Sara Isabel Pires de Oliveira

INTEGRATED INSTRUMENTATION OF A DIRECT OPHTHALMOSCOPE

Thesis submitted to the University of Coimbra in fulfillment of the requirements for the degree of MSc. in Biomedical Engineering under the scientific supervision of PhD João Manuel Rendeiro Cardoso.

September 2016

Universidade de Coimbra
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Dissertation submitted to the University of Coimbra to fulfill the requirements of the Master of Science in Biomedical Engineering program

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“Whatever you are, be a good one”
William Tackeray

Aos meus pais, João e Elisabete
e em memória dos meus avós, João e Manuel
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A todos, um sincero obrigado!
Abstract

Due to the transparency of the anterior ocular structures, the retina can be seen non-invasively from the outside, for example, with a direct ophthalmoscope. The inspection of that highly metabolically tissue is of the most interest for clinicians, not only for ophthalmologists, as it is an excellent way to detect eye and systemic diseases. Therefore, the necessity of store, share and reassess the retinal exams are of utmost importance in the clinical environment. However, the most part of the ophthalmoscopes do not present any data recording system. This ophthalmoscope limitation has been identified and served as motivation for this work.

The main goal is to redesign an ophthalmoscope, the PanOptic™ ophthalmoscope, from Welch Allyn, with a built-in acquisition system that not compromise the observation protocol of examination by direct ophthalmoscopy. This approach has an evident advantage in clinical environments where there is no easy access to a conventional fundus camera, such as in emergency room and for examination of bedridden and/or uncooperative patients. In addition, it would provide a better way of data storage, sharing and reassessment of retinal exams. Furthermore, such device would be essential in an educational environment because it would allow an efficient monitoring, in real time, of the student’s technique of examination, during their internship and learning process.

Initially, the fundamental requirements of the device have been identified, with the assistance of a specialist (neurologist). After this step, the project start with the understanding of the internal structure of the PanOptic™ ophthalmoscope and its way of work. Two possible prototype architectures were idealized and analysed in a bench test and from there the prototype was designed. The successive modifications were tested using an artificial target (an eye model developed during this work) and in vivo. The prototype structure was designed based on the PanOptic™ ophthalmoscope and its optical components were reused. The illumination system was redesigned and an acquisition system was introduced in the internal structure of the device.

Despite the acquisition of retinal images with good quality was not possible, it can be concluded that the project was successfully developed to meet the identified clinical necessities, in compliance with the objective of acquiring images of the eye fundus simultaneously with the direct visual inspection. In fact, the acquired images have proved that the construction of an ophthalmoscope with an internal image acquisition system is possible.

**Keywords:** ophthalmoscopy, optical instrument, direct ophthalmoscope, PanOptic™ ophthalmoscope, digital retinal imaging, prototype design
Resumo

Sendo o olho formado por estruturas transparentes, é possível ver a retina de forma não invasiva usando, por exemplo, um oftalmoscópio direto. O exame desta estrutura com elevada atividade metabólica é da maior importância para alguns clínicos, que não apenas os oftalmologistas, uma vez que permite o diagnóstico de doenças, não só oculares, mas também sistêmicas. Assim, o armazenamento, a partilha e a possibilidade de reavaliar exames retinianos são da maior importância em ambiente clínico. No entanto, a maior parte dos oftalmoscópios não permite a aquisição de imagem. Esta limitação foi identificada e serviu de motivação para este projeto.

O objetivo deste projeto é redesenhar e adaptar um oftalmoscópio, mais concretamente o oftalmoscópio PanOptic™, da empresa Welch Allyn, para incorporar um sistema de aquisição de imagem na sua estrutura, de forma a não comprometer o protocolo de exame da retina por oftalmoscopia directa. Esta abordagem apresenta vantagens evidentes em ambientes clínicos em que não é possível o acesso fácil a uma câmera de fundo convencional como, por exemplo, no serviço de emergência ou na observação de doentes acamados e/ou pouco colaborantes. Para além disso, este tipo de dispositivo permitirá o armazenamento, a partilha e a reavaliação de exames retinianos. Em ambiente académico, um oftalmoscópio com estas características será também muito importante, já que permitirá uma melhor e mais eficaz avaliação da técnica de exame dos alunos de Medicina, durante o processo de aprendizagem.

No início do projeto foram identificados todos os requisitos necessários para o dispositivo junto de um especialista (neurologista). Para além disso, foi feito o reconhecimento da estrutura e do modo de funcionamento do oftalmoscópio e assim, foram idealizadas duas arquitecturas. Depois de realizar testes de bancada e, de acordo com os resultados obtidos, o protótipo começou a ser desenvolvido. As sucessivas modificações foram sendo testadas com um alvo artificial (desenvolvido durante este projeto) até ser obtido o protótipo final, que também foi testado in vivo. A estrutura do protótipo foi desenvolvida com base no oftalmoscópio PanOptic™ e foram usados os seus componentes óticos. O sistema de iluminação foi redesenhado e foi introduzido um sistema de aquisição de imagem no interior do dispositivo.

Apesar de não ter sido possível obter imagens da retina com boa qualidade, pode concluir-se que o projeto apresentou avanços para o cumprimento das necessidades dos clínicos, cumprindo o objectivo de validar a possibilidade de adquirir imagens retinianas em simultâneo com a visualização directa. De facto, as imagens adquiridas provam ser possível a construção de um oftalmoscópio com um sistema de aquisição de imagem embutido.

**Palavras-chave:** oftalmoscopia, instrumento óptico, oftalmoscópio directo, oftalmoscópio PanOptic™ imagem retiniana digital, design de protótipo
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Chapter 1

Introduction

This chapter intends to present the motivation behind this project as well as its main objective. It is also presented the previous work developed and the team project colleagues, that contributed for the development of this project. At the end, the master thesis structure is presented.

1.1 Motivation

The cameras usually used for retinal photography, such as fundus cameras, provide high quality images but are, in general, expensive, require pupil dilation and should be operated by a highly skilled and trained operator. Moreover, these devices are large and bulky systems, with a fixed position, requiring the movement of the patient to where they are located. For all that reasons, it is necessary to have a compact, lower input power and hand-held device, with proper illumination of the retina and an image acquisition system, that enables a wide field of view of the eye fundus [1].

An ophthalmoscope is a passive optical device with an integrated illumination system that enables the observation of the retina by direct visual inspection. Currently, the recording of images obtained by direct ophthalmoscopy is only possible with an external coupled digital camera. Furthermore, there are some optical devices, called hand-held fundus cameras, that have an internal camera with a coupled external LCD that displays video and image. With the development of technology, have also emerged smartphone applications that use the existing camera and software of the phone to acquire/show retinal images. However, none of these options are suitable for an efficient clinical use, since they require changes of the exam protocol. With this type of device, the clinician does not have the opportunity to perform a
direct inspection of the retina which, because the lack of position references, turns
the examination more difficult.

To overtake this limitation, it is intended that the acquisition of fundus images
could be performed by a built-in acquisition system, without compromise the obser-
vation protocol and the procedure of examination by direct ophthalmoscopy.

The approach intended with this project has an evident advantage in clinical en-
vironments where there is no easy access to a conventional fundus camera, such as
in emergency room and for examination of bedridden and/or uncooperative patients.
In addition, it would provide a better way of data storage, sharing and reassessment
of retinal exams. Furthermore, such device would be essential in an educational envi-
ronment because it would allow an efficient monitoring, in real time, of the student’s
examination technique, during their internship and learning process.

1.2 Goals

The goal of this project is to adapt and redesign a direct ophthalmoscope, more specif-
ically, the PanOptic™ ophthalmoscope from WelchAllyn, frequently used in clinical
practice, in order to allow digital image acquisition (photo and video) during the
ocular fundus examination, without compromise its traditional way of use. In detail,
the project aim the reset of the optical configuration and the addition of an internal
image acquisition system.

1.3 Previous work

Preliminary work in this scope, with similar goals to this project, have been per-
formed by MSc Taissa Pereira, in 2011, as hers final project to obtain the master of
science degree in biomedical engineering [2], at University of Coimbra. The project
was developed in Blueworks and in the optics laboratory at Institute of Biomedical
Research in Light and Image (IBILI). Several prototypes were idealized and tested
which had resulted in a case with an image sensor that fits, externally, into the
PanOptic™ ophthalmoscope. Although the final prototype allows the video/image
acquisition, it is not possible to acquire images while the physician is examining the
patient’s eye [2,3].
1.4 Main project team

This project was suggested by M.D. João Lemos, neurologist from Centro Hospitalar da Universidade de Coimbra - CHUC and it was developed with the contribution of PhD João Manuel Rendeiro Cardoso, MSc Pedro Guilherme da Cunha Leitão Dias Vaz and PhD Luís Filipe Requicha Ferreira, from Electronics and Instrumentation Group (GEI) of University of Coimbra, and M.D. João Manuel da Fonseca Gomes de Lemos, as scientific and technical supervisors.

