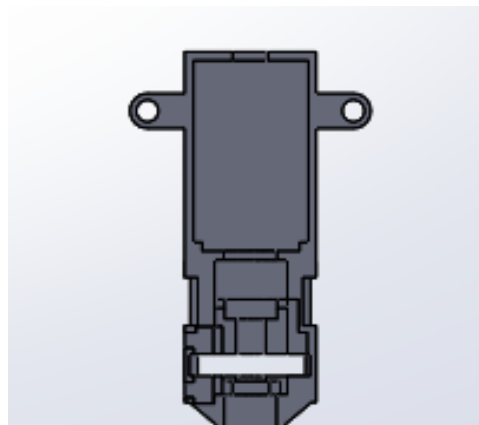
Figure 4-3: Model of Back Piece.

To model the case where the electronic components are in, it was necessary to take measurements of the Arduino Nano (4.318 cm x 1.8542 cm), HC-05 Bluetooth module (2.794 cm x 1.524 cm), and the potentiometer, so Figure **4-3** presents the top part of the back piece where these elements are in. Also, the 3D model includes a space for the required wires, and

a bed to have fixed the potentiometer, so its edge is the only mobile element there.
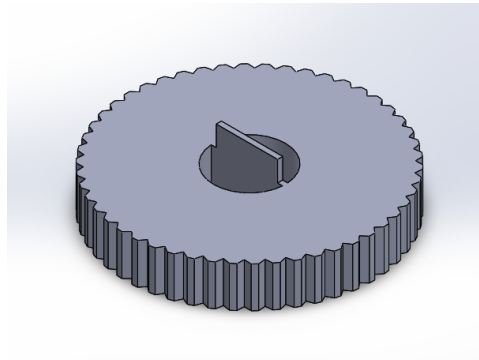
Figure 4-4: Wheel that is attached to potentiometer.

Finally, the wheel is the third 3D printed piece in the prototype. This one is the element the user interacts with to select a filter through its angular position, so it is assembled to the potentiometer edge.

4.3 Graphical User Interface

The graphical chosen distribution is horizontal, because that is the position the smartphone has using the headset.
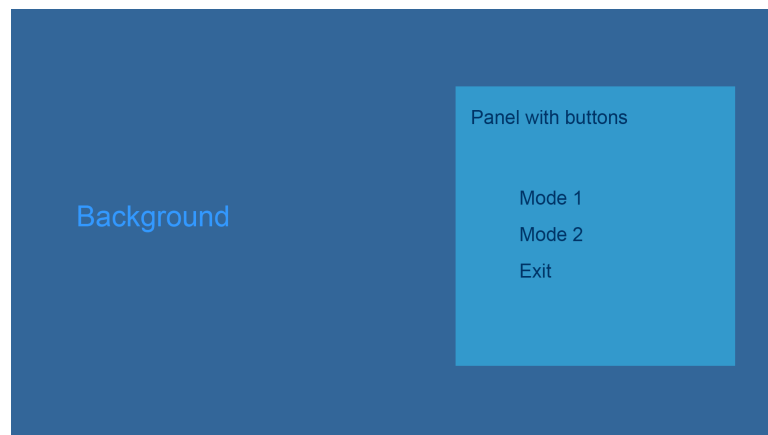
Figure 4-5: Start Menu.

4.3.1 Start Menu

The start menu comprises two main elements, the background and the Button Panel. The background has included the name of the application and a 3D model of direct ophthal-

moscope. In the other hand, the button panel has a button to start the training using the complete stuff, and another one to start the same training without headset, but that module is not included in this document. Also, an exit button to finish to close the application.

4.3.2 VR Training
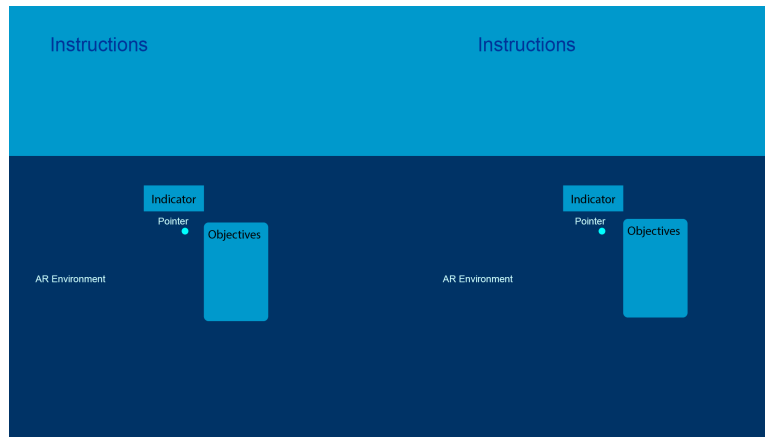
Figure 4-6: General interface for case 1. Play at Home.

.

