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**ÚSTAV INTELIGENTNÍCH SYSTÉMŮ**


# CREATING A DEPTH MAP OF EYE IRIS IN VISIBLE SPECTRUM

**VYTVOŘENÍ HLOUBKOVÉ MAPY OČNÍ DUHOVKY VE VIDITELNÉM SVĚTLE**

**MASTER'S THESIS**
**DIPLOMOVÁ PRÁCE**


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# Master's Thesis Specification

22246

Student: **Kubíček Martin, Bc.**
Programme: Information Technology Field of study: Intelligent Systems
Title: **Creating a Depth Map of Eye Iris in Visible Spectrum**
Category: Signal Processing
Assignment:

1. Study the literature about iris imaging, especially using natural light (visible spectrum).
2. Design an optic illumination for eye iris with a low stress and very high comfort for the iris or use an existing solution.
3. Collect a database with eye irises in high resolution and sharpness, if possible including veins and arteries in sclera, with minimally 100 samples.
4. Select and implement the most sufficient macro stacking method and create the resulting image with the best depth of field.
5. Compare the created images with existing technology and evaluate their benefits or suggest further improvements.
6. Based on the achieved results create a methodology for iris scanning.

Recommended literature:

- Zhang D., Guo Z., Gong Y. *Multispectral Iris Acquisition System*. Multispectral Biometrics, Springer, 2016, pp. 39-62, ISBN 978-3-319-22485-5.
- Trigg G.L. *Encyclopedia of Applied Physics*. Wiley, Vol. 23, p. 628, ISBN 978-3527294763.

Detailed formal requirements can be found at http://www.fit.vutbr.cz/info/szz/

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# Abstract

The aim of the master thesis is to propose and introduce in practice the methodology of scanning the iris of an eye in the visible spectrum. It emphasizes the quality of images, credible color rendering in comparison to the real basis and, in particular, the continuous depth of sharpness that could reveal previously unexamined aspects and details of the iris. Last but not least, the thesis will also focus on minimizing exposure to physical stress tot he iris. Part of the methodology is a precise procedure for iris imaging while ensuring image consistency. This will allow the creation of an iris database that tracks their evolution in time or other aspects such as the psychological state of the person being scanned. To start with in practice, the anatomy of the human eye and especially that of the iris is presented. Known methods of iris scanning are given. Then, there is a section about proper iris lighting. This is necessary for the desired level of image quality but at the same time it exposes the eye to great physical stress. It is therefore necessary to find a compromise between these factors. Important is the very description of the methodology itself as it describes in detail the scan. Furthermore, the thesis deals with necessary post-production adjustments, such as compiling images with different depths of sharpness into a single continuous image or applying filters to remove defects from the images. The last part of the thesis is divided into evaluation of the results and the conclusion in which is discussed the possible extension or modification of the methodology so that it can be used outside the laboratory conditions.



# Abstrakt

Diplomová práce si dává za cíl navrhnout a uvést v praxi metodiku snímání oční duhovky ve viditelném spektru. Klade přitom důraz na kvalitu snímků, věrohodné podání barev vůči reálnému podkladu a hlavně na kontinuální hloubku ostrosti, která odhaluje dosud nezkoumané aspekty a detaily duhovky. V poslední řadě se také soustředí na co nejmenší vystavení duhovky fyzickému stresu. Metodika obsahuje přesné postupy jak snímat duhovku a zajišťuje tím konzistentnost snímků. Tím umožní vytvářet databáze duhovek s ohledem na jejich vývoj v čase či jiném aspektu jako je například psychologický stav snímané osoby. Na úvod je v práci představena anatomie lidského oka a zejména pak duhovky. Dále pak známé způsoby snímání duhovky. Následuje část, jež se zabývá správným osvětlením duhovky. To je nutné pro požadovanou úroveň kvality snímků zároveň ale vystavuje oko velkému fyzickému stresu. Je tedy nutné najít kompromis mezi těmito aspekty. Důležitý je popis samotné metodiky obsahující podrobný popis snímání. Dále se práce zabývá nutnými postprodukčními úpravami jako je například složení snímků s různou hloubkou ostrosti do jednoho kontinuálního snímku či aplikací filtrů pro odstranění vad na snímcích. Poslední část práce je rozdělena na zhodnocení výsledků a závěr, v němž se rozebírají možné rozšíření či úpravy metodiky tak, aby ji bylo možné použít i mimo laboratorní podmínky.



# Keywords

iris, scanning, visible spectrum, bepth map, depth of field

# Klíčová slova

duhovka, snímaní, viditelné světlo, hloubková mapa, hloubka ostrosti


# Reference


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# Rozšířený abstrakt

V dnešní době, kdy jsou otázky bezpečnosti stále více zmiňovány, a to i laickou veřejností, je potřeba tyto vědní obory rozvíjet a posouvat dále. Zejména pak biometrii, jenž pracuje s unikátními vlastnostmi člověka, které nelze jednoduše ztratit, zapomenout, či si nechat odcizit. Avšak s rostoucím vývojem moderní techniky, není poslední jmenované takový problém. Proto je potřeba přicházet se stále novými metodami, jak získávat lepší a přesnější biometrické data. Ať už díky kombinaci jednotlivých biometrických dat a vytvoření multimodálních biometrických systémů, tak díky zvyšování kvalitativních nároků na jednotlivé biometriky či hledání úplně nových jako je tomu například u DNA.

Většina výzkumníků tedy cílí na zlepšování kvality výsledných dat. To sebou však často přináší velmi zdlouhavé a mnohdy náročné snímání. Protipólem jsou výrobci biometrických zařízení a běžní uživatelé, kteří takovému zdlouhavému snímání nechtějí být podrobeni. Cílí především na rychlost a pohodlnost při snímání, než na kvalitu a přesnost. Určitou roli zde hraje i marketingový faktor, v němž někteří výrobci slibují použití nejmodernějších metod a technologií, přičemž opak je pravdou či jsou použité metody značně okleštěné, právě z důvodu většího pohodlí pro uživatele. Je tedy čím dál větší výzvou mezi těmito skupinami najít společný průnik.

Těmi nejčastěji zmiňovanými metodami jsou: 3D/2D sken obličeje, otisk prstu, snímání sítnice, případně duhovky. Duhovka společně se sítnicí jsou nejméně skloňované a to z důvodu, že k jejich snímání je potřeba speciálního hardwaru. Proto se těmito biometrickými daty zabýváme spíše v rámci rozvoje pro medicínské účely.

Tyto faktory byli hlavní motivací pro počáteční zkoumání a následné vyvíjení metodiky, jenž bude využívat dostupnější hardware a generovat výsledky v odpovídající kvalitě. Tato práce popisuje zkoumání metodiky snímání lidské duhovky ve viditelném světle za použití běžně dostupných fotoaparátů a příslušného vybavení. Dává si také za cíl eliminovat stresové faktory, kterým jsou snímaní lidé vystaveni. Jednak psychické, ze strachu z obrovských přístrojů, jenž se používají u oftalmologů a druhak výraznému snížení fyzického stresu, kterému je snímané oko podrobeno, ve chvíli kdy je potřeba správně osvětlit duhovku. V poslední řadě pak práce cíli na kvalitu vyprodukovaných snímků, jenž budou následně sloužit pro další zpracování.

V kapitole 2 je obecně popsaná anatomie lidského oka a především duhovky. A to hlavně z důvodu, že je potřeba vědět, jak celý oční systém funguje, znát jeho specifika a detaily na které je možné se při tvorbě metodiky zaměřit. Dále lze v kapitole 3 nalézt popis stávajících metod snímání oční duhovky, kterému v dnešní době stále vévodí snímání v infračerveném spektru, ale také pomalu rozvíjející se snímání ve viditelném spektru. Pro snímání ve viditelném spektru je poté klíčové speciální zdroj světla, to udává míru detailu, ale také vystavuje snímané oko určité míře stresu. Těmito aspekty a hlavně návrhem vlastního řešení se zabírá kapitola 4. V kapitole 5 je popsána výsledná metodika, jenž byla vytvořena postupným iterováním teoretických znalostí a experimentováním. Obsahuje také poznatky, které při postupném vyvíjení metodiky vznikli z experimentálního testování. Na výsledné snímky vzniknuté z metodiky, byly aplikovány nejrůznější postprodukční metody. Zejména metody zabývající se skládáním makro snímků s cílem dosáhnout, co nejlepší možné kvality snímků. Dále také rozličné obrazové filtry pro zvýraznění hloubkové mapy duhovky. Popsané výsledky lze najít v kapitole 6. V poslední řadě bylo důležité zhodnocení dosáhnutých výsledků a porovnání s existujícími řešeními. Především z pohledu kvality hloubkové mapy, úrovně stresového faktoru pro lidské oko a celkového pohledu na metodiky a použité technologie. Zmíněny jsou také jevy, které bylo možné pozorovat během snímání a vykazovaly podobné rysy, mezi většinou snímaných.