1.5 Document overview

This thesis is composed by 6 chapters. In chapter 1 an introduction of the project is presented, that includes the motivation of the project, its goals, the previous work developed, the project team and the structure of the thesis. In chapter 2 an ophthalmological background is presented, which includes the anatomy of the eye, the history of ophthalmoscopy, an overview of the ocular fundus examination in clinical practice and the differences between the two types of ophthalmoscopes (direct and indirect). The state of the art of the current devices used for direct ophthalmoscopy is presented in chapter 3. In chapter 4 the method used to develop this project is presented and its results are showed and discussed in chapter 5. Finally, in chapter 6 the conclusions are presented, as well as the future work of this research.
Chapter 2

Ophthalmological background

In this chapter the anatomy and physiology of the eye is presented, as well as the history of ophthalmoscopy and an overview of the retina examination. It is also presented the ophthalmoscope designs, addressing their main characteristics and the major differences that distinguishes them. As in this project it was used a direct ophthalmoscope, it is described the procedure of retinal inspection with this device.

2.1 Eye’s anatomy and physiology

The eye is a sensory receptor that focuses light on the retina - a light-sensitive surface at the back of the eye - using a lens and the pupil - an aperture whose diameter increase or decrease in order to adjust the amount of entering light [4]. The focus is maintained on the retina at different distances between the object and the eye by muscular contractions that change the thickness and curvature angle of the lens. The energy bandwidth of visible light (wavelength between 400 nm and 700 nm) is transduced into nerve impulses by the photoreceptors of the retina. The electrical signal is then transmitted to the optical cortex of the brain, by the optic nerve, where it is interpreted [5].

Light enters the eye through the cornea, a transparent layer of tissue that forms the anterior part of the sclera. After passing through the opening of the pupil, it reaches the lens: a crystalline and biconvex structure. The portion of the eye located behind the lens is filled with a thick, viscous substance known as the vitreous humour, that helps to maintain the shape of the eyeball and gives the retina an even surface for the reception of clear images. The cornea and the lens together bend incoming light rays to focus on the retina (figure 2.1 and table 2.1) [4–6].
### Table 2.1: Structures of the Human Eye (adapted from [5])

<table>
<thead>
<tr>
<th>Structure</th>
<th>Localization</th>
<th>Composition</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibrous tunic</td>
<td>Outer layer of eyeball</td>
<td>Avascular connective tissue</td>
<td>Provides location and support for rods</td>
</tr>
<tr>
<td>Sclera</td>
<td>Posterior outer layer, white part of the eye</td>
<td>Tightly bound elastic and collagen fibers</td>
<td>Supports the lens through suspensory ligaments, determines its thickness and secretes aqueous humor</td>
</tr>
<tr>
<td>Cornea</td>
<td>Anterior surface of eyeball</td>
<td>Dense connective tissue - transparent</td>
<td>Supports the lens, protects the eyeball from damage, and transmits and refracts light</td>
</tr>
<tr>
<td>Vascular tunic</td>
<td>Middle layer of eyeball</td>
<td>Highly vascular pigmented tissue</td>
<td>Supplies blood to the eyeball and maintains the shape of the eyeball</td>
</tr>
<tr>
<td>Retina</td>
<td>Prismatic portion of internal tunic</td>
<td>Photoreceptors, neurons (rods and cones)</td>
<td>Transmits and transduces impulses to the brain</td>
</tr>
<tr>
<td>Ciliary body</td>
<td>Anterior portion of vascular tunic</td>
<td>Smooth muscle fibers and glandular epithelium</td>
<td>Supports the lens through suspensory ligaments, determines its thickness and secretes aqueous humor</td>
</tr>
<tr>
<td>Iris</td>
<td>Anterior portion of vascular tunic</td>
<td>Pigment cells and smooth muscle</td>
<td>Regulates the diameter of the pupil and hence the amount of light entering the eye</td>
</tr>
<tr>
<td>Lens</td>
<td>Between posterior and vitreous chambers</td>
<td>Transparent tightly arranged protein fibers</td>
<td>Refracts light and focuses it onto the fovea (area of sharpest vision)</td>
</tr>
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2.1. EYES ANATOMY AND PHYSIOLOGY
2.1.1 Retina

The internal layer of the eyeball, the retina, profiles the posterior 3/4 of the eyeball and it is the start of the visual pathway [6]. This structure is located in the back of the eye. When observed through the pupil with an ophthalmoscope, the retina presents a criss-crossed pattern with small arteries and veins that nourish the anterior surface of the retina. They all enter/exit from one spot, the optic disk, that is also where the neurons of the visual pathway form the optic nerve and exit the eye (figure 2.2(a)) [4,6].

Retinal layers

The retina consists in two layers: an external pigmented layer and an internal neural layer. The pigmented layer is composed by epithelial cells with melanin and it is placed between the choroid and the neural layer. Melanin absorbs stray light rays, which prevents reflection and scattering of light inside the eyeball, ensuring a sharp and clear image on the retina. The neural layer is an extension of the brain responsible for visual data processing, before sending electrical impulses through the optic nerve. This layer contains three major types of retinal neurons - photoreceptors, bipolar cells and ganglion cells - separated by two zones, the outer and inner synaptic layers, where synaptic contacts happen (figure 2.2(b)) [5,6].
Photoreceptors

The photoreceptors are the neurons responsible for the conversion of light into electrical signals and are divided into two types: rods and cones. Both photoreceptors contain molecules, called pigments, that disassociate in response to light - photochemical reaction that produces action potentials in the optic nerve [5]. Rod allows vision with low light and are used in night vision, when objects are seen in black, white and shades of grey, rather than in color. Cones are responsible for high-acuity vision and...
color vision during daytime, when light is brighter. There are blue, green and red cones which are sensitive to blue, green and red light, respectively. The stimulation of various combinations of the three types results in color vision.

The sharpest vision region, responsible for the highest visual acuity - the fovea - has a very high density of cones (20:1 ratio of cones and rods). From photoreceptors, visual information flows to bipolar cells, and from there to ganglion cells, which axons extend posteriorly to the optic disc and exit the eyeball as the optic nerve (figure 2.2). The optic disc is known as a blind spot, as it is not possible to see any image that strikes this site, because it contains no rods or cones. [4,6].

2.2 Ophthalmoscopy - historical background

There have been attempts to peek into the unknown back of the eye since the 18th century. However, only in the mid 19th century, several scientists noticed that if they kept a light source pointed at the subject very near the eye, in case of an emmetropic eye (the light focuses accurately on the retina and the vision is perfect), they could view the red reflex of the retina [10,11]. Before the invention of the ophthalmoscope, Purkyně had observed that under certain conditions of illumination the human eye could be made luminous and in 1825 he started to use lenses to examine the back of the eye [12]:

"I examined the eye of a dog by using the spectacle lens of a myope and placing a candle behind the dog's back... I found the light as the source, which is reflected from the concavity of the spectacle lens into the interior of the eye. From there it is again reflected. I immediately repeated the experiment on a human eye and found the same phenomenon."

- Jan Evangelista Purkyně [12]

Charles Babbage, in 1847, was the first to construct an instrument for looking into the eye and it was probably the first practical ophthalmoscope (figure 2.3(a)). It was a simple piece of mirror with a central silver patch rubbed off to make it transparent [10,11].

A few years later, Helmholtz tried to obtain an image of the retina by conceiving an instrument that would allow his own eye to be placed in line with the light ray entering and leaving the eye of the subject. In 1851, he achieved that using three essential components: a light source, a mirror to guide light towards the subject's eye and a device to focus the image on the retina. This instrument was known as
2.3 FUNDOSCOPIC EXAMINATION IN CLINICAL PRACTICE

Figure 2.3: Ophthalmoscope origins (adapted from [10]).

‘Augenspiegel’, that means eye mirror (figure 2.3(b)) [12]:

”(...) It is, namely, a combination of glasses, by means of which it is possible to see the dark background of the eye, through the pupil, without employing any dazzling light, and to obtain a view of all the elements of the retina at once, more exactly than one can see the external parts of the eye without magnification, because the transparent media of the eye act like a lens with magnifying power of twenty. The blood vessels are displayed in the neatest way, with the branching arteries and veins, the entrance of the optic nerve into the eye, etc. (...) My discovery makes the minute investigation of the internal structures of the eye a possibility.”

- Hermann Von Helmholtz [12]

So, Helmholtz is recognized as the inventor of the direct ophthalmoscope that inspired a golden age of ophthalmology that included the first in vivo descriptions of central retinal artery occlusion in 1855, papilledema in 1860, and optic disc atrophy in 1861 [13]. This invention was followed by many technical variations that improved illumination, reflection and refractive errors of both patients and physicians. Rekoss added movable lenses for easier focusing and Epkens introduced a mirror with a hole for increase illumination [12, 14].

2.3 Fundoscopic examination in clinical practice

As the function of the eye requires, the anterior ocular structures are optically transparent so, with proper techniques, the retina is visible from the exterior, non-invasively. Being a highly metabolically tissue, the inspection of the retinal is an
excellent way to detect, diagnose and manage eye diseases, as well as systemic diseases that also affect the retina [15]. As the retinal microvasculature is part of the brain’s vascular system, responding to stress and disease the same way, this structure also helps to predict neurovascular diseases. Furthermore, the retinal ganglion cell layer projects axons to the brain, through the optic nerve, and consequently neuro-degenerative diseases can be detected in retina [16].