The VR training has an interface comprising elements for providing useful information to the user for their guidance. that distribution is included in the Tutorial and the training as well. The interface is composed of the following components:

- Instructions Area: This area is in the top region where all the instructions are set up, so the user can read clearly what the application requires to.

- The pointer: This is the cursor, the element that the user uses to interact with the virtual components in the scene, the cursor.

- The indicator: The indicator is the element to offer a feedback to the user. This element is temporally available (1.5 seconds every time the user does a selection) and it makes the user knows if they are or not right.

- Objectives Panel: This panel contains a check list with the organs and areas the user has to identify in the application for each eye case presented in the application.

4.4 Visual Components

This section presents the current elements used in the virtual world.

4.4.1 Modelling Process

The application employs different 3D models, some of them were modelled using Blender 3D. Figure **4-7** presents the eye 3D model where all the different pathologies are in. That model comprises a mesh where the pathologies textures are set in, another one for the pupil, and finally, the sclera mesh.
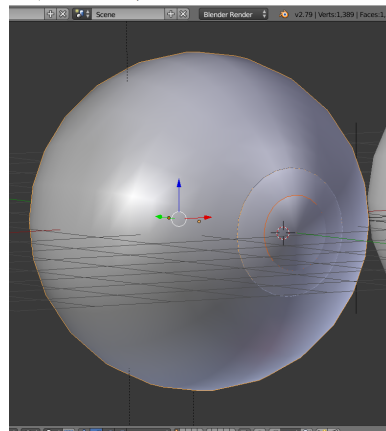
Figure 4-7: 3D Eye Model in Blender 2.76.

4.4.2 Texturing Process

All the model meshes use a base diffuse material; however, the textures are the images displayed in the mesh according to the UV mapping previously done. Figure **4-8** presents the texturing process and it is divided into four steps. Step A is the mapping process, so the mesh is projected over a 2D space. Step B is the resulting plane exportation, so it is saved as reference map image. Step C is finding the pathology image. Step D is the location of the pathology image in the reference map image. Finally, the resulting image is set up into the mesh material in Unity Engine.

4.5 AR Component

The AR component allows the device tracking and the interaction between the virtual scenario, and the real world for this project. To get the AR component it is required of two elements. The first one is the marker, the image of reference in the real world that is processed to get its current position and orientation. The second one is the image processing that requires a camera and a processor to calculate the current image position and orientation.

  For Unity there are a wide range of different tools and assets to use Augmented Reality,
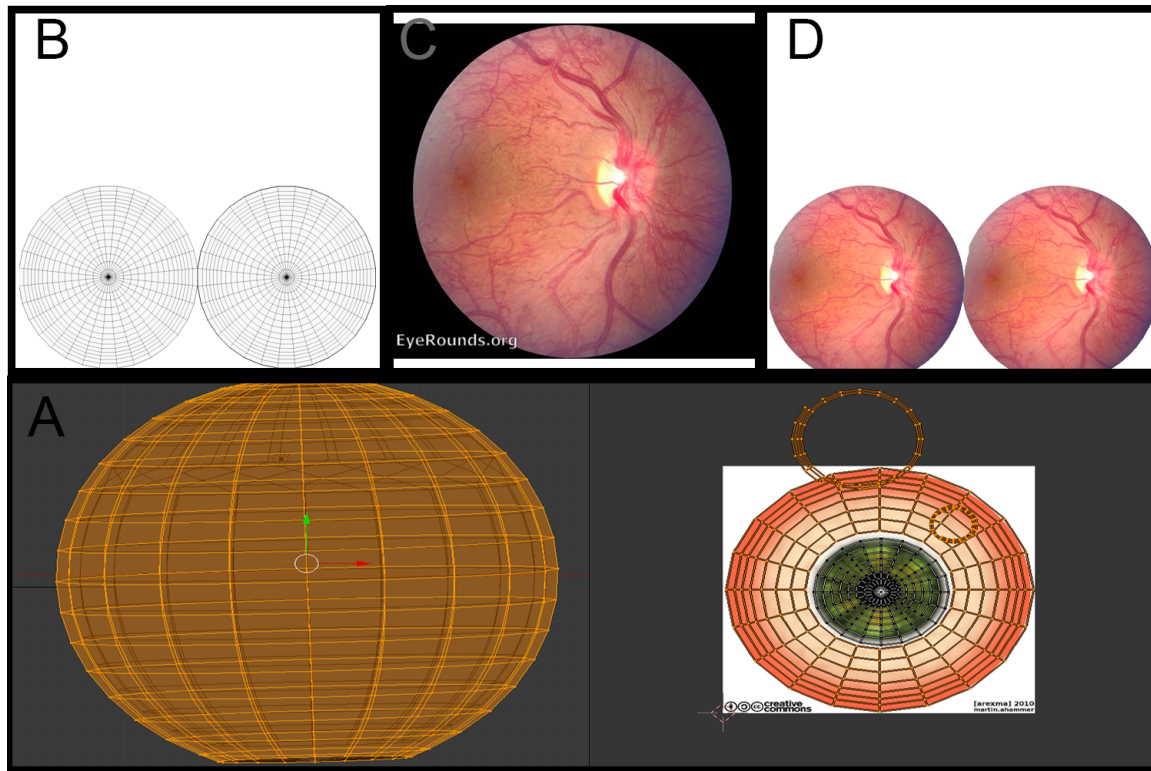
Figure 4-8: Texturing process.