Díky metodice tak vznikla unikátní databáze očních duhovek ve vysoké kvalitě, jenž bude dále podrobená zkoumání v rámci výzkumné skupiny STRaDe a také bude poskytnuta oftalmologům ze zkoumání pozorovaných jevů během snímání. Databáze se bude nadále rozvíjet a s ní také metodika, jejíž možné další vylepšení jsou zmíněné v rámci práce a došlo k nim zejména zpětným analyzováním výsledků.

# Creating a Depth Map of Eye Iris in Visible Spectrum

## Declaration

I declare that I have prepared this Master's thesis independently under the supervision of prof. Ing., Dipl.-Ing. Martin Drahanský, Ph.D. Further information was provided by MUDr. Tomáš Mňuk. I have listed all of the literary sources and publications that I have used.

.....
Martin Kubíček
May 22, 2019


## Acknowledgements

I would like to thank prof. Ing., Dipl.-Ing. Martin Drahanský for supervising this work and for providing a lot of valuable advice that contributed to this work. Furthermore, I would like to thank MUDr. Tomáš Mňuk, for providing professional materials and advice on ophthalmology.

# Contents

# Chapter 1

# Introduction

The aim of this work is to design and develop a methodology, thanks to which it would be possible to create a stacked macro photograph of the iris of the eye in the visible light spectrum. A photo thus created, which consists of multiple photographs with different depth of field, is used to create a model. This methodology is carried out in the colour spectrum, and thus the resulting model also contains information about the colour of the iris.

Nowadays, with the issue of security being of utmost interest and with the greater use of biometrics for safeguarding, there is the need to find and explore better and newer methods of scanning and preserving biometric data, for example by combining them (multi-modal biometric system). For example, connecting fingerprints and blood vessel patterns or improvements to the scanning, and thus obtaining better quality biometric data for comparison. This necessity also arises thanks to modern technology, the development of which has seen great advances and, at the moment, allows us to make sensors so small that they can easily fir into a mobile phone or into other smart devices. The quality of the sensors themselves has improved as well as the data generated by them, however this also means an increase in the difficulty of their verification. Last but not least, is the fact that these technologies today are much more accessible and it is possible to carry out their reverse engineering or get the required biometric data. This then contributes to the emergence of increasingly better methods, how to bypass current biometric systems, for example, using a fake lens with a printed iris or an artificially generated fingerprint.

The main motivation to create this methodology is, first of all, that it would create a database of high-quality images of the iris of the eye, which will be of importance, both for further use in biometrics, and for use in medicine or in any other field of science. The created methodology will then include accurate and constant conditions for how images are made. Subsequently, it will be possible to observe in time the development of individual irises and, thanks to this, observe pathological factors of the iris. An important factor in the methodology is the very scanning in the visible light spectrum, which adds an aspect that allows checking even the colour of the iris, changes or possible development over a period of time, of which could be beneficial especially in the field of medicine, where this situation has only partially been solved. Another aspect, to which colour contributes is a new level of safety and the robustness of biometric systems, current systems do not take into account the colour of the iris and rather combine this technology with other elements of biometrics, creating more demanding multi-modal biometric systems that are not very convenient for the imaged object. Thus, the aim is to fully exploit the potential that colour of the iris offers to create a robust system without the need to scan more biometric data.

In this work, the anatomy of the human eye is generally described in Chapter 2, and mainly, the anatomy of the iris. Chapter 5 further describes the methods of scanning the iris of the eye, mainly subsequent scanning in the infrared and visible spectrum. First of all, then the necessary equipment for scanning problems of various methods, and more concretely, their results. Chapter 5.1 then, in detail focuses on scanning in the visible light spectrum, especially on the biggest problem, namely lighting and the proposal. Chapter 5 follows with describing the methodology of scanning itself and the components used. Chapter 6 then covers the creation of stacked macro photographs, applying filters and creating the resulting images. Chapter 7 contains an assessment of the results and a comparison with images obtained using the IR method. The conclusion and plans for possible expansion or improvement of the methodology can be found in Chapter 8.

# Chapter 2

# The Human Eye

The human eye is one of the most important paired organs in our body. It provides one of the basic human forms of perception, in this case, is sight, which serves to orient and perceive space or to discern colours. The eye is made up of the eye ball and other associated organs, of which are the oculomotor muscles. Thanks to these 6 muscles, more precisely 4 lateral and 2 oblique muscles, the eye is the most mobile organ of the human body. The eyeball has the shape of an asymmetrical ball with a diameter of about 25mm and is located in the eye socket.[12]

The 3 basic structures of the eye are the cornea, the lens and the vitreous body, which are designed to be flexible and concentrate incoming rays of light so that they fall into the place of the sharpest vision, that is on the retina. These rays creating an image on the retina are greatly reduced and, most importantly, inverted as opposed to the actual subject. Light rays hitting the retina trigger chemical transformations in photosensitive cells.[21] We divide these cells into rods, that serve to perceive the intensity of light, and cones, that are colour vision receptors. Subsequently, the cones are divided according to according to their pigmentation into red, green and blue.

In general, the basic parts of the human eye and its functionality can be described this way. Subsequently in this chapter we will analyse it more from the anatomical point of view and then focus primarily on the iris, that is, how it is formed and everything it contains in its structure. From this information can then be deduced, what data should be scanned and what information can be extracted from it.

## 2.1 Anatomy of the eye

A sagittal incision of the human eye (figure 2.1), respectively, of the eyeball reveals a wall that consists of three tissue layers:

- **The outer layer**, or sclera, is a thick opaque ligamentous membrane on the surface of the eye ball. It forms the solid envelope of the eye ball, which, in anterior part of the surface, changes into a transparent cornea.

- **The middle layer**, called the choroid, also envelops the entire eyeball and is located between sclera and retina. It is very rich in capillaries and also contains cells with brown pigment. These prevent light rays scattering inside the eye. The front is formed by a ciliated body and the Iris. In the posterior part, it is then connected to the edges of the optic nerve.
- **The inner part** formed by the retina.

The eye also consists of two chambers in which aqueous humour, a derivative of blood plasma, circulates The chambers are as follows:

- **The anterior chamber:** a slotted space located between the cornea and the anterior part of the iris.
- **The posterior chamber:** a slotted space located between the posterior part of the iris and the anterior part of the lens.

The remaining inner spaces of the eye ball are filled with the vitreous body, a transparent, jelly-like mass.

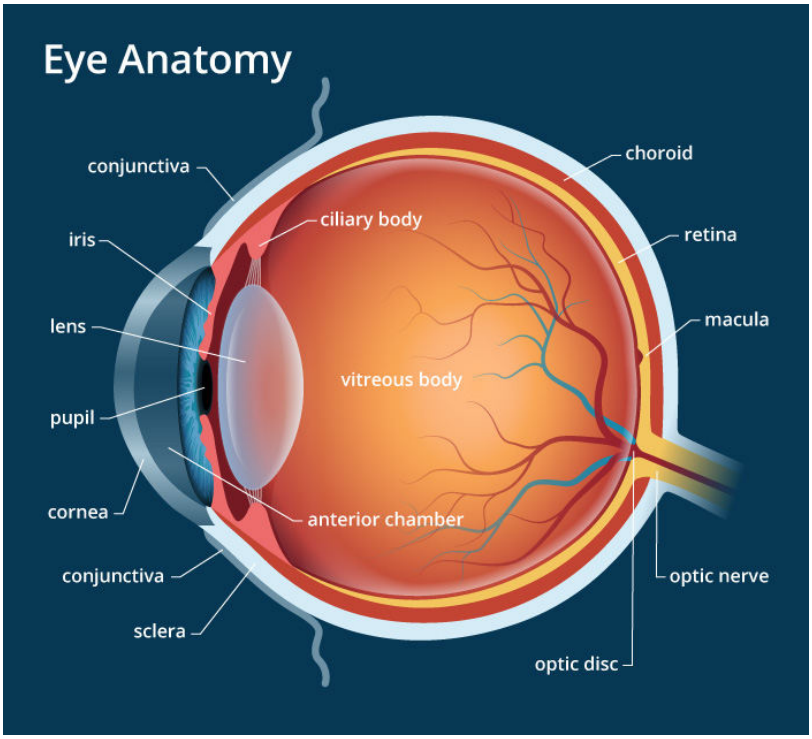


Figure 2.1: Vertical cut of the human eye (taken from [26])