2.3.1 Possible pathologies diagnosed with retinal imaging

As it allows the diagnosis of many medical conditions, the ocular fundus examination have influence in clinical decision making and in patient outcomes [13], being important for more clinicians than just ophthalmologists [17]. In comparison to the ophthalmologist, the internist, neurologist or pediatrician look, essentially, for funduscopic manifestations of systemic disease and less for local ocular disease [16]. For example, for the ophthalmologist, the fundoscopic exam is essential in the identification of retinal detachment (figure 2.4 - 4), glaucoma and macular degeneration (figure 2.4 - 6). For the neurologist it is important for the identification of, for example, papilledema (figure 2.4 - 7), optic disk pallor and retinal vascular occlusion (figure 2.4 - 3).

Some systemic diseases can be diagnosed with the observation of the fundus, by the identification of retinal manifestations. For example, diabetic retinopathy (figure 2.4 - 2 and 8) is a complication of diabetes mellitus, hypertensive retinopathy (figure 2.4 - 5) is related to systemic hypertension and pathologies of the retinal vascular network can be related to stroke and cardiovascular disease [16].

Features of interest in an ocular fundus image

In a fundus image, the optic nerve is a reference point and a feature of interest to indicate the neurologic health status. Moreover, the measurement of parameters such as the vessel diameter, bifurcation geometry, vascular tortuosity and global complexity of the vascular network is used to evaluate the state of the microvasculature and, consequently, to identify systemic diseases. The retinal microvascular network is optimized for efficient flow, therefore deviations from this optimal state may be related to vascular damage (figure 2.5) [16].
2.3. FUNDOSCOPIC EXAMINATION IN CLINICAL PRACTICE

Figure 2.4: Some pathologies that can be diagnosed by fundoscopic examination (adapted from [18]). (1) Healthy Fundus, (2) Non-Proliferative Diabetic Retinopathy, (3) Central Retinal Vein Occlusion, (4) Retinal Detachment, (5) Hypertensive Retinopathy, (6) Macula Degeneration, (7) Papilloedema, (8) Proliferative Diabetic Retinopathy.

Figure 2.5: Features of interest in an ocular image (adapted from [16]).
2.4 Ophthalmoscope Designs

The ophthalmoscope consists in an optical instrument designed for the visual examination of the structures of the inner eye. It has three fundamental parts: an illumination system, a reflecting device and a viewing system. The illumination system is essential to increase the amount of light that enters the eye and, consequently, is reflected by the retina, in a way that the observer can see an image of the fundus of the eye. The reflecting device, responsible for directing light into the patient’s eye, can be either a mirror or a reflecting prism. The viewing system allows the observer to see the light reflected from the subject’s eye [8,19,20].

An ophthalmoscope can be conceptually classified as direct or indirect depending on the assembly of its viewing system. Using the direct ophthalmoscope the retina is seen directly and using the indirect ophthalmoscope it is observed an image of the retina [11].

2.4.1 Direct Ophthalmoscope

A direct ophthalmoscope is a small hand-held device generally used as a preferred instrument for routine inspection of the eye’s fundus. This device consists in an optical system used to direct the emitting light (figure 2.6 - 7) into the patient’s eye (figure 2.6 - P). The light emerging from the patient’s eye passes back into the same optical axis, forming an upright and virtual image of a small portion of the retina, directly on the observer’s fundus (figure 2.6 - O). The main idea behind the optical design of the direct ophthalmoscope is that the illumination axis have to be as close as possible of the observer’s viewing axis. This is achieved using a mirror/reflecting prism (figure 2.6 - 1) to conduct the illuminating beam into the patient’s eye, as detailed in figure 2.6. [20–24].

If both the patient and examiner are emmetropic, the light rays reflected from the patient’s retina emerge parallel and will be focused in examiner’s retina without any accommodative effort [21]. The standard direct ophthalmoscope is constructed only with lenses (figure 2.6 - 3 to 6) to focus the light onto the mirror/reflecting prism [24]. However, additional spherical lenses (figure 2.6 - 2) can be introduced in the visual path in order to correct any refractive errors (myopia and hypermetropia), in either the observer or patient [8,25].

Direct ophthalmoscopy has a magnified view of the retina that permits an easier perception of small and/or dynamic changes of the ocular fundus. The wide avail-
ability and portability of the direct ophthalmoscope make it suitable to use when other methods are unavailable. Furthermore, this device is relatively low cost and it has a practical use for critical care patients [13]. However this technique is difficult to master and requires considerable practice to reach the proficiency needed. It has a small field of view (FOV), that makes the scanning of the entire retina difficult and it also has undesirable reflections of the anterior ocular structures, particularly the cornea [13, 25].

Direct ophthalmoscopy procedure

The procedure to exam the fundus of the eye by direct ophthalmoscopy is composed by several steps that should be followed to obtain satisfactory results:

- The examining room should be semi or completely darkened (but it is not mandatory);
- The patient is asked to look, straight ahead, at a point as far as possible in the room, which will help to keep the eye relaxed and the pupil dilated;
- To examine the patient’s right eye, the practitioner stands at the patient’s right side and uses the right hand and the right eye, and vice versa;
- The ophthalmoscope is held vertically in front of the practitioner’s eye with the
light beam directed towards the patient’s eye (the head/hand/ophthalmoscope should be moved as one unit);
- The exam starts at about 15 cm from the patient and slightly to the temporal side (about 15 - 25° from center), where the red reflex of the retina should appear;
- In case of refractive errors (from the patient, the practitioner or both) the focusing wheel should be adjusted, to focus the red reflex;
- The practitioner rests his free hand on the patient’s forehead, holding the upper lid of the eye with the thumb, and slowly moves towards the patient following the red reflex until the retina is seen;
- To look around the retina the practitioner should ”pivot” the ophthalmoscope, angling up, down, left and right [26,27].

2.4.2 Indirect Ophthalmoscope

An indirect ophthalmoscope consists in a head-mounted illumination and viewing systems (figure 2.7 - 2 to 7) and a hand-held condensing lens (figure 2.7 - 1) [23], more exactly a convex lens, usually with +20 diopters (D) or +13D [21] (a diopter is a optical power measurement unit of a lens or a curved mirror, equal to the inverse of the focal length in metres [8]). The illuminating light beam passes through the condensing lens (placed at a arm length from the observer) and enters the patient’s eye (figure 2.7 - P). The light reflected from the retina passes backwards through the condensing lens and forms a real, inverted and reversed image, in an intermediate position between the lens and the observer (figure 2.7 - O) [21,23,25].

The magnification and FOV of the image depend on the dioptric power of the convex lens, on the diameter of the lens, on the position of the lens in relation to the eyeball and on the refractive state of the eyeball. With stronger lens, the image will be smaller but brighter and the FOV will be more extended, and vice versa [28].

In the same way as the direct ophthalmoscope, this device can have additional spherical lenses (figure 2.7 - 4) in the visual path in order to correct any refractive errors (myopia and hypermetropia) that defocused the retina image [25].

Indirect ophthalmoscopy has binocular vision with depth perception (stereoscopic vision) of the patient’s retina and a wider FOV that makes it suitable for the examination of the periphery of the fundus [8,22]. However, with this technique, the obtained image is inverted and the small magnification can induce the loss of small lesions [22]. Furthermore, the type of ophthalmoscope used in this technique has the
2.4. OPHTHALMOSCOPE DESIGNS

Figure 2.7: Optical design of a conventional indirect ophthalmoscope (adapted from [25]). (O) observer’s eyes, (P) patient’s eye, (1) hand-held convex ophthalmoscopic lens, (2) low-power field lens, (3) front surface mirrors, (4) correcting lenses, (5) spherical mirror, (6) light source and (7) condenser lens.

axes of the viewing and illumination systems separated causing handling and adjustment problems [29]. Regarding the patient, it should be used a mydriatic agent to induce dilation of the pupil [21] and the illumination is intense [8], which can cause some discomfort.

Although a detailed perspective about the indirect ophthalmoscope has been presented, it is relevant to highlight that this is not the most used device in clinical practice, specifically by ophthalmologists. In fact, in an ophthalmological appointment, the slit lamp is the most commonly used device. However, the indirect ophthalmoscope previously presented is more resembled with the direct ophthalmoscope that is intended to redesign.

2.4.3 Direct vs. Indirect Ophthalmoscope

The main differences between the ophthalmoscopes types is that a direct ophthalmoscope provides a higher magnification (≈ 15X) but a smaller FOV (5°), whereas an indirect ophthalmoscope gives a better overview of the retina (≈ 25°) but a smaller magnification (3 - 5X, for 20D and 13D lens, respectively) [21,28] (figure 2.8).
In terms of operation, the use of indirect ophthalmoscope requires more practice for proficiency than the direct ophthalmoscope because of its construction and because of the type of the formed image. The segregation between the viewing and illumination axes and the formation of an inverted and reversed image make the apparatus alignment and the data interpretation more difficult [30].

Table 2.2: Summary of the main features of direct and indirect ophthalmoscopes.