Figure 4-9: Image target selection

however, the criteria to chose a specific tool for this project are related to:

- **Unity compatibility.**

- **Android compatibility.**

- **Documentation:** It is necessary to have documentation in case it is required help

to solve issues and errors.

- **Marker Customization**.

- **Well tracking**: It is very important to have a well tracking. The reason is to provide a training tool that does not require extra skills to the trainee to use it. A bad tracking might make them feel discomfort using the application.

In this point, there are two options that satisfy the above requirements, Vuforia and AR-Toolkit. Doing previous testings, ARToolkit did not render properly the 3D eye models in the smartphone, something that Vuforia met well, so Vuforia is the chosen tool for this purpose. To create the marker it was necessary to follow the following steps (see Figure **4-9**):

Step A: Image Selection. The chosen image is searched in a Creative Commons Zero (CC0) license stock, www.pexels.com, so legally, it is possible to use the chosen image, modify it, and replicate it.
Step B: Image Rating. Vuforia offers an online platform to rate the chosen image, and its valoration is directly proportional to the tracking capability.
Step C: Image Improvement. Also, it is necessary to add a texture to create more reference points and improve the image tracking for the application. That texture is from pexels.com as well, and as result, the Vuforia rating is five stars, so the marker is well trackable by the application.

4.5.1 Stereoscopic Vision

The stereoscopic vision is done using a duplication of the AR cameras in Unity, so there is a dual projection of the scenario in phone's screen, however, this is not the unique step to guarantee the stereoscopic vision, also, it is required to adjust some camera parameters to set up properly the visualization in the screen. These parameters are position in X and Y edges, and the size displaying W (width) and H (height). Those values were set up manually to be adjusted for a proper and clear visualization for Google Cardboard.

4.6 Software Programming

The software programming is approached in two main fields explained below for this application, communication, and validation.

4.6.1 Communication

This project uses the "Android & Microcontrollers / Bluetooth" asset for Unity, to make the Bluetooth communication possible between the smartphone and the ophthalmoscope prototype.
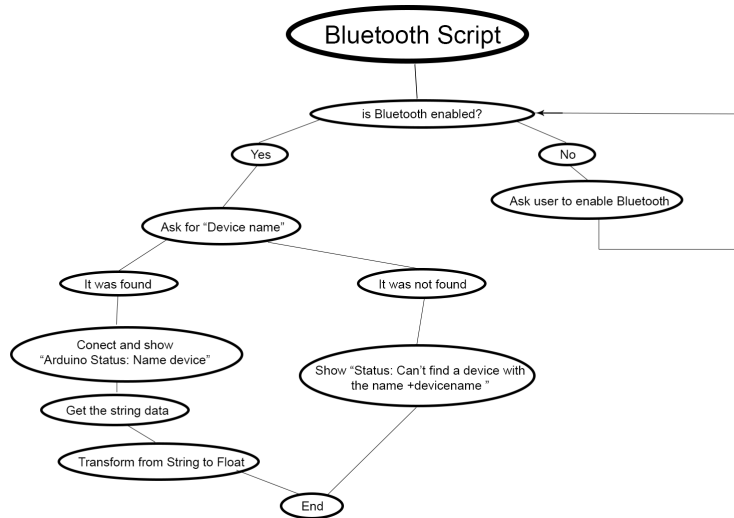
Figure 4-10: Communication Asset Diagram.