A detailed description of the individual functional parts of the eye ball as depicted by a sagittal cut in figure 2.1:

- **The cornea**(*lat. cornea*), domed-shaped, clear tissue, located in the anterior part of the eyeball. One of the most sensitive parts of the human body, thanks to the large number of nerve endings present, but it is not, however, permeated with blood vessels, which it gives it its transparency. Due to extreme sensitivity, it is prone to irritation, which leads to lacrimation and squinting. Basically, it affects the direction the rays of light are spread and is therefore the most important refractive of the eye. The cornea optical strength ranges from 40 - 43D, which roughly represents 2/3 of the total optical strength of the eye.[21]

- **The iris**(*lat. iris*), is a smooth, circular muscle with a circular opening in the middle. By its stretching or shrinking, the size of the opening (pupil) changes. This mechanism serves to regulate the amount of light that penetrates into the interior, it thus acts as an aperture. More of which will be in the following sub-chapter 2.2.

- **The pupil**(*lat. pupilla*) is a circular opening in the centre of the iris of the eye. The pupillary light reflex, that is, how much it constricts or dilates, is determined by two groups of muscles: the iris sphincter muscle and the iris dilator muscle. These regulate the amount of light coming into the eye. The lens can be found behind the pupil.

- **The lens**(*lat. lens crystallina*) is a 4mm non-homogeneous biconvex bulging connecting body with a posterior surface that is more curved. The body is made of a rigid jelly-like and perfectly transparent mass. It hangs on the ciliary body with the help of the fibres known as the zonule of Zinn.[24] Its main function is the refraction of light, so that all incoming rays of light converge to one point on the retina, which is achieved by means of accommodation, changes in the dioptre strength of the eye with the help of the arching of the anterior surface of the lens. Accommodation depends on the distance of the object from the eye and allows you to focus on a given object. The optical strength of such a lens is then in the range of 15-20D.

- **The ciliary body**(*lat. corpus ciliare*), radially arranged muscle made up of smooth muscle fibre. The lens hangs on this muscle with the help of thin fibres. The body contributes significantly to lens accommodation, thanks to contractions of its musculature. This changes the curvature of the lens, thereby modifying its optical strength. From the blood that flows through the capillaries of the body intraocular fluid, called ventricular water, is produced. The latter then nourishes without the need vascular tissue of the eye, more precisely the cornea and lens, thereby maintaining the shape of the eye.

- **The vitreous body**(*lat. corpus vitreum*) is a clear gel-like tissue that fills the inner space of the eye ball, more precisely, between the lens and the retina. It serves to maintain the internal pressure of the eye ball and helps to keep of the spherical shape of the eyeball.

- **The macula**(*lat. macula lutea*), a round area with the greatest density of cones located in the visual axis of the eye. It is therefore the point of sharpest vision. This specific area located on the retina is yellowish-green in colour, which gives it its common name, **the Yellow Spot**.

- **The retina**(*lat. retina*), a thin multi-layered membrane that forms the inner wall of the human eye, the thickness of this membrane ranges from 0.2 mm to 0.4 mm.[12]

on which the sensory cells are located. The cells are then divided into rods, which are sensitive to the intensity of light and thus serve to its perception, especially the perception of the level of detail (for example, light without colour information - black and white). Cones, on the contrary, are receptors of coloured vision. Which are further divided according to their pigment and sensitivity to wavelength, to red, green and blue. There is also a blind spot on the retina, which is the point where the optic nerve enters the of the eyeball. There are no light-sensitive cells at this point, so there are neither rods nor cones and because of this the retina does not perceive images at this point. The macula, which is the point of sharpest vision can be found near the blind spot.

- **The optic nerve**(*lat. nervus opticus*) is the convergence point in the blind spot into which they all neuronal fibres of ganglion cells penetrate the wall of the eyeball.[24] In this way, the optic nerve, which is a paired sensory cerebral nerve, is created. It transmits visual information from the retina to the visual centres.

- **Choroid**(*lat. choroidea*), a brown pigment layer enveloping the eyeball that is located between the sclera and the retina. In the anterior part, it passes into the ciliary body, and in the posterior part it connects to the edges of the optic nerve. The choroid is densely permeated with blood capillaries, these then nourish the deep layers of the retina. It also prevents the scattering of light rays inside the eyeball.

- **The sclera**(*lat. sclera*) is a white, rigid and opaque, ligamentous membrane on the outer surface of the eye. In the front part of the eye, it passes into the cornea, and the optic nerve comes out of it in the back. The oculomotor muscles are also attached to it. The thickness of this membrane ranges from 0.3 mm to 1mm.[8]

## 2.2 Anatomy of the iris

A significantly pigmented spur of the choroid is located frontally between the lens and the eye sclera, thus also separating the anterior and posterior ocular ventricles. Thanks to pigmentation, it prevents the passage of light into the inner part of the eye other than through the pupil. The surface is irregular with a large number of folds and grooves. Its average size is approximately 12mm, the width depends on the current size of the pupil.[21]

The functioning of the iris is very similar to the principle of the aperture at the photographic lens, this being the regulating the level of light entering the eye. The iris is associated with the delicate muscles that dilate the pupil when there is not enough light or constricts the pupil in sufficient or stronger light.[32] Such regulation is called accommodation of the pupil and it cannot be influenced at will, it happens spontaneously. The dilating muscle lies transversely to the border of the iris, attached to the muscle then lies along the border of the iris. Constricting and dilating of the iris creates visible circular lines or grooves on its surface. In addition to these formations, white lines formed by the blood capillaries of the iris can be observed. The pupil can constrict to a minimum diameter of 1.5 mm and dilated maximally up to a diameter of 8mm. Besides light conditions, the pupils can also respond to psychological or chemical signals.[7]

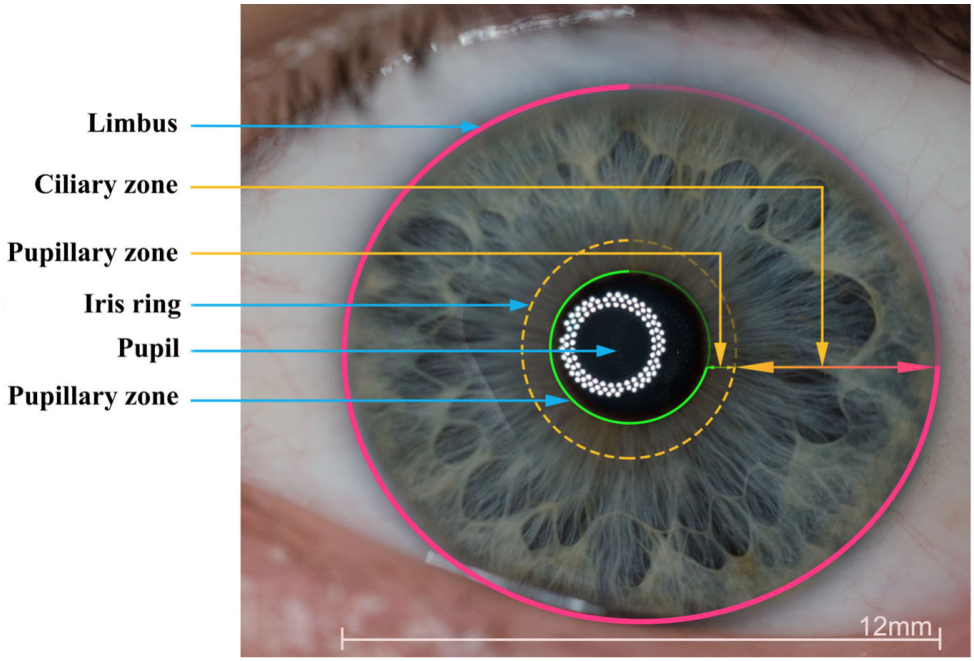


Figure 2.2: Detailed frontal image of the iris

### 2.2.1 The basic components

- **The limbus**(*lat. limbus corneae*) is the lateral area of the border transition between the sclera and the lens. It can also be considered to be the border with the iris. It is the thinnest part of the iris 0.5 mm, and sometimes it is also referred to as the root of the iris.