<table>
<thead>
<tr>
<th>Features</th>
<th>Direct Ophthalmoscope</th>
<th>Indirect Ophthalmoscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>small (usually, pocket size)</td>
<td>large (headset + handheld lens)</td>
</tr>
<tr>
<td>Vision</td>
<td>monocular</td>
<td>binocular (stereoscopic vision)</td>
</tr>
<tr>
<td>Image</td>
<td>virtual, erect</td>
<td>real, inverted</td>
</tr>
<tr>
<td>Illumination</td>
<td>not as bright</td>
<td>bright</td>
</tr>
<tr>
<td>Condensing lens</td>
<td>not required</td>
<td>required</td>
</tr>
<tr>
<td>Field of view</td>
<td>small ($\approx 5^\circ$)</td>
<td>large ($\approx 25^\circ$)</td>
</tr>
<tr>
<td>Magnification</td>
<td>$\approx 15X$</td>
<td>3 - 5X (20D - 13D)</td>
</tr>
<tr>
<td>Work distance</td>
<td>observer close to patient</td>
<td>observer far from patient</td>
</tr>
<tr>
<td>Local condition</td>
<td>not required</td>
<td>dark room</td>
</tr>
<tr>
<td>Mydriasis</td>
<td>not required</td>
<td>required</td>
</tr>
</tbody>
</table>
Chapter 3

State of the art

In this chapter some solutions available in market for the evaluation of retina is presented. They were divided in four types: standard direct ophthalmoscopes, the PanOptic™ ophthalmoscope, hand-held fundus cameras with image display and smartphone applications. It is also presented, the preliminary work developed with the PanOptic™ ophthalmoscope.

3.1 Standard direct ophthalmoscopes

The standard direct ophthalmoscope used in clinical practice nowadays is an evolution of Helmholtz-Babbage ophthalmoscope. The illumination and viewing axes remain very close together but, instead of a mirror with a hole, it uses a small mirror beneath a hole of 3 mm in diameter - the viewing aperture (figure 3.1). The ophthalmoscope also has two thumb-wheels. The horizontal wheel (the aperture wheel) allows the operator to adjust the diameter, shape, and color of the illumination beam. The vertical wheel (the compensation lenses wheel) allows the insertion of lenses just behind the viewing aperture to compensate possible refraction errors of both the observer and patient (figure 3.1) [20].

There are several companies that provide this type of direct ophthalmoscopes such as Riester, Heine, Welch Allyn, Keeler, Zumax and many others [31]. Although there are some differences between them, essentially in lightning systems, the ophthalmoscopes are very similar in size, format and basic features, such as their FOV of about 5° (figure 3.2).
3.2 PanOptic™ ophthalmoscope

The PanOptic™ ophthalmoscope (figure 3.3), developed by WelchAllyn (Skaneateles Falls, New York, USA), was introduced in 2001 [13] and it has revolutionized the direct ophthalmoscopy with better observation conditions. Actually, it provides an easy entry into the eye, in conjunction with a wider field of view [32].

The optic system of this device (patented Axial PointSource™ optical system) differs from the conventional direct ophthalmoscope as it allows the convergence of light to a point at the cornea, diverging from there towards the retina. In a standard direct ophthalmoscope, the light is projected directly onto the observer’s retina. That is the reason of a wider field of view (more panoramic view of the fundus) [13].

The PanOptic™ ophthalmoscope has a dynamic focusing wheel, with a focusing range of -20D to +20D, that enables a continuous and smooth adjustment of the focus for an optimised view. It also has an aperture dial with 3 spot sizes (micro, small and large), to regulate the diameter of the light beam that enters the patient’s eye, a red-free and a cobalt blue filter. Furthermore, this device has a rubber piece on the patient’s side that helps to maintain the proper viewing distance and the necessary stabilization and orientation for the inspection, as well as it occludes the ambient light.

The four main advantages of PanOptic™ ophthalmoscope over the conventional direct ophthalmoscope are:
CHAPTER 3. STATE OF THE ART

(a) Standard ophthalmoscope from Welch Allyn
(b) Heine Beta® 200S
(c) Professional ophthalmoscope from Keeler

Figure 3.2: Some examples of standard ophthalmoscopes available in market (adapted from [31]).

- an enhanced FOV in the undilated eye, typically in the order of 25°;
- a 26% increase in magnification, which enlarges 4X the image; of the standard ophthalmoscope, improving resolution of the eye fundus and allowing fine detail (for example, it is possible to view vascular changes more easily);
- an increase in the working distance between the clinician and the patient, which gives more comfort for both;
- glare and reflections extinguishment that prevents their undesired interference [32].

These advantages make the diagnose of retina pathologies more reliable, the examination more comfortable and the results more acceptable [33].

3.3 Hand-held fundus cameras with image display

3.3.1 Visuscout® 100

Visuscout® 100 (figure 3.4(a)) developed by Zeiss (Oberkochen, Germany) is a hand-held fundus camera with a compact and lightweight design that can be easily transported and fitted into any practice setup. It is a non-mydriatic device with a precision autofocus system that allows a clear fundus examination without the dilation of the patient’s eye. This device acquires color, red-free and IR images, with a 40° FOV,
Figure 3.3: The Welch Allyn PanOptic™ ophthalmoscope (adapted from [32]).

that can be transferred to a PC or mobile device by WiFi. This camera is built with
nine internal fixation LEDs that help the correct alignment of the patient and also
facilitate the capture of peripheral images. As a major disadvantage, the Visuscout®
100 is only suitable for the examination of patients with a pupil diameter of 3.5 mm
or higher [34].

3.3.2 Pictor Plus

Pictor Plus (figure 3.4(b)) developed by Volk Optical Inc. (Mentor, Ohio, USA)
enables nonmydriatic fundus examination with a 40° FOV. It allows the acquisition
of both digital images and videos of the optic disc, macula, and retinal vasculature
that can be transferred by WiFi or USB. The 10 illumination levels and focusing
(automatic or manual, diopter compensation -20D to +20D) can be adjusted to
produce high-resolution reflection-free images and, beyond color images, it offers red-
free images for a better contrast. As a major disadvantage, the Pictor Plus is only
suitable for the examination of patients with a pupil diameter of 3 mm or higher [35].

3.3.3 Smartscope® PRO

The Smartscope® PRO (figure 3.4(c)) developed by Optomed (Oulu, Finland) offers
a precise, reliable and high-quality digital fundus imaging through undilated pupils,
with a FOV of 40°. This device main features include an autofocus system, diopter
compensation (-20D to 20D), color, red-free and IR imaging, nine internal fixation
targets for a better peripheral image and WiFi/USB connectivity. As a major
disadvantage, the Smartscope® PRO is only suitable for the examination of patients with a pupil diameter of 3.5 mm or higher [36].

### 3.3.4 Horus Scope

The Horus Scope (figure 3.4(d)) developed by JedMed (St. Louis, Missouri, USA) is a hand-held ophthalmoscopic camera for visualize the retina and capture video/images. The built-in auto-focus technology helps to obtain quick and clear images of the fundus, through a nonmydriatic eye. This system also includes seven internal fixation points, which help to aid the patient in ocular positioning. Its wide 45° FOV grant the imaging of a wider area than many other systems on the market. This device is also available in a manual focus version, but with lower FOV of 40°. The acquired data can be easily transferred to a personal computer [37].

### 3.3.5 VersaCam™ α

VersaCam™ α (figure 3.4(e)) developed by Nidek Co., Ltd. (Gamagori, Japan) provides high quality digital imaging of the retina with a 45° horizontal FOV and a 40° vertical FOV. The auto-focus system allows easy image capture and the seven internal fixation lamps equipped with the device helps the maintenance of a stable fixation. Beyond autofocus, this device also has the option of manual focus. The acquired images can be saved on a SD memory card or transferred to a PC by a mini USB port [38].

### 3.4 Smartphone applications

#### 3.4.1 D-EYE System

The D-EYE (figure 3.5(a)) is a built-in lens system, magnetically attachable to a smartphone, to record images and videos of the ocular fundus. This device is based on the principle of direct ophthalmoscopy and takes advantage of the smartphone camera’s autofocus to rectify the patient’s refractive error (diopter compensation -12D to +6D). Shortly, the light emitted by the smartphone’s flash LED is send into the eye by a mirror and the reflected light beam is directed to the camera with a beamsplitter (coaxial illumination and imaging paths). The D-Eye is used with a smartphone application that reduces the intensity of flash LED and switches between
3.4. SMARTPHONE APPLICATIONS

(a) Visuscout® from Zeiss [34]

(b) Pictor Plus from Volk Optical Inc. [35]

(c) Smartscope® PRO from Optomed [36]

(d) Horus Scope from JedMed [37]

(e) VersaCam™ α from Nidek Co. Ltd. [38]

Figure 3.4: Current hand-held fundus cameras available in market (images adapted from references in captions).
manual and autofocus. When examining a dilated pupil (the acquisition is difficult for pupil diameters smaller than 2.5 mm), the system captures a 20° FOV for a single fundus image at a distance of 1 cm from the patient’s eye [39]. It is available for iPhone SE, 5, 5S, 6, 6S, 6 Plus and 6S Plus [40].

### 3.4.2 PEEK - Portable Eye Examination Kit

Similar to D-EYE, the Portable Eye Examination Kit - PEEK (figure 3.5(b)) is an ophthalmoscopy adaptor attachable to a smartphone. Briefly, it is a plastic shell with a single-piece custom plastic optical assembly, that attaches to the back of the mobile phone. On the adapter, the smartphone’s white flash LED is deflected through the optical assembly to turn the illumination path and the field of view of the camera coaxial. This device can be used with the smartphone’s camera in the video recording mode or with an ophthalmology-dedicated software and the typical FOV is 30°, with dilated pupils [41]. This adapter will be available this year, 2016, for the most common smartphone, such as iPhone, Samsung, Sony and HTC [42].