The communication script includes two main tasks (see Figure **4-10**). The first one is to look whether the phone Bluetooth connection is enabled or not, the second one is to ask if the there is a Bluetooth device named "HC-05" or not. If there is a Bluetooth device with that name, the program starts getting the data is coming from that device, then, that data (string) is converted to float, so the application can work with those values in other script.

4.6.2 Validation
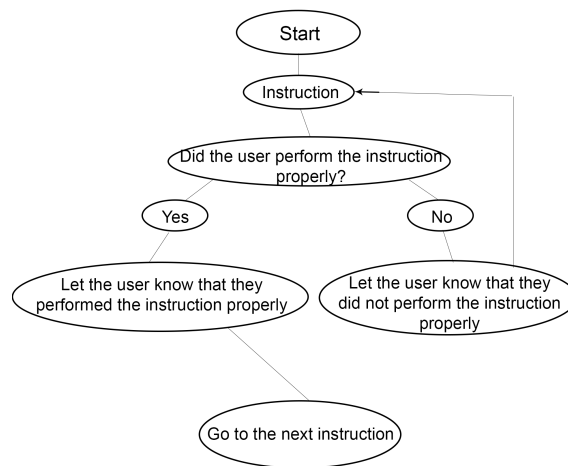
Figure 4-11: Diagram of validation scripts

The validation component in the program comprises an instruction, the verification whether that instruction was properly performed, and a feedback to the user (see Figure **3-7**). This component is present in each required identification case within the application, since the tutorial until the last pathology presented to the trainee in the ophthalmoscope simulator. It is important to highlight that the verification component will not change the instruction until the user identifies successfully the required element.

4.7 Assembly

In this point, it is important to have all the physic components ready and available to be joined each other, such as the 3D printed pieces, the circuit in the prototyping board, and also the external elements like the battery and screws. Figure **4-1** presents a step-by-step summarized guide to assembly the prototype.
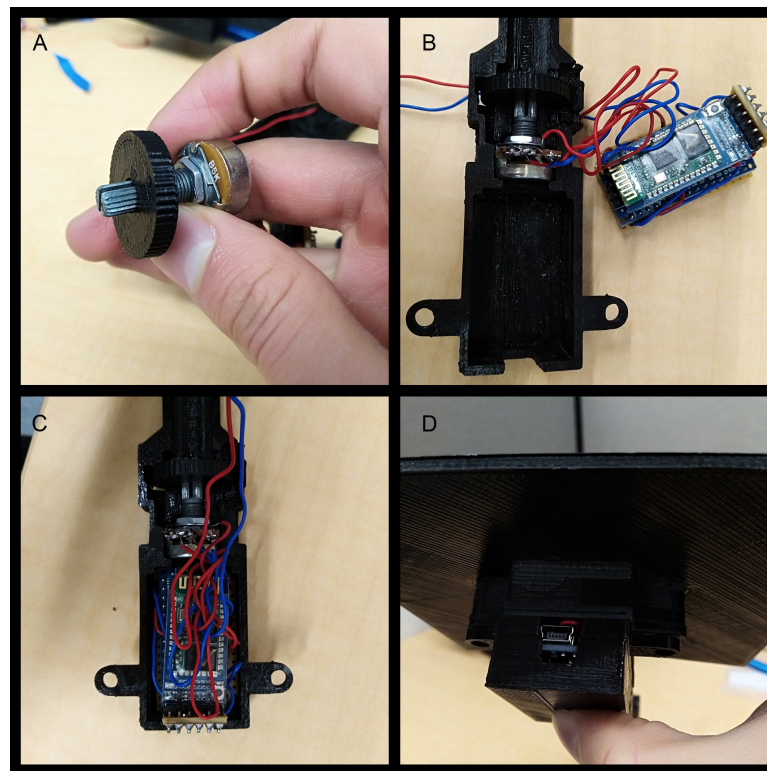
Figure 4-12: Step by step for the general assembly.

- **Step A:** Join the wheel to potentiometer's edge.

- **Step B:** Locate the potentiometer joint in the back case.