- **The iris collarette**(*lat. collarette*) is a developed area located on average 1.5 - 2mm from the pupillary edge that divides the iris into two distinct, large parts: **the ciliary part** and **the pupillary part**. It has the shape of a wavy circle and is the widest part of the iris (0.6 - 1mm).

- **The ciliary zone**(*lat. zona ciliaris*) extends from the root of the iris (Limbus) to the iris mesentery. The width of the area is 3 - 4mm, and therefore it is the largest area of the iris. It is further divided into three parts. The first one closest to the mesentery is relatively smooth and features the appearance of rays-like furrows. Then, in the middle part, there are circular constriction furrows. The peripheral part is then characterized by the numerous appearance of crypts.

- **The pupillary zone**(*lat. zona pupillaris*) a relatively flat area that runs from the pupillary edge to the iris mesentery. In proportion to the ciliary zone it is smaller, with a width of 1 - 2mm. There are not as many furrows on it as on the ciliary zone.
- **The pupil**(*lat. pupilla*) is a hole through which the sunlight passes into the eye. It is located roughly in the middle of the iris, however, its position is not exactly central. The size of the pupil under normal conditions is 3 - 4mm.
- **The pupillary margin**(*lat. margo pupillaris iridis*) is a thin hem bordering the pupillary zone and pupil. A dark edge can be observed on it, which rises to the foreground. This pigmented part protrudes from the back of the iris and makes the pupil look dark. Sometimes, this is called *the pupillary ruff*.

### 2.2.2 Features

The distinctive features of the iris develop in the first eighteen months of life, then the texture and features of the iris remain unchanged(except for colour). Significant changes then only occur with diseases or injuries of the iris. The anterior stroma cornea (*lat. substantia propria*) is formed by elastic and collagen fibres, the latter are then interwoven with smooth muscle. The posterior stroma is formed by a deeply pigmented two-layer tissue.

The combination of features, colour and texture are characteristic for every iris, and this also applies even to the irises of the same person. The individual colours of the irises can then differ from each other (more later in sub chapter 2.2.4). This creates more than 400 unique markers, which are used in biometrics, in particular for identification and verification.

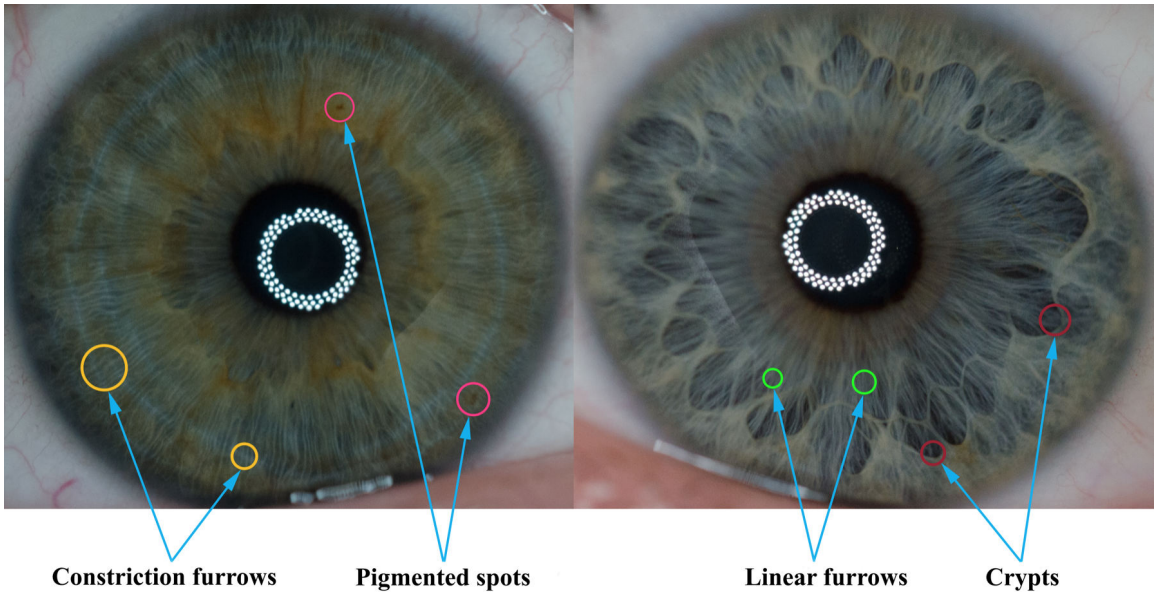


Figure 2.3: Sample of typical shapes in the iris of the eye

The texture then creates a couple of basic shapes, among the most significant and best visible are **Crypts**(*crypts*). These are formed by sparse ligament, in which there are numerous pigment cells, smooth muscle cells and a network of blood vessels.[27] Most often they have a circular, depressed form. The crypts that are located near the iris ring are then called Fuchs. Then, there are **pigmented spots**(*pigment spots*). These can be found anywhere on the iris except the pupils. These are small brown spots of irregular shape. **Furrows** are narrow, light formations. They are divided into two basic types, namely linear, which most often occur in the pupillary part, and the constriction furrows, in which movement can be observed when the pupil dilates. Constriction furrows are found predominantly in the ciliary part of the iris. Small, regular spots of white or grey colour that form a circle in the stroma of the iris around its perimeter, are called **the Wolfflin nodes**. Finally, various arched ligaments can also be found, rings, coronas, ridges.

### 2.2.3 Colour

The colour of the iris is one of its most pronounced properties. This depends primarily on the thickness of the ligament stroma, the density, the filling of the blood vessels and the pigment, which shines through from the posterior part of the iris. It is produced by pigment cells, or **melanocytes**, which can also be found in the stroma of the iris. Although there is a near inexhaustible range of colour combinations of Iris, the pigment cell produces only one pigment. This is a dark colour known as melanin. There are two forms of melanin: **eumelanine**(*brown-black*), which is primarily responsible for the dark colour of the iris and for protection against UV rays, and **pheomelanine**(*yellow-red*), which occurs in the iris only to a very small extent or not at all and causes, for example the yellowish fragments of the iris.[19]

The exact colour and, most importantly, its intensity is influenced by a lot of other factors. For example, the number of pigment cells in the iris, the latter greatly affects the saturation of colour or the content of red components in the blood circulating through the ophthalmic organ, which, to a small extent, affects the colour. Thus, the range of colours varies from light blue, through green blue, or green, or varying degrees of grey to light brown, which then gradually passes on to deep, dark shades. Such eyes then are said to be black eyes.[33] The iris acquires shades of blue if there are few pigment cells. The light reflected from the back pigment layer then has a blue colour. If the pigment is also found in the stoma, green or brown shades are obtained. These also depend on the intensity of the pigment that the melanocytes produce.

Among other things, **the OC2 gene**, located on the *15th chromosome*, is responsible for colour. A second gene, **GEY** or **EYCL1** can be found on the *19th chromosome* in the green or blue variation, the latter also contributes greatly to the colouring of the eyes.[18]

The colour stabilizes during the first 3 years of life. Newborns tend to have a light blue to light purplish colour. This later fades away during the first year of life, mainly darkening. From the 3rd year of life, more significant changes in colour take place. However, the colour is not constant and oscillates around its base. Mainly due to hormones, which largely affect the formation of pigments in the body. In addition, the state of health or stress also affect the production of pigmentation to some degree. The exact mechanism how these changes work in the production of melanin, and therefore changes of colour is currently still not entirely known.