### 3.4.3 iExaminer™

The Welch Allyn iExaminer™ (figure 3.5(c)) turns the PanOptic™ ophthalmoscope (describe previously) into a mobile digital imaging device. It aligns the optical axis of the PanOptic ophthalmoscope to the visual axis of the iPhone camera to capture high-resolution pictures of the fundus and retinal nerve. The storage and display of images is done by the iExaminer app. The iExaminer is available for iPhone 4, 4S, 6, 6S, 6 Plus and 6S Plus [43].

### 3.4.4 Volk INview

The Volk INview (figure 3.5(d)) is a new ophthalmic camera device, attachable to iPhone or iPod, that allows the capture of wide-angle color images of the retina. The patient’s pupil must be dilated, because it requires a minimum of 5 mm for pupil diameter, so this is a mydriatic device. It requires the use of a mobile application (Volk INview mobile app) that automatically detects and selects the images with higher definition and more focused, acquiring images quickly and easily. This device obtains a wide 50° FOV to visualize the entire fundus in one image. The images are stored with patient data and can be easily exported to a computer. Volk INview is available for iphone 5S, 6 and 6S and for iPod Touch (6th generation) [44].
3.5 Exploratore solution

Preliminary work in this scope, with similar goals to this project, have been performed by MSc Taíssa Pereira, in 2011. In that project, several prototypes were idealized and tested which had resulted in a case with an image sensor that fits, externally, into the PanOptic™ ophthalmoscope, as it can be seen in figure 3.6. The prototype consists in a 3D printed plastic case divided in two separated parts: one that includes the image acquisition system (webcam) and other that fits into the observer’s side of the PanOptic™ ophthalmoscope. The final version has small magnets, introduced in order to join these two pieces together, which makes the removing process of the sensor much easier and faster [2].

Although with this prototype is possible to acquire retinal images, the main goal of the project was not accomplished, as it is not possible to perform the direct visual inspection simultaneously with the acquisition of images. In fact, as the plastic piece
that contains the camera is mounted at the observer’s side, it is necessary to choose between the image acquisition and the direct observation of the retina. Another important constraint is that, although the final prototype allows the acquisition of color images, as it can be seen in figure 3.7, the quality of these images is not similar to the quality of the direct visual inspection.

Figure 3.6: Prototype developed by Taíssa Pereira in 2011 (adapted from [2]).

(a) Camera’s case  (b) Prototype mounted on the PanOptic™

(c) Camera dismounted from the PanOptic™

Figure 3.7: Clinical tests results obtained in 2011 (adapted from [2]).

(a) Right eye  (b) Left eye
Chapter 4

Methods

In this chapter the methodology used in the progress of this project is presented. It started with the recognition of the fundamental requirements of the device, with a neurologist from CHUC. Knowing what was necessary, it was important to understand the internal structure of an ophthalmoscope, in this case the PanOptic™ ophthalmoscope, to idealize the possible prototype designs. Some architectures were analysed in a bench test and from there the prototype was designed. The successive modifications were tested, with an artificial target and later in vivo, up until the final version. The main characteristics of the prototype (illumination system, image acquisition system and optical configuration), as well as the bill of materials are presented in this chapter.

4.1 Requirements of the device

To start this project, it was essential to know all the features and requirements for the intended device, as well as its functionality and purpose. For this step, the contribution of the neurologist João Lemos was essential, as the examination of the retina is an common procedure in this medical specialisation - neurology.

The most important characteristic that this prototype must include is the ability to acquire images and/or record video at the same time that it is used as a regular ophthalmoscope, using the standard clinical protocol. The image acquisition is of great interest because it would enable to store retinal exams of a patient, useful to follow the evolution of health/pathological condition. Furthermore, it would allow to share of the retinal images between clinicians, as well as the reassessment of exams, important for second opinions and for the improvement of diagnosis.
The obtained images should be color images, for better discrimination between health and pathological conditions, and they should have good image quality, the most similar to the clinician observation as possible.

Practicality and portability were fundamental remarks to take in account. In fact, it was required that the device should be kept the smallest as possible and that the exam protocol should remain unchanged. So, it was of preference to have a prototype with a built-in image acquisition system. Furthermore, as it is intended to be used in clinical environments where there is no easy access to a conventional fundus camera, it is fundamental that the device could work on battery and that the image transmission could be wireless.

Table 4.1: Summary of the requirements of the device.

<table>
<thead>
<tr>
<th>Requirements Classification</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandatory</td>
<td>- Acquisition of images and/or video simultaneously with direct visual inspection;</td>
</tr>
<tr>
<td></td>
<td>- Maintenance of the exam protocol;</td>
</tr>
<tr>
<td>Fundamental</td>
<td>- Portability: working on battery and wireless image transmission;</td>
</tr>
<tr>
<td></td>
<td>- Practicality, small size and lightweight;</td>
</tr>
<tr>
<td></td>
<td>- Color images with similar quality to visual inspection;</td>
</tr>
<tr>
<td>Optional</td>
<td>- Internal acquisition system;</td>
</tr>
</tbody>
</table>

4.2 Reverse engineering

4.2.1 PanOptic™ ophthalmoscope structure and operating principles

After the identification of all the characteristics needed for the final device, it was of most importance to know, in detail, the internal structure of the device it was intended to redesign, the PanOptic™ ophthalmoscope. For that, the ophthalmoscope, provided by the neurologist João Lemos, was fully dismantled and its components were identified.
The internal structure of the ophthalmoscope is composed by two essential optical systems: the illumination system and the optical imaging system. The illumination system consists in a halogen light bulb (figure 4.1(a) - 6), an aperture dial (3 size holes and color filters), a condensing lens (figure 4.1(a) - 5), all encapsulated in a metal cylinder at the ergonomic handle grip, a polarizer and a small mirror (figure 4.1(a) - 4).

The optical imaging system consists in an ocular lens (figure 4.1(b) - 4), inside a cylinder, with a focusing wheel, an imaging lens (figure 4.1(b) - 7), a polarizer, orthogonally oriented with the polarizer of the illumination system, and an objective lens (figure 4.1(a) - 3). This last component is part of the illumination system too, as it is responsible for the convergence of the light beam into the pupil. The optical elements work together to provide a wide field of the retina, without pupil dilation [1].

As well as the internal structure, it was relevant to know how the PanOptic™ ophthalmoscope works. As it can be seen in figure 4.1, the fundamental optical characteristic of this ophthalmoscope is the proximity of the illumination and the observer’s viewing axis. The patent of the device [1] was important to know both the internal structure and the operating principles.

**Illumination system**

The illumination system is designed in order to produce light rays that converge at the patient’s pupil and diverge thereafter to the retina (patented Axial PointSource™ optical system [32]). The light, emitted by an halogen lamp or a LED lamp (figure 4.1(a) - 6), is focused onto a mirror (figure 4.1(a) - 4), by a condenser lens (figure 4.1(a) - 5). Then, the light rays passes through the objective lens (figure 4.1(a) - 3) that is responsible for converging the light exactly in the pupil (figure 4.1(a) - 1). The mirror is mounted at an angle of 3.8 degrees from the imaging axis, and its normal intersects the imaging axis at the objective lens. As the orientation of the filament matches the shape of the mirror, the size of these element is minimized [1].

With this converging illumination system, a much higher percentage of incident light rays enter the pupil to illuminate the retina and a wider field of the eye fundus is illuminated. Furthermore, less unwanted light is received by the imaging system, since the light reflected by the outer structures of the eye is reduced [1].
4.3. POSSIBLE OPTICAL/ILLUMINATION DESIGNS

(a) Schematic diagram of the illumination system

(b) Schematic diagram of the imaging system

Figure 4.1: Light rays scheme adapted from (adapted from [1]). (1) patient’s eye, (2) practioner’s eye, (3) objective lens, (4) mirror, (5) condensing lens, (6) light source, (7) imaging lens and (8) ocular lens.

Optical imaging system

The optical imaging system of the device includes the objective lens, a polarizer, the imaging lens and the ocular lens, all of them being aligned by the same axis - the observer’s viewing axis [1]. The light rays reflected by the retina pass through the pupil towards the objective lens (figure 4.1(b) - 3), that focuses the parallel light beams from the patient’s eye (figure 4.1(b) - 1) into a retinal image focal plane, between the objective lens and the imaging lens (figure 4.1(b) - 7). Then, this lens converge that light rays into the eyepiece focal plane, that is conjugate to the observer’s retina (figure 4.1(b) - 2). Between the imaging lens and the observer’s retina there is an ocular lens (figure 4.1(b) - 8), responsible for the adjustment of image focus, when the clinician’s and/or the patient’s eyes have refractive errors. This lens is the only moving part of the optical imaging system and it is adjusted by a focusing wheel. The ocular lens focusing range is between -20D and 20D [1].

4.3 Possible optical/illumination designs

Knowing the specifications of the PanOptic™ ophthalmoscope, its operating mode and the necessities of the new device, two possible architectures for a prototype with an internal image acquisition system were idealized. The first architecture consisted in a
camera placed in the original illumination system location (ophthalmoscope handle). In turn, the illumination system would be substituted by a LED source placed above the ophthalmoscope, at the patient’s side. A beamsplitter should be placed between the objective lens and the mirror, on the observer’s viewing axis, right underneath the new light source, so that this configuration may be possible. With this element, the light is diverted towards the objective lens and the light reflected by the retina can pass backwards through the imaging system.