- **Step C:** Put the circuit in the back case.

- **Step D:** Join the front and back case each other using the screws.

5 Results

This chapter presents the components that the validation process comprises, it includes the System Usability Scale [77], the preliminary study, the analysis, and a general description of the final prototype.

5.1 System Usability Scale

The System Usability Scale is a test to determine the usability through a liker-scale, so it quantifies the user perception about how they are feeling using the element of study. This test uses ten statements with an agreement or disagreement scale for each one, generating a final score that defines the usability perception [77]. To calculate the final score, it is necessary to follow the steps bellow:

- Generate the average for each question

- for questions 1, 3, 5, 7 and 9, the contribution is the average minus 1. The final value is between 0 and 4. Then, multiply the value by 2.5.

- for questions 2, 4, 6, 8 and 10 the contribution is inverse, so it is needed to take 4 and subtract the average in the question minus 1. The final value is between 4 and 0. Then, multiply the value by 2.5

- Add all the values, the final score is between 0 and 100. If the test has a score over 68 points, the system would be considered above the average

5.1.1 Preliminary Study

The population selection comprises a range between first and third year medicine students (n=11). It means the chosen population includes students with and without knowledge about the eye semiology, it provides a general view to determine which are the elements to improve in the application itself.

5.1.2 Analysis.

The Table **5-1** presents the general result for SUS test. The final score for the application is 84.77, it indicates that participants found usable the Ophthalmoscope Simulator with

Table 5-1: SUS General Result.

Question/Scale	Average	SUS Value
I think that I would like to use this system frequently	4.45	8.63
I found the system unnecessarily complex	1.72	8.18
I thought the system was easy to use	4.27	8.18
I think that I would need the support of a technical person to be able to use this system	1.81	7.95
I found the various functions in this system were well integrated	4.63	9.09
I thought there was too much inconsistency in this system	1.36	9.09
I would imagine that most people would learn to use this system very quickly	4.36	8.41
I found the system very cumbersome to use	1.27	9.32
I felt very confident using the system	4.09	7.72
I needed to learn a lot of things before I could get going with this system	1.72	8.18
	SUS Score:	84.77

Augmented Reality, although it still requires improvements. The study in depth is presented in the percentile analysis.

5.1.3 Percentile Analysis

The Table **5-2** presents the percentage study for the SUS test. Those percentages represents the portion of students who chooses each agreement level for each assessment. Also, the study employed 11 medicine students from Universidad Militar Nueva Granada in Bogotá. Following there is the percentage analysis.

The first question has an agreement of 81.81%, during the process, the participants were excited with the simulator and they expressed curiosity about the device, and the procedure, in the case of first year medicine students who have not previous knowledge about eeye semiology and the fundoscopy neither. It means that they were interested in the simulator and if they have one, there is a possibility that they use it frequently. For the second question, more than 80% of students found the application unnecessarily complex, and this is actually good because the simulator uses the mixed reality, a technology a that is not commonly used for this purpose, even they expressed that they did not use this kind of technology before, so it is a good point for the simulator.

The third question is related with the second one, so the same percentage of students consider that the simulator is not complex and, in fact, the simulator is easy to use. In the other hand, the fourth question ask about if it is needed or not a technical person available for using the simulator. The same percentage considered that it is not needed a technical person.

Questions five and six are related each other and ask about the integration of the elements in the system, so the 81.81% of students consider the simulator as a well integrated tool, even almost the 90% of them expressed strongly disagree with the affirmation that the system is inconsistent.

The question seven ask for the learning speed to use the simulator, 9.09% of the students consider that the user might not learn quickly to use the simulator, other 9.09% is in the midpoint; however, the 81.81% of the participants consider that most people would learn to use the system quickly.

Questions eight and nine ask about the user experience, about what did they feel using the application. The big portion felt confident using the simulator and they were not cumbersome during the training, however, they expressed strange sensations looking around through the headset.

Finally in the last question, the 81.81% of the students considered that it is necessary to learn many things before to use the system, this point is important because there were students without the knowledge about eye semiology and they could finish the simulation well.

Table 5-2: Percentage Agreement and Disagreement.