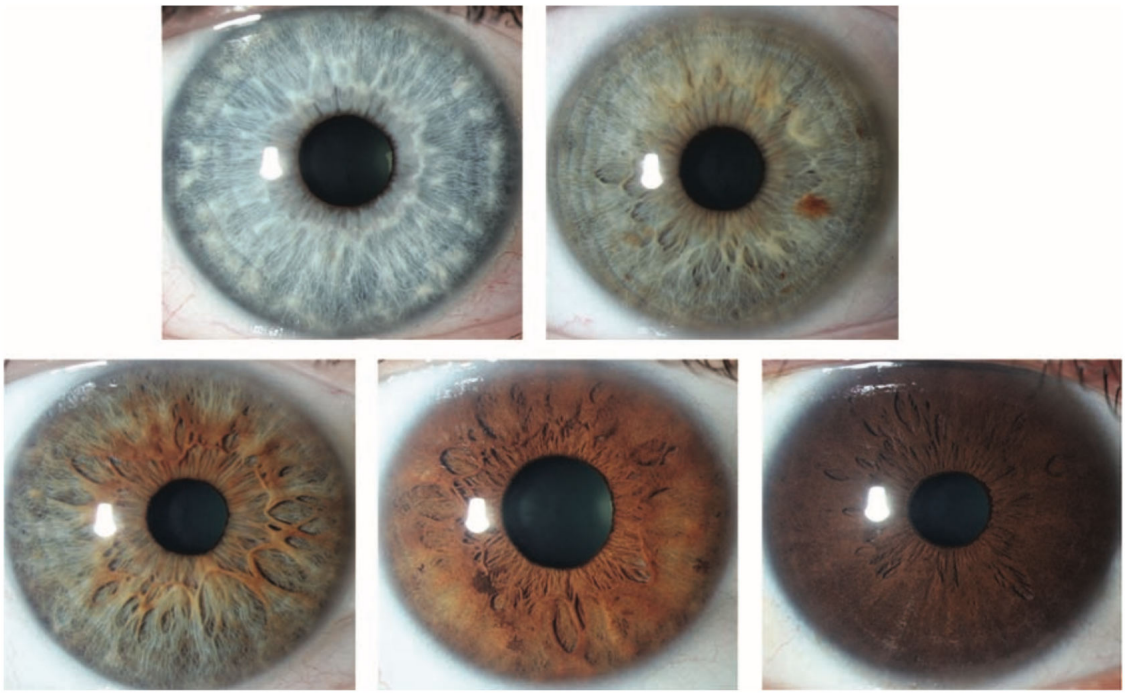

Figure 2.4: An overview of the basic colours of the iris. *Top left:* blue; *top right:* blue-green; *bottom left:* green-brown; *bottom centre:* light brown; *bottom right:* dark brown; (taken from [2])

### 2.2.4 Diseases

Multi-colouring of the iris is called **heterochromia**. This is caused by a lack of or excess of melanin production and either affects part of the iris(*Heterochromia iridis*) or the whole iris(*Heterochromia iridium*). In complete heterochromia, a colour difference can be seen in between the one iris and the other. In the partial form, two types are recognised: **central** and **sectoral**. The most common form of heterochromia is central and this is observed as a differently-coloured circle, which most often occurs around the centre of the iris. While the sectoral form can be described as a non-specifically shaped segment, which differs in colour from the rest of the iris.

Heterochromia can be congenital, that is, genetic in origin, or arise as a result of disease of the iris or from injury. It is not a physiological phenomenon that requires a medical diagnosis, as it does not directly threaten health. It is very rare and occurs only in a small percentage of the human population. There is no evidence of a link between the occurrence of heterochromia and gender.[33]

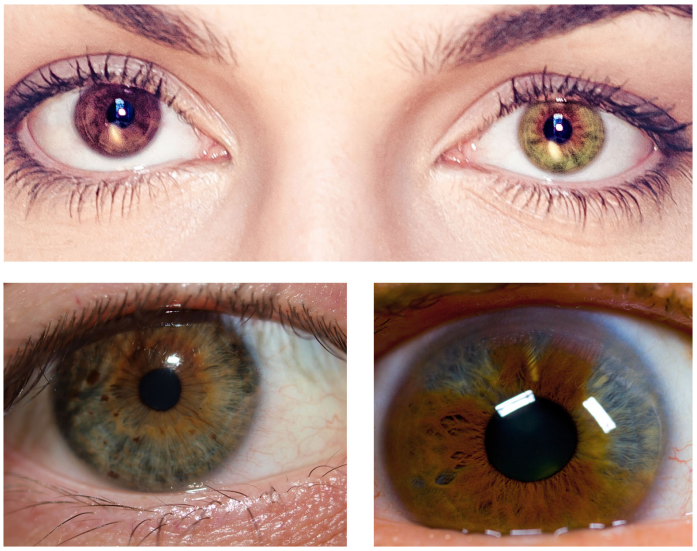

Figure 2.5: An example of heterochromia. *Top:* complete; *right:* central; *left:* sectoral

**Albinism** is a rare genetic disorder that stops the formation of the melanin pigment. (*Albinismus ocularis*), specially affecting only the eye. Lack of pigmentation is seen not only in the iris, but also in the ciliary body or in the retina. The missing pigmentation in the iris then causes the iris to have a pink colour. This is due to the fact that the missing pigment does not absorb coloured rays, and therefore it is uncoloured. Thus, the pink colour is formed by the shining of the red colour from the choroid. People with this disease tend to be light-sensitive. Treatment of this disease is difficult, contact lenses with an artificial iris help the condition by reducing the degree of glare.[33]

**Nevi** are benign pigment spots. They often occur in the iris and are even used as one of the features for identification. During puberty, these nevi can then increase in size and, in rare cases, develop into melanoma. It infiltrates the iris surroundings and can be malignant. However, due to the small danger of metastasis, there is no pressure to excise it.[33]

# Chapter 3

# Imaging the iris

The purpose of iris imaging can be divided into two large fields. One of them is **ophthalmology** (*ocular medicine*) and the second is **biometrics**. In the case of Ophthalmology, such emphasis is not placed on the detail of the picture, since most symptoms of Iris disease or injury are commonly visible. Biometrics, on the other hand, works the other way round. Details here are of the greatest importance as well as the speed of creating the image and its possible processing. Therefore, in biometrics, new ways are always being sought to effectively scan the human iris. Out of range of modern technologies and, most importantly, the reduction in size of sensors, iris scanning can now be used as a security element in smart phones. Here, however, the speed of the system is placed above the reliability of scanning itself and evaluation of the image. Therefore, they are built in such a way that the quality of the images is not especially good, but their evaluation is very fast. Most such systems usually do not even check features of the iris but rather the position of the pupil and other major parts of the eye.

Scanning can be divided into two main fields, according to the spectrum in which the iris is scanned. Scanning in light from the **near-infrared spectrum region**(*NIR*), this uses an infrared LED diode to illuminate the iris. This contributes to highlighting the distinctive features of the iris and ensures the overall purity of the image, since there are not many disturbing elements in the scanned spectrum. However, the images taken in this spectrum lack colour information. This is the method most often used in biometrics. The counterbalancing this is scanning in **the visible light spectrum**(*ordinary light*). A classic camera or smart phone is enough to take such pictures. The biggest drawback of this solution is the volatility of the image quality, more specifically, the level of detail being such as to make it possible to evaluate the image. The quality of the picture depends on many factors. However, with proper picture quality and the level of detail, it can provide us with better information than the images taken in the infrared spectrum, in particular information about colour.

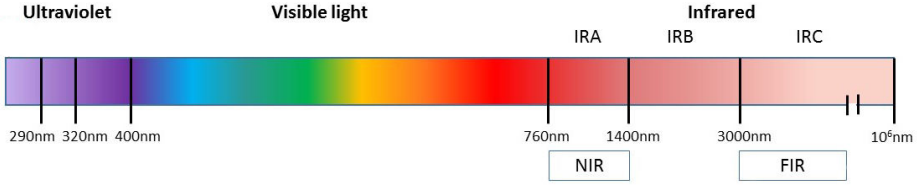


Figure 3.1: The light spectrum (taken from [1])

## 3.1 Infrared spectrum

**NIR - Near infrared** uses the 750 - 1400nm wavelength range, though for scanning a value of 850nm is used.[6] Radiation of this wavelength is not absorbed by melanin and, thanks to this it has very good permeability even with a highly pigmented Iris (black eyes). Another indisputable advantage of this solution is that this wavelength does not dazzle the scanned person, since the human the iris is not sensitive to this wavelength. However, this wavelength fails to provide sufficient information about the pigmentation itself. Most CCD sensors, however, are not adapted to scan such a wavelength. Thus, while maintaining the desired quality, special equipment has to be used.[6] Other disadvantages associated with scanning are the necessity to take off the glasses or remove contact lenses, moreover, the human eye is not used to this wavelength. Instinctively, it is not so capable of reacting, for instance, by blinking. The maximum NIR illumination is set at 10 $mW/cm^2$.[3] The scanning distance is limited to tens of centimetres. A considerable degree of unreliability then appears in systems that use NIR during changes, for numerous inflammations or in removing the iris in people with translucent disability of the ophthalmic background or after cataract surgery. Systems using this method of scanning can easily cracked thanks to very high quality photographs or a contact lens with the iris printed on it. To reduce the likelihood of penetration, it helps vivacity detection.