The second architecture consisted in a camera placed above the ophthalmoscope, at the patient’s side with the illumination system held in the original place. In this hypothesis, as well as in the hypothesis explained above, a beamsplitter should be placed between objective lens and the mirror, on the observer’s viewing axis. But in this case, this element would be right underneath the camera to divert the light reflected by the retina towards the image acquisition system, making the illumination of the fundus of the eye possible, simultaneously.

4.4 Development of an artificial target (eye model)

In order to test the configurations idealized before, it was necessary to develop an artificial target that could simulate the human eye. Furthermore, the designed prototypes must be tested in a controlled environment before the in vivo tests, in order to easily assess its performance and to not exhaust the volunteers. Due to these reasons, a simplified model in accordance with the characteristics of an emmetropic human eye has been developed (figure 4.2).

The human eye is capable of seeing objects at different distances because its lens is a dynamic structure. The eye lens can change its shape to modify its refractive power, however, in a relaxed state, the eye has about 60D. This refractive power corresponds to the combination of the refractive powers of both the lens and the cornea. The other important component of the eye that must be considered in the construction of a eye model is the pupil. This element also can change its shape but, when examined with a direct ophthalmoscope, has a diameter between 2 and 8 mm [45].

Taking into account these conditions, a simplified model of the human eye was developed using a printed target, a plastic sphere and a convex lens. The printed target was, initially, a retinal image but, because of the lack of printing contrast, it was changed to the 1951 USAF resolution test chart [46]. This target was placed in the bottom of the sphere to simulate the location of the retina. The sphere was made
of polyethylene and had a diameter of about 33 mm. The convex lens had a focal length of 25 mm that corresponds to 40D (this was the available lens with a focal length near the emmetropic eye). The distance between the lens and the target was about 26 mm. To simulate the pupil it was used a piece of black cardboard with a center hole of about 5 mm. This model was hold in place by a set of plates and rods. This structure has been attached to an optical bench in order to increase stability.

4.5 Optical bench test setup

Between the two options for the architecture of the prototype, it was clear that, in terms of size, there was a design that involved a bigger final device. In fact, with the second architecture, it should be added an external structure to the original size, for the acquisition system. With the first architecture, the original space of the illumination system could be used for the acquisition system and the new light source, a LED (single or a matrix) of small dimensions, could be placed at the exterior of the ophthalmoscope without taking up too much space.

Knowing this spatial constrain, it was decided to start with testing the first design, in an optical bench test setup, that can be seen in figure 4.3. The optical bench test setup consisted in the ophthalmoscope (figure 4.3 - 1), supported by a lab clamp, aligned with a camera (figure 4.3 - 4 and 5), supported by a plate attached to the optical bench, and with the artificial target (figure 4.3 - 6), also attached to the optical bench. The artificial target was placed at the patient’s side of the ophthalmoscope, such as in a real retinal inspection. The camera was placed instead of the original illumination system, but, due to size constraints, it was placed in the outside of the handle grip. In this configuration, the light reflected from inside of the eye model is deviated to the acquisition system by the internal mirror (figure 4.1(a) - 4) of the
ophthalmoscope, of about 8.5 x 4 mm, that is at the field of view of the camera.

This test was performed before the introduction of the beamsplitter, so the LED illumination (figure 4.3 - 2) was placed in front of the mirror, parallel to the viewing axis, and oriented to the objective. The power supply of the LED was done with a voltage source connected to a simple regulation circuit. Even without the beamsplitter, this test reveals that the camera, placed in the original illumination system site, and the mirror together could be used to image the target located at the back of the eye model (see section 5.1).

4.6 Prototype development

After the analysis of the optical bench results (see section 5.1) a complete prototype, including the shell, has been developed. In this prototype, the illumination system was also redesigned in order to improve the amount of light that reaches the eye. All the external structures have been designed with the CAD software, Autodesk Inventor® 2016, and printed in black PLA (polylactic acid, a thermoplastic) using the MakerBot Replicator 2 Desktop 3D Printer [47]. The optical components (lens and mirror) has been reused from the provided PanOptic™ ophthalmoscope.
4.6. PROTOTYPE DEVELOPMENT

4.6.1 External structure

First prototype

The first developed prototype has been done in order to replicate the shape of the PanOptic™ ophthalmoscope and the goal of this design was to include a beamsplitter holder in the original structure of the device. For that, the first design of the ophthalmoscope (figure 4.4) is composed by a larger structure (light grey structure), that holds all the lenses, and a smaller piece that holds the beamsplitter and the illumination system (dark grey structure). The used beamsplitter is a glass plate of 12 x 19 mm, with a refractive index of about 1.472 and a reflection/transmission ratio of 10/90. It is aligned with the optical imaging system and it is mounted at an angle of 45 degrees from the viewing axis. The illumination system is placed at the top of the smaller piece, with the LEDs mounted on the internal face connected, through the holes on the lid, to the LED’s driving circuit mounted on a breadboard, as used in the bench test setup.

This prototype was helpful to validate the first possibility of design, that is, the use of a beamsplitter to deviate the light towards the eye (see section 5.2). However, since the smaller piece was not to stable and the ophthalmoscope structure did not have an efficient close system, to hold on the right and left pieces together, this prototype was not suitable to be hold on vertically. Additionally, the camera’s lens could not be inserted into the ophthalmoscope, which made impossible to handle the device as a whole. Considering these constraints, the second prototype has been developed.

Second prototype

This prototype was developed to rectify the beamsplitter support of the first prototype, in order to guarantee the maximal stability of the ophthalmoscope. Furthermore, it was intended to include the image acquisition system in the inside of the prototype shell.

As it can be seen in figure 4.5 - 1 and in the figure 4.6(b) - 9, the second prototype has already the beamsplitter holder as part of the ophthalmoscope assembly. It was kept at an angle of 45° with the viewing axis, aligned with the lenses system and also aligned with the illumination system. In this design it was also included a holder in front of the camera’s lens, to include a polarizer for the digital imaging system.

The light source has been, again, mounted at the top of the ophthalmoscope
structure (figure 4.6(a) - 2 and 3), right above the beamsplitter. More specifically, the illumination system was assembled in a square lid, that fits into the main piece (figure 4.5 - 2), with the LED in the internal face (facing the beamsplitter) and the LED’s driving circuit (figure 4.6(a) - 3) at the exterior. The power supply can be either a battery (figure 4.6(a) - 1) or a USB cable (figure 4.6(a) - 5). Furthermore, the camera’s lens can be inserted into the structure (figure 4.6(b) - 7) (see section 5.3) and, with the locks added (figure 4.5 - 3), this new prototype presents a better stability.

Final prototype

The second prototype, introduced in the last section, had already a good stability and a good illumination system, that did not diverged to much. In fact, it was possible to hold it vertically and almost of the entire light beam entered through the pupil. However, it was necessary to be careful and hold the camera body tightly, so it can be maintained in place. Furthermore, it was necessary to improve the convergence of the light beam into the pupil entrance, so that the illumination of the eye fundus could be done properly. In order to correct these features, another prototype was developed (figure 4.7) from the second one and it turns out to be the final prototype developed during this work. (see section 5.4).

As it can be seen in figure 4.7, and in comparison with the draw of the second prototype (figure 4.5), a solid case for the camera’s body has been added (figure 4.7(a)
Figure 4.5: Half-shells of the second prototype design. (1) beamsplitter holder, (2) fit for the illumination system lid, (3) locks and (4) camera’s polarizer holder.
Figure 4.6: Second prototype structure. (1) battery, (2) LED’s holder, (3) LEDs driving circuit, (4) power supply switch, (5) USB cable, (6) prototype, (7) camera, (8) mirror and (9) beamsplitter.
(a) Right shell

(b) Left shell

Figure 4.7: Half-shells of the final prototype design. (1) patient’s eyepiece fit, (2) fit for the illumination system lid, (3) beamsplitter holder, (4) camera’s polarizer holder, (5-6) locks and (7) camera’s body case.
Figure 4.8: Final prototype structure. (1) camera, (2) prototype structure, (3) USB cable, (4) focusing wheel, (5) LEDs holder, (6) LED’s driving circuit and (7) patient’s eyepiece.
With this design, the camera is held in place by the structure, as well as the lens, leading to an improvement of the imaging acquisition system alignment. All the other features were maintained equal, since it was proved that they were functional (figure 4.7(a) - 2 to 6).

Another feature of interest that was taken into account in this version was the use of the patient’s eyepiece of the original ophthalmoscope (figure 4.8(a) - 7). In fact, this piece is important to block the ambient light and to maintain the proper viewing distance. To be possible to use this rubber piece, easily and efficiently, a structural holder was added in the patient’s side of the prototype (figure 4.7(a) - 1).

### 4.6.2 Illumination system

As described during this chapter, in all the developed prototypes, the illumination system was placed at the top of the ophthalmoscope, at the patient’s side. Firstly, four warm white (3200 K) LED’s, linearly aligned, have been used. They had a 2.7 x 2.0 mm package, a viewing angle of 120°, a luminous flux of 4 lumen (lm) with a forward voltage of 3.2 V and a forward minimum current of 20 mA. They were mounted as a parallel of two LED’s in each branch, in order to reduce the input voltage, as the total forward current of four LEDs in series would be 12.8 V. The total light flux was about 16 lm.