Question/Scale	Strongly disagree	Disagree	Centre point	agree	Strongly agree
I think that I would like to use this system frequently	0%	0%	18.18%	18.18%	63.63%
I found the system unnecessarily complex	54.54%	27.27%	9.09%	9.09%	0%
I thought the system was easy to use	9.09%	0%	0%	36.36%	54.54%
I think that I would need the support of a technical person to be able to use this system	45.45%	36.36%	9.09%	18.18%	0%
I found the various functions in this system were well integrated	0%	0%	9.09%	18.18%	72.72%
I thought there was too much inconsistency in this system	81.81%	9.09%	0%	9.09%	0%
I would imagine that most people would learn to use this system very quickly	0%	9.09%	9.09%	18.18%	63.63%
I found the system very cumbersome to use	81.81%	9.09%	9.09%	0%	0%
I felt very confident using the system	9.09%	0%	18.18%	18.18%	54.54%
I needed to learn a lot of things before I could get going with this system	54.54%	27.27%	9.09%	9.09%	0%

Table **5-3**: Variance and Standard Derivation for SUS Result

Participant	SUS score	Variance	Total Variance	Standard Derivation
01	92.5	59.71		
02	92.5	59.71		
03	87.5	7.44		
04	97.5	12.72		
05	100	15.23	227.79	15.0927
06	62.5	496.07		
07	77.5	52.89		
08	67.5	298.34		
09	97.5	161.98		
10	57.5	743.8		
11	100	231.87		

Also, the Table **5-3** presents a variation around 15 points in the SUS score, so the minimum range is since 69 points until almost the 100 points in the SUS, indicating that the most of the scores present the application as usable, and over the average; however, there are data dispersed under that range such as it is the case for the participant whose SUS score is 57.5, the lowest score for in the test.

5.2 Simulator.

Figure **5-1**: General view of the simulator.

Figure **5-1** presents the general view of the ophthalmoscope simulator itself. In summary, the system comprises a mobile application offering a stereoscopic vision in the Augmented

Reality environment, a start menu, a 3D Printed prototype and a user Manual (see Figure **5-2**) that includes the instructions to replicate the project, assembly instructions, installation, and training.

Figure 5-2: User Manual to replicate the simulator

5.3 Publications.

- D. Acosta, A. Uribe, B. Kapralos, N. Jaimes. Development of a smartphone augmented reality eye examination tool. INTED 2017, valencia, Spain, 6-8 March, 2017 (Conference).

- M. Nguyen, D. Acosta, D. Gu, A. Uribe, B. Kapralos, M. Jenkin and K. Kanev ,Virtual Eye Fundus Examination. SimOne Expo 2017, Mississauga, ON, Canada, 30 November - 1 December, 2017. (Demo).

6 Conclusions

Using the current available technologies such as 3D printing, prototyping micro-controllers like Arduino, and free game engines like Unity 3D, it is possible to design and build a prototype of simulator for eye examination that allow to offer a different experience to complement the traditional training without the need of wait for a patient volunteer, or expensive manikins.

Due to the simulator requires elements such as a smartphone, a headset like Google cardboard, and technologies for prototyping, it is possible to reply it in different countries with an inversion lower than 100 USD, it makes this project accessible for many people in the world. This project helps not only to memorize the eye fundus anatomical information, but it allows to identify those elements in different cases of the normal eye, such as Cotton Wool Spots, Neovascularization, Copper Wire Vessels and Papilledema, it allows to detect that something is wrong inside the eye and that it might be a sign of a pathology.

Eye fundus examination is a commonly procedure performed for professionals in the world; however, a proper fundoscopy allows to detect anomalies inside the eye, but to get it, it is necessary to have some skills to do this procedure, and those skills are got with training. So this kind of technologies try to support that training looking for new alternatives or tools to complement the traditional learning and training.

One of the most important things to keep in mind is that the kind of technology does not matter to bring new experiences that allows, at least, to make medicine students feel comfortable during their training. It was possible to see with this project that used mixed reality that, in fact, it is a technology in development by different brands and devices.

6.1 Future work

This application has many improvements to do in the future, it means that it is possible to add different features to create a better experience, such as the inclusion of a score system, the inclusion of the tutors in the simulator providing the possibility to give a kind of feedback to them. It is important to see the possibility to improve the interaction with the virtual patient such as the inclusion of animations and other factors that are related with the patient behaviour to give a more realistic experience to the students. Finally, the improvement for the 3D models would be planed, so the student might feel the deepness sense with models that include the blood arcades modelled in 3D because all the blood vessels are part of the

internal textures for each models. Also, it is possible to thing in other user interface where all the interactions with the mixed reality are more intuitive than the current one.

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