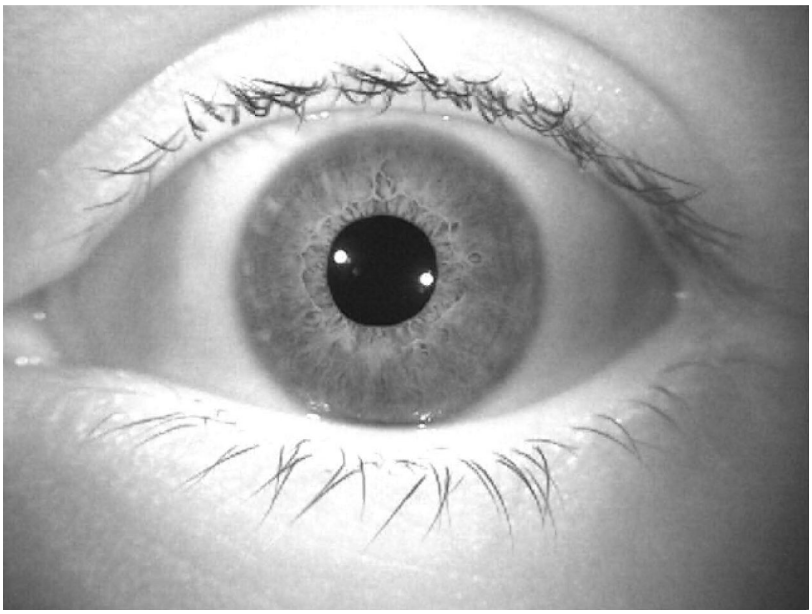

Figure 3.2: Sample image of the iris in NIR (taken from[23])

## 3.2 The visible spectrum

The 380 to 780nm wavelength spectrum is visible to the human eye. These wavelengths are successfully absorbed by melanin in the iris of the eye and therefore, it does not obtain similar data quality as would be in the case of the NIR spectrum. However, this compensates for the fact that it is possible at this wavelength to transfer a large amount of information about pigmentation. The wavelength contains all the colour components that are needed to describe the colour of the iris. So then it is possible in this spectrum to observe all the significant features that it contains. The level of detail is closely related to the sufficient intensity of the surrounding environment, in particular to illuminate very pigmented irises, a high intensity of additional light is needed.[3] in case of insufficient illumination, the murmur of the image and its degradation come. It brings even more complications, because the human eye is sensitive to that wavelength and, from a certain intensity of light, scanning the subject's eye becomes uncomfortable and can be dangerous for the eye. Very often, quite a lot of light artefacts appear in the images. These are caused by the reflection of some parts of the wavelength off the cornea. No special devices are needed to scan the iris at this wavelength, it is enough to use ordinary CCD sensors.

The inclusion of colour information in the image prevents the basic ailments from which NIR scanning suffers. For instance, printing a fake iris on paper or on the lens, which should then overlay the original one. The colour on both fakes will not be the same as in the case of the reference image (not even considering compensation). Thus, the need to test vivacity, due to suspicion, disappears in the fakes.

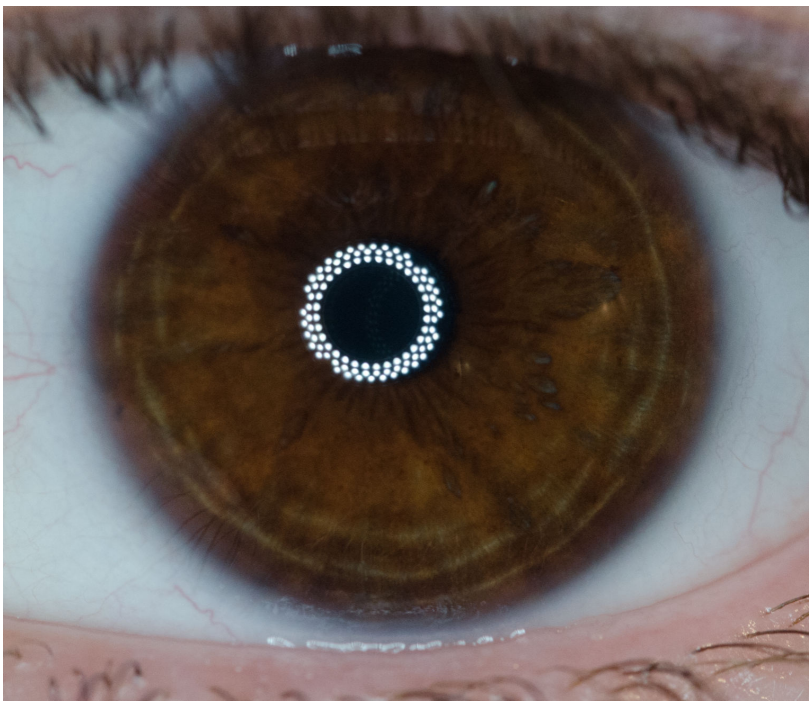

Figure 3.3: Demonstration of the iris image in the visible light spectrum

# Chapter 4

# Lighting

The design of the methodology for scanning in the visible light spectrum is a very demanding discipline. The visible spectrum has a lot of technical and, mainly, physical barriers which should be taken into account right in the first draft of the entire methodology. One of the most important aspects is the sufficient intensity of light (*illumination*) of the iris. Thanks to the sufficient intensity of illumination acting on the iris, it is possible to extract more information from the details, which stand out in the visible spectrum and in this way achieve higher quality images than would be the case with the **NIR** spectrum.

Higher light intensity also largely contributes to the elimination of noise in the resulting images, a factor that mainly smaller sensor formats suffer from, with the so-called crop factor, than is in classic photographic film. However, light intensity cannot be set too high, as it would lead to dazzle the scanned person, which means that there is a lot of brightness in the field of vision, or also there may be damage to organs of the eye. It is therefore necessary to find a compromise between a sufficient measure of light intensity and the comfortable median for the human eye.

The colour of the light colour or **chromatic temperature** must also be taken onto consideration as this significantly affects the resulting colour of the image by transmitting colour contamination into it. This contamination then significantly degrades the informational value of the colour of the iris.

## 4.1 Light colour

Chromatic temperature is divided into 3 categories depending on how the given colour appears on the temperature range. These are: **warm**, **neutral**, and **cold** colours. Warm colours typically have a temperature defined from 1000K to 4000K. Although this temperature range, which represents, for example, the heat of a candle or light bulb, is the most tolerated by the human eye, it adds too much colour contamination in the resulting images in the form of an orange-yellow tinge. The neutral temperature is represented by temperature in the range of 4000K - 6500K. This range most faithfully simulates daytime white light that generates the slightest or no colour pollution (with the exception of extreme values). Cold light is defined by temperatures higher than 6500K. Such colour temperature of sunlight can typically be observed on a cloudy day or in foggy weather. Colour contamination is then generated in the form of a blue tinge.[31]

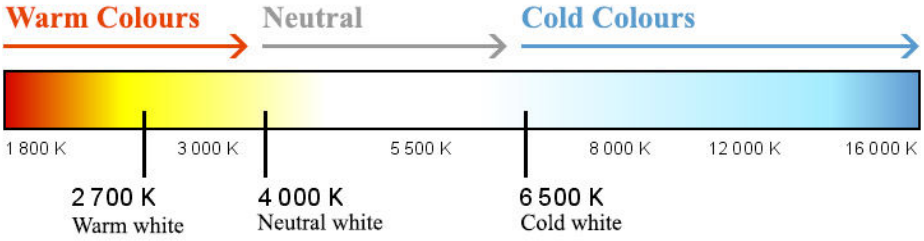


Figure 4.1: Range of colour temperature (taken from [31])

## 4.2 The degree of illumination

Scanning, as in the NIR spectrum, takes place at in close distance to the human eye. These are units of up to tens of centimetres. At such a small distance it is necessary to take into account the thermal damage to the retina, because huge amounts of light fall on the lens, which is transformed into a single beam that is then focused on the retina of the eye. **Radiation intensity**(*Irradiance*) $E_e$ (formula 4.1) is defined as radiant flow on a unit area[$W/m^2$].[25]