When the second prototype was tested for the first time, it was clear that the light intensity was not enough. In fact, it was necessary for the light intensity to be about four times higher. Furthermore, the LED line arrangement lead to a large loss of luminous power since the illuminated zone was much larger than the pupil. Also due to this arrangement, a large reflex from the LED was seen on the cornea, making the orientation of the ophthalmoscope very difficult. All these issues showed that this was not a feasible solution.

In order to correct these problems, it was used a single LED, with a higher intensity. This LED was a warm white (4300 K) high brightness LED, with a 3.5 x 3.5 mm package, a viewing angle of 120°, a luminous flux of 47.5 lm with a forward voltage of 9.6 V and a forward minimum current of 50 mA. As discussed, this luminous flux was not sufficient and so, it was used about 94 mA that corresponds to about 75 lm, to obtain a light intensity more similar to the PanOptic™ ophthalmoscope. After a new test with the second prototype, it was verified that the use of a single LED reduced the undesired reflex of the cornea and that the percentage of light entering the pupil was bigger. In figure 4.9, the final assembly of the illumination system is presented,
as well as the LED driver circuit.

In spite of the convergence of light has been improved in the second prototype, it was thought that using a small convex lens placed in front of the led could be helpful to narrow the light beam that enters the pupil. Actually, this lens focuses the light beam and reduces its diameter at the beamsplitter surface. Therefore, this lens allows the entrance of much more light through the pupil (figure 4.8(b)).

As it can be seen in figure 4.6(a), the second prototype had the possibility of using, as the power source, either a 9V battery or a USB cable. However, at the final stage of the project it was thought that this battery was no longer needed, as it will be always used a cable for the camera. For this reason, in the final prototype, this battery was removed and it was used only the USB cable (figure 4.8(a) - 3). However, the electrical circuit is prepared for the connection of the battery.

Initially, a potentiometer (1 kΩ) was included in the circuit, in order to control the LED current and therefore the light intensity. In the final circuit, this component was maintained but its control function has been reduced. The potentiometer effect do not produce any light intensity change on the final LED, due to the driver circuit configuration. The resistors, 56 Ω and 1 kΩ, have been placed in parallel in order to obtain a specific resistor equivalent value (53 Ω). The light intensity control could be recovered with a simple modification.

4.6.3 Image acquisition system

For the acquisition system it was used an already available compact VGA camera, the GUPPY PRO F-036B (figure 4.10(a) - 1) from Allied Vision. This is a small 8-bit camera with a 1/3" CMOS sensor, a maximum frame rate of 64 fps, a resolution of 752(H) x 480(V) and a body dimension of 48.2 x 30 x 30 mm (L x W x H). The digital interface of this camera is the IEEE 1394a protocol, known as FireWire. Since this technology allows high-speed data transfer (400 Mb/s) and communication in two directions simultaneously (full-duplex) it is adequate for real time data acquisition [48]. In this case, the possibility of live video was the main reason to choose a FireWire camera.

Several lenses (C-mount fit) have been tested with this camera and the only one available that allows the formation of an image of the artificial target was the one with a focal length of 25 mm (figure 4.10(a) - 2).

The software used to record video was AVT UniCam Viewer, a camera interface
4.6. PROTOTYPE DEVELOPMENT

(a) Illumination system assembly

(b) Electrical circuit

Figure 4.9: Illumination system.

for AVT IEEE 1394a cameras (figure 4.10(b)). The image control parameters used during image acquisition and video record were the shutter time, the camera gain, the grey level, the brightness and the image resolution. The first two parameters were controlled automatically by the application and the last two parameters were maintained as default values. Regarding the image resolution, it was used the maximum resolution of the camera sensor, that is 752(H) x 480(V).

Although its good characteristics, this camera is not a suitable option to use in a final device ready to be used in clinical environment, as it should always be connected to a PC. It should be used a color camera with wireless communication, such as Wi-Fi or bluetooth technologies.
(a) GUPPY PRO F-036B (1) with a 25 mm lens (2).

(b) AVT UniCam Viewer interface

**Figure 4.10:** Image acquisition system.
Chapter 5

Results and Discussion

In this chapter the images acquired in the course of the project with the artificial target and \textit{in vivo} are presented. The problems encountered in each stage of the prototype development are discussed, as well as their consequences in the obtained results. Some considerations about the optical imaging system are also presented.

5.1 Optical bench test results

As described in the last chapter, an optical bench test was developed to test the idealized architecture. The results of this assembly can be seen in figure 5.1 and the main conclusion that can be drawn is that it is possible to acquire images of the target with this optical design. In fact, it is possible to place the image acquisition system in the location of the original illumination system. Moreover, the small mirror, initial part of the illumination system, can be used to deviate the light beam reflected by the retina towards the camera.

At this stage, it was not possible to use the beamsplitter, as it was used the PanOptic™ ophthalmoscope original shell that has no possible holder for that component. However, the LED illumination was placed in front of the mirror, parallel to the viewing axis and oriented to the objective, in order to illuminate the artificial target. Although the absence of the beamsplitter and the simplicity of this system, it was useful to verify that the original illumination system can be substituted and located in a different site.

Another relevant result, that can be clear seen by comparison of the two images acquired in the bench test, is the effect of using polarizers. As in the PanOptic™ oph-
thalmoscope, a linear polarizer has been positioned in front of the LED illumination and another one, in a cross-position, has been positioned in front of the imaging lens. In addition, another linear polarizer was placed, orthogonally with the LED polarizer, in front of the camera’s lens. This last polarizer was used in order to eliminate direct reflections of the illumination system towards the camera. The image acquired without this polarizer (figure 5.1(a)) has a white reflex at the center, that comes directly
from the light source. Conversely, in the image acquired with the polarizer (figure 5.1(b)) this reflex is completely absent, proving the importance of the polarizer of the camera’s lens to improve the image quality.

5.2 First prototype results

After the results of the bench test setup, the first prototype was developed and tested. The same simple LEDs system was included in this prototype but using a beamsplitter to direct the light towards the eye. In this assembly, the illumination system was placed at the top of the device with the beamsplitter in the viewing axis, aligned with the lenses of optical imaging system, and the LEDs mounted above it. The camera was placed, as in the optical bench test setup, in the exterior of the ophthalmoscope shell.

Comparing the results obtained in the bench test (figure 5.1) and the results obtained with the first prototype (figure 5.2) it is clear that these latest images are slightly darker. This can be explained by the introduction of the beamsplitter, that reflects only 10% of the LEDs light towards the target and transmits 90% of the light reflected from the eye model. However, this light reduction is not so significant, and it can be corrected by the automatic adjustment of the camera parameters. Thus, the architecture idealized is suitable for the acquisition of images of the fundus.

Even regarding the comparison of the two results, it is important to remark that the reduction of the magnification of the acquired image is explained by the variation of the distance from the ophthalmoscope to the artificial target. There are also some undesired light in the right side of the images, due to the entrance of ambient light into the prototype through the gap between the left and right side of the structure.

As well as it was verified in the optical bench test, the use of polarizers in cross positions, in front of the LEDs and in front of the camera’s lens, have reduced (figure 5.2(b)) the undesired reflection in the acquired image (figure 5.2(a)).

5.3 Second prototype results

In order to improve both the image acquisition and the illumination system, the second prototype was developed. With this assembly, the beamsplitter was included in the prototype structure, the camera was placed inside the shell and the illumination system was changed.
5.3. SECOND PROTOTYPE RESULTS

Figure 5.2: Artificial target images acquired with the first prototype.

The inclusion of the camera inside of the ophthalmoscope structure was a clear improvement, since it have allowed the acquisition of images of the artificial target with an increased field of view and magnification (figure 5.3). Moreover, the approximation of the camera to the mirror facilitates the scan of the entire artificial target, from one side to another (figure 5.3(a) to 5.3(c)). Although it can be seen the beamsplitter edge, it was not too relevant in the observation of the target. However, to improve the visualization, this component can be substituted by a larger one.
Figure 5.3: Artificial target images acquired with the second prototype.
In this prototype, the illumination system was changed for a single LED with a higher light intensity which led to a better illumination of the artificial target. Because of that, the acquired images are brighter than the previous ones.

5.4 Final prototype results

One of the changes made in this final prototype was the case for the camera’s body. This simple structure allows the maintenance of the camera position which brings more stability to the prototype. Before its construction, it was analysed the best orientation of the camera and it was set in such a way that the acquired image was the most similar to the obtained by direct visual inspection. Although the final acquired images are mirrored, they are upright (figure 5.4).

Regarding the image acquisition system, a lens with a manual focusing system was used, that has proved to be an unstable system to acquire images with a similar sharpness. Although this system has been used in the previous prototypes with relative success, during the image acquisition with the final one it was difficult to achieve the optimal focus. This is the reason why the final images (figure 5.4) are much more blurred than the images acquired with the second prototype (figure 5.3).

The use of this lens is also a major constraint in the use of this prototype for the in vivo inspection. That system forces the examiner to be constantly looking at the PC monitor to adjust the lens focus, in order to obtain sharper images. As the visual inspection requires the use of a focusing wheel too and both the patient and the examiner are constantly making small movements, the focusing process becomes very difficult and uncomfortable.