The maximum intensity of such radiation is then defined by the European Union into two basic groups. *Group I* is limited by the maximum value of **1 mW/cm$^2$**, at this value, the human eye is not put to almost any physical stress and there is no threat of damage. *Group II* is defined by the following scale of values **1 - 10mW/cm$^2$**. The human eye here is then subjected to physical stress. However, more pronounced damage does not occur if the eye is not exposed to this for a long time. Values exceeding the limits of **10mW/cm$^2$** are very dangerous for the eye and permanent damage to the human eye occurs even during short-term exposure. These restrictions generally apply to the entire range of visible light and the NIR spectrum.[30]

$$E_e = \frac{\partial \Phi_e}{\partial A} \tag{4.1}$$

An important factor is also the total time of light flow from the light source to the eye of the scanned person. At this level, two different approaches are generally recognised. The first is short-term exposure (in the order of milliseconds) to extremely high light intensity. This approach is mainly used for photographic flashes, when a very strong light is discharged for a short period of time. The duration of the discharge is then directly dependent on the exposure time. An extreme discharged light, though in a very brief flash of time, is very stressful for the eyes and unpleasant for the scanned person. The second approach exposes the scanned eye to long-term light radiation. The effective light intensity is then typically several times lower than in the first approach, and the eye is not subjected to such physical stress. The eye also adapts partially or completely after a certain time when the light source acts on it. Another advantage of this approach is the pupils are constantly constricted (more in chapter 2.2) therefore a larger area of the iris can be seen, which provides more information. In the first approach, the rapid transition from insufficient light to a large amount of light as result of the discharge may cause the pupil not having enough time to constrict to their original status and thus depriving us of information. Its behaviour can be observed in the left image from figure 4.2, which was taken using a flash system. Thus, it can be seen that the pupil did not constrict quickly enough to its normal size. In this

image, the lack of light intensity can also be seen, this causes a low level of detail, and hence poor image quality. On the contrary, in the image on the right in figure 4.2, it can be seen that the pupil has a standard size and the illumination intensity is enough to be able to see all needed levels of detail.

Figure 4.2: Comparison of photos with differing intensities of light source.

## 4.3 Proposal

First, it is necessary to express mathematically and, after that, to determine the necessary intensity of light. The intensity of light must then be converted to the intensity of radiation and verified that it does not exceed the permitted limits and therefore that the health of the scanned person cannot be compromised. For the mathematical expression will be used features and formulas for calculating the exposure time, where they are used the basic exposure value, therefore, if required the intensity was higher than the permit limits, it will be necessary to adjust the basic value of the exposure time and slightly reduce the quality of the images.

Exposure is the amount of light per area. More precisely, the amount of light that for a certain time will act on the image sensor. This value is significantly influenced by the shutter speed, which indicates for how long it is opened, and therefore the light can flow to the sensor. The second value affecting exposure is the lens aperture, which behaves similarly to the pupil in the human eye and lets in only as much light as its value indicates. It regulates the amount of light with the help slat that reduce or enlarge the aperture through which can rays of light can flow. The value of the aperture also, to some extent, affects the depth of sharpness of the image. Its value then, in the end, is constant. To some extent, the shutter speed is also constant, which must be very small, thanks to the micro-movements of the eye. These would, over a long period of time, cause blurring of details. The exposure value **EV** is acquired by applying the formula 4.2, **N** designates the aperture value and **t** is the shutter speed. Thanks to the exposure value, it is easy to calculate the necessary light intensity **E** using formula 4.3. It can also be expressed using brightness **L** and the following formula 4.4.

$$EV = log_2 \frac{N^2}{t} \tag{4.2}$$

$$E = 2.5 \times 2^{EV} \tag{4.3}$$

$$L = 2^{EV-3} \tag{4.4}$$

Due to constant illumination, unwanted reflections in the eye will occur. Since these reflections cannot be significantly prevented, at least they should be directed away from the iris, preferably into the pupillary part of the eye. This will keep images made clean and without loss of information. For this reason, a light source of circular shape is chosen, which is placed directly on the lens, thus using the principle of a macro flash. This ensures that a scanned person staring directly into the centre of the lens has the light source projected directly into their pupil. It is also necessary that the outside diameter of the source is not too large and does not exceed the size of the pupil, which would then be constricted in that case.

When creating a depth map, it is necessary to create the largest set of images of one iris with different depths of field. using an algorithm, the image sets are then combined into a single image with a continuous depth of field. Such a connection is very demanding and it is necessary to detect edges or points that will then be used to compose individual frames. Artificial anchor points have to be made. These will take the form of coloured diodes that are placed in the shape of a symmetrical cross. Always the same colour diodes are found on the vertices and horizontals. In the case of design 4.3, the red diode is on the vertical and green on the horizontal.

5500K LEDs provide the light source itself, this temperature is generally used as a source of neutral white light. As can be seen in design 4.3, the LED diodes are placed in double-rows with no diodes overlapping. This allows for the creation of continuous light around the entire circumference of the ring. The double row then allows for a change in intensity by activating and possibly deactivating individual rows. The source itself then must be diffused. However, a central diffuser cannot be used as it would obscure the colour diodes. It is therefore necessary to select diodes that are already diffused.

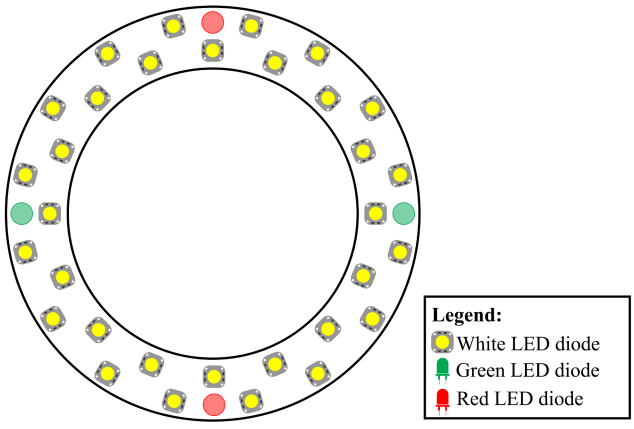


Figure 4.3: Desing circular lightning

# Chapter 5

# Methodology

Since there are not many specialised articles or information covering this issue, the theoretical basis for the methodology has to be derived from other sectors. Then, various combinations or variations of this information have to be made to meet the needs of this methodology. Information is drawn mainly from the fields of photography, physics and ophthalmology. As with any industry, there are exceptions that confirm the rule. Theories exist that are deliberately violated, especially when it is necessary to transform certain methods such that they can be combined with others.

Thus, the theoretical base only determines the outlines (boundaries) within which it is necessary to stick in order to achieve the desired results. The exact or, at least, similar data can then only be reached by empirical research. Therefore, established theories, as outlined in Chapters and , cannot be fully relied upon, but rather taken as a basis for help. Often, while the methodology was being developed, changes were made to the original thesis which, in some respects, proved to be impractical or did not lead to the desired results. Changes have often been iterative, as many of them came about only after more thorough investigation.

As the scanning and development of some of the necessary components is still ongoing, the methodology can be considered to be experimental. Therefore, it cannot be stated that identical results will be reached if any other than the described or modified components will be used. The identical results may not be reached even when using precisely described components, as there are too many factors that can affect the result. We will try to eliminate these factors by narrowly specifying the complete set-up of all components to avoid greater data diversity.

## 5.1 Lighting

The first important step in the methodology was to rework the lighting. This greatly affects the quality of scanned pictures. Whether it be 'readability' of the minutiae in the iris or colour contamination of the resulting image, and the significant damage to one of the major minutiae - the colour of the iris. See Chapter for more information on these consequences.

As a solution, the commercially readily available **Aputure Amaran Halo AHL-HN100 LED Light Macro** was used for the initial set of test images. Even though this light is intended for taking macro shots, it has proved to be unsuitable for our purposes. On the one hand, its maximum intensity of permanent illumination was not sufficient, but also the accessory flash, which was designed to simulate lightning, did not work. It was too aggressive and irritated the eye. In addition, its intensity was not sufficient as the discharge time was much shorter than that of standard flashes. Removing the plastic diffuser did not help either. The intensity of illumination has increased, but it has still did not reach the required threshold that was needed. However, this commercial solution has served to design a custom solution. Its initial design can be found in the theoretical section in Chapter 4.3.

### Changes from design

The resulting lighting has undergone considerable changes, mainly due to the fact that originally the design planned with separate LED diodes. However in practice, these are not very useful nor are they commercially readily available. The following changes to the original design were the most significant:

- **Removing coloured LED diodes -** The circular base is equipped with LED strips, so when adding separate marker LEDs the strips have to be interrupted, connected to a separate coloured LED and then reconnected to the strip. In addition, when changing intensity (voltage) of the LED strips, the intensity of the auxiliary LEDs would also decrease, their meaning would then lose value.
- **Removing the LED diode chessboard layout -** In the original design, the LED diodes were arranged in a chessboard layout. This arrangement using LED strips is not possible and the strips were then mounted in three concentric circles around an inner circle. This allows uniform intensity throughout the entire length.
- **Use of a permanent power source -** Although the battery version would allow the entire setup to be more flexible, making such a device would be costly and impractical. When using a constant power source, various techniques can be used to modulate the intensity. For example a **DIMMER**, which allows for regulation of intensity. A similar mechanism can be used for battery systems, but these are technically and financially more demanding and do not reach such qualities as a constant power source.