The final prototype, as well as the previous ones, was tested with the artificial target (figure 5.4) but it was also tested in vivo (figure 5.5). As can be noticed comparing the figures 5.4 and 5.5, there is a huge difference between the results obtained with the artificial target and in vivo. In fact, it was much easier to see the target in the back of the eye model than the fundus of the human eye. In the first case, the target was seen immediately when the procedure was started, but in the second case, it was difficult to obtain a clear image of the retina, even by direct visual inspection. By following the examination protocol it was expected that the red reflex of the retina would be easily visible from a large distance to the patient. When the examiner approaches the device towards the eye, the image of the retina should become more clear and bigger. However, the result was not so clear, and it was difficult to move towards the visualization of the eye fundus, since the red
Figure 5.4: Artificial target images acquired with the final prototype.
5.4. FINAL PROTOTYPE RESULTS

Figure 5.5: *In vivo* images acquired with the second prototype.
reflex reference, seen in figure 5.5(a), was easily lost and the image was blurred. Another important aspect responsible for the difficulty to obtain retinal images is the misalignment of the camera and the mirror, causing the misalignment between the direct visual inspection and the image acquisition. In fact when the observer gets closer to the patient’s eye, the image of the eye is no longer centered. This problem has proven to be difficult to resolve, as the mirror is inside the device and so, it can only be moved when the prototype is dismounted.

In this final prototype, the illumination system was also changed: it was placed a small convex lens in front of the led, in order to improve the convergence of the light beam. The illuminance (luminous flux incident in a surface, per unit area) of the final illumination system, as well as the illuminance of the illumination system of the second prototype and the illuminance of the illumination system of the PanOptic™ ophthalmoscope, were measured with a multimeter. The original device had an illuminance of about 1800 lux, the second prototype had an illuminance of about 1390 and the final prototype had an illuminance of about 2800 lux. Comparing the obtained values, it can be concluded that the second prototype had an illuminance more similar to the PanOptic™ ophthalmoscope than the final prototype. It may seem that the illumination system used in the second prototype is more suitable than the illumination system of the final prototype, however it should be taken into account the quantity of light that enters the eye. In fact, the diameter of the light beam of the second prototype was much bigger than the diameter of the light beam of the PanOptic™ ophthalmoscope, that means that the quantity of light that enters the eye is much smaller. Although the illuminance of the final prototype is higher than the original device, the diameter of the beam light remains bigger (but smaller than in the second prototype) therefore, not all the light enters the eye.

5.5 Optical imaging system

Regarding the considerations done in section 5.4, about the quality of in vivo acquisitions, there are some remarks that should be taken into account, to understand the bad quality of both the visual inspection and the image acquisition.

Although all the dimensions, distances and axes were respected in the drawing process of the prototype, they have been measured in the original ophthalmoscope, using a caliper, which increases the dimensional errors. Moreover, the 3D printing technique used to build the structure was not enough precise to reproduce the prototype with a high resolution. Therefore, these two constraints have made that the
alignment of the optical components could not be fully ensured, which has influence in the image quality of both imaging systems (optical and digital).

Beyond this problem with the optical alignment, the ware of the PanOptic™ ophthalmoscope lenses also had influence in the quality of the images. The landed device was not a brand new one and the lenses have been used in the assembly of all the prototypes developed in the course of the project. Probably, the intensive mounting and dismounting process, even with caution, together with the cleaning, caused the waste of the coating of the lenses, which have led to a reduction of the quality of the viewing system. In fact, this have caused a blurring and yellowness of the image seen by direct visual inspection. Another possible cause for the yellowness is the difference between the emission spectrum of the original illumination system and the used LED.
Chapter 6

Conclusion

Throughout this project, a direct ophthalmoscope with a built-in image acquisition system was developed. The prototype was designed based on the structure of the PanOptic™ ophthalmoscope, from Welch Allyn. In fact, with this project it was intended to adapt and redesign this device, frequently used in clinical practice, nowadays.

In general, although the main objective has not been completely achieved, as it was intended to obtain retinal images with good quality, it can be concluded that the project was successfully developed towards the fulfillment of the clinical necessities. In fact, it was proved that the inclusion of an image acquisition system inside the structure of the ophthalmoscope is possible simultaneously with the direct visual inspection. To be possible to have a device with total portability, autonomy and good quality image acquisition, this project should be further developed, taking in account all the clinical requirements that could not been already satisfied.

The major challenges of this project were to learn how to use the CAD software, Autodesk Inventor, essential for the prototype development, the construction of a suitable illumination system, in particular, how to get a small and adequate light source and the acquisition of retinal images.

The main setbacks found in the course of this work are related with the time of acquisition of material and components, that affects the progress of work and with the requirement of have aligned optical components, that could not be fully ensured. Furthermore, the wear of the available lenses, from the provided ophthalmoscope, turned out to be relevant in the quality of the final obtained results.

This project have shown the important role of Engineering in medical performance. Indeed, the reunion of this two areas, increasingly dependent, is of great
importance for the development of better technology and, in consequence, the technical development of the clinical practices.

6.1 Future work

In order to develop this project towards a finished device that could be used in clinical environment, some considerations have to be taken into account to fulfill the entire requirements. So, since it was not possible to complete this tasks, the proposed future work is:

- to improve the alignment of the optical components;
- to improve the image quality;
- to improve the image acquisition with an autofocus acquisition system;
- to miniaturize the prototype as much as possible;
- to make the prototype portable;
- to develop an algorithm of image processing.

To overcome the problem of the optical misalignment, it is thought that using a 3D printing technique with a higher resolution, such as the selective laser sintering technique (SLS) [49], or a metal structure to hold the lens, could be two possible solutions. Since these alternatives should increase the precision of the alignment of the optical components, the quality of the direct visualization and image acquisition is expected to be improved.

Beyond the alignment of the optical components, the image quality was affected by the bad condition of the lenses. In fact, the ware of this components have caused a progressive reduction of the quality of the obtained images. To improve this quality it should be used new lenses therefore implying the acquisition of a brand new PanOptic™ ophthalmoscope or the acquisition of other equivalent lens available in the market. In particular, to improve the acquisition of digital images similar to what is seen looking trough the device, the position/size of the mirror should be changed in order to align the image acquisition with the direct visual inspection.

To resolve the problem of the manual focus system, it should be used a lens with a autofocus system, such as a liquid lens or a lens with an electrically tunable mechanical focus system. The first type, consists in a sealed cell with two immiscible, transparent liquids, oil and water, with different refraction indexes but exactly the same density. The liquid lens external shape is fixed and only the internal liquids
change shape: the shape of the oil drop is changed by electrowetting (modification of a surface’s wetting properties by applying an electric field) [50]. The second type, consists in a lens with an external motor, responsible for the adjustment of the focal length, that is tunable by a current controller. These may be two potential solutions, but they were not possible to use in this project because of their high acquisition cost.

Regarding the requirement of portability of the ophthalmoscope, and to overcome the fact that the developed prototype must be always connected to a PC, it should be used a camera with wireless communication, for example, wi-fi or bluetooth technologies.

As soon as retinal images have been obtained, an algorithm of image processing should be developed in order to, be possible to control some image parameters, that could improve the acquisition quality. Among these parameters the most commonly evaluated are image colour, focus, contrast and illumination [51]. A personalised interface could be essential for a higher proficiency level of the acquisition process.
Appendices
Appendix A

Final prototype views

Figure A.1: Final prototype front left view with dimensions.
Figure A.2: Final prototype back right view with dimensions.
Figure A.3: Final prototype left view with dimensions.
Figure A.4: Final prototype design total views.
# Appendix B

## Bill of Materials

Table B.1: List of materials used in the final prototype assembly.

<table>
<thead>
<tr>
<th>Component</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical lenses</td>
<td>Welch Allyn</td>
<td>PanOptic ophthalmoscope lenses: objective, imaging lens and ocular</td>
</tr>
<tr>
<td>Beamsplitter</td>
<td>Edmund 31-416</td>
<td>12 x 19mm, 10R/90T, plate beamsplitter</td>
</tr>
<tr>
<td>Polarizers</td>
<td>Thorlabs LPVISE2x2</td>
<td>2” x 2” linear polarizer sheet</td>
</tr>
<tr>
<td>Passive electronics</td>
<td>Farnell</td>
<td>Resistors, potentiometer, capacitors, veroboard, etc</td>
</tr>
<tr>
<td>LM7805CT</td>
<td>Farnell 1102157</td>
<td>Linear Voltage Regulator</td>
</tr>
<tr>
<td>DCDC IR0512S</td>
<td>Farnell 1860988</td>
<td>Isolated board mount DC/DC converter, 12V</td>
</tr>
<tr>
<td>LEDs</td>
<td>Farnell 2097585</td>
<td>High brightness LED, warm white, 45.7 lm</td>
</tr>
<tr>
<td>Camera</td>
<td>Edmund 59-039</td>
<td>FireWire 1/3” CMOS Monochrome Camera</td>
</tr>
<tr>
<td>Camera lens</td>
<td>Edmund 67-715</td>
<td>25mm C Series VIS-NIR Fixed Focal Length Lens</td>
</tr>
<tr>
<td>Prototype shell</td>
<td>Ogami</td>
<td>Black PLA 3D printing - MakerBot Replicator 2</td>
</tr>
</tbody>
</table>
Bibliography