### Prototype

As has already been mentioned, the prototype is based on a commercial solution from which is draws mainly its shape and general functionality. The shape is annular due to the fact that such a shape can be easily placed in the pupil. There will be no loss of data in the iris due to the light source overlap. The internal power then allows the light to be placed directly on the lens. This creates direct illumination of the iris. There is no need to specifically position the eye or user. By looking directly into the lens, we maximize the amount of data in the iris and eliminate the unwanted glare that arises due to corneal rounding when viewed indirectly.

2mm thick Plexiglas was used for the prototype ring base. The diameter of its inner ring is 8cm so that it can be placed on the used lens. The total ring diameter is 18cm. There are LED strips with **SMD LED diodes of type 5730** on it. These are placed in three concentric circles, as shown in the figure below 5.1.

Figure 5.1: LED strips on a plastic annular base

These, according to specification, have the input power set at **14,4W** per meter tape, being used with **1,5m** of LED strip being used, with an overall output is around **22W**. The temperature is then declared between the values **6000 - 6500K**, which was not the originally stated value for the design. However, this slight colour shift is calculated in the post-production part and will be compensated. The angle of light of each LED diode is then **120[stupnu]**. This ensures greater light scattering and thus less light intensity, which reduces the eye stress factor. The luminous flux is then given with a value of **1200lm** per meter of LED strip. The total radiation intensity, at maximum power incident on the eye, is not higher than $\mathbf{2.2mW/m^2}$, which is equal to risk group II (see chapter 4.2).

Since the prototype will only be used in laboratory conditions, it was possible to use LED strips that have only **IP20** protection. The **IP20** degree of protection refers to an *electrical device that adequately protects against electric shock from dangerous contact with the finger*. It is resistant to the penetration by small foreign objects and is not protected against water.[14] The power supply is then provided by means of **12V** DC voltage, which is controlled by the so-called *„Dimmer“* (shown in scheme 5.2). It can regulate the supply voltage in the range of **3 - 12V**, which allows for the manipulation of light intensity. Another thing that was not needed in laboratory and, mainly, in testing conditions was LED diode cooling, itself. These tend to overheat over longer periods of time (more than 20 minutes), which does not help their performance and, in particular, lifespan.

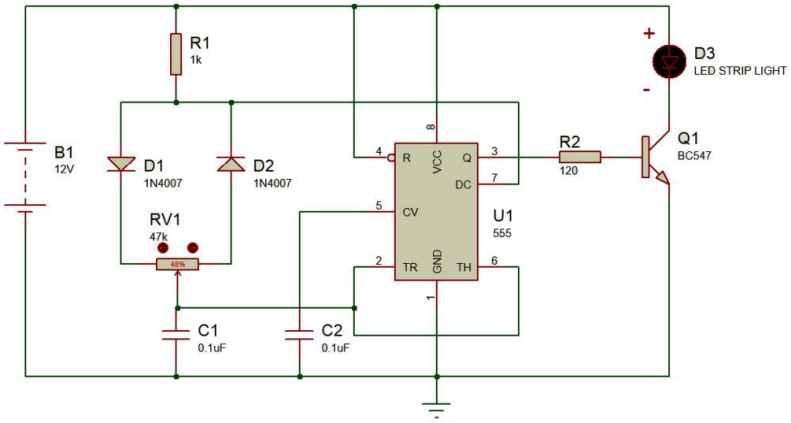


Figure 5.2: Prototype wiring diagram

The prototype is equipped with a **temporary diffuser**. One of the reasons being because of the softening of the light, which should significantly reduce the physical stress to which the eye is exposed and, secondly, because of the greater light scattering. For the time being, a diffuser made of white, waxed baking paper was used as it has similar optical properties to translucent, diffusing Plexiglas, which would be time consuming and financially demanding for the purposes of this prototype. This technique is widely used in photography.[28]

### Prototype testing

After the putting together the first lighting prototype, it had to be thoroughly tested. Given the time constraints that arose because the prototype took too long to make, it was clear that it would not be possible to produce original lighting from the prototype. The prototype was then used for all other scans, or it underwent minor modifications. The first extensive testing found several bugs that had to be resolved on the go:

- **Flickering LED diode -** This is a well-known phenomenon, as seen in Figure 5.3. It occurs when using LED lights that are connected to the mains. This is caused by cyclic voltage. The current is reduced to a value that does not keep the LED lit up, so the LED turns off, creating a flicker. Typically, the network is under a voltage of **230V** at a frequency of **50Hz**. Such a voltage has a characteristic sine wave, so within the space of a second its value is zero twice. This may cause some interference in the circuit behind the power supply. The dimmer itself interrupts the power supply to the LED strips, thereby controlling the current flow, causing a fluctuating change in light intensity. This multiplies the frequency of this phenomenon. One way to reduce this phenomenon is to remove the dimmer from the setup prototype. However, this results in not being able to adjust light intensity. Other options are, for example, using ballast, the installation of which would be too demanding in the prototype. The use of a capacitor that would be placed on a dimmer would greatly reduce voltage fluctuations. The most effective option is to change the camera settings to eliminate this effect. More in chapter 5.2.

- **Unsatisfactory size -** Originally, the prototype was designed for a different lens and camera. This setup had a greater minimum focal length. This was also in to relation the greater distance of the light source from the scanned eye. This problem can be solved by moving the light on the lens closer to the camera (i.e. away from the eye) and increasing the light intensity.

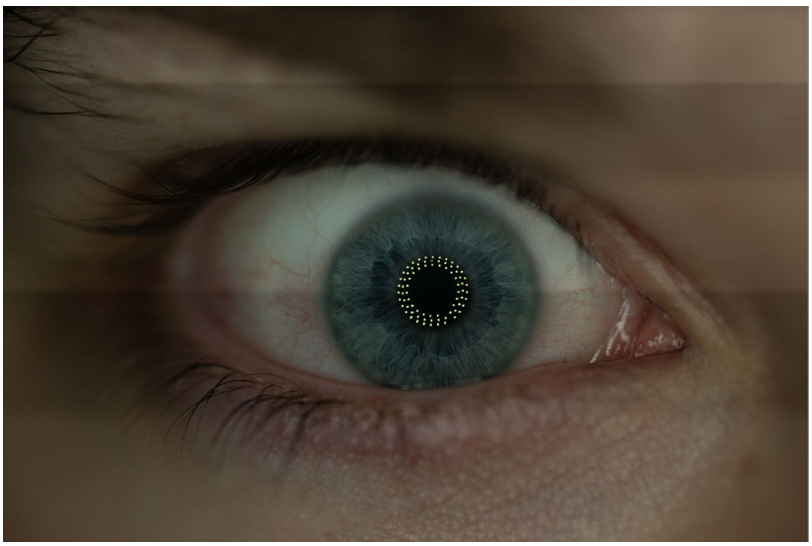

Figure 5.3: An example of a flickering fragment in a photograph

When creating a test set of images, the prototype intensity was set to **1/3 of its maximum power** after the first series of tests even with the diffuser attached. This output produced almost no physical stress to the eye, so it was possible to keep the eye open at all times. For better results, it is advisable to increase the light output setting. However, greater light intensity caused a tendency for the subject to close the scanned eye so as to regulate the greater intensity of light flowing on the retina. Thus, there was no direct exposure of the eye to excessive stress, but evoked a condition that only caused a defensive response. The layered diffuser could then lead to softer light and hence the ability to set the output to higher required values.

### Prototype modification

The most important modification of the prototype will be the replacement of the plexiglass mat and the installation of LED strips into the printed circuit. This will solve the diode cooling problem. Also, the individual mounted diodes themselves will be improved. On the other side of the printed circuit board, an enhanced phase-dimming mechanism will be placed, which should completely eliminate the flickering problem. Thus, the amount of wiring will be reduced and the handling of the entire lighting system will be improved. The printed circuit board can then be inserted into a protective cage.

## 5.2 Technology

There was also a significant change in the technique used, as opposed to the proposed design. For example, a **Nikon D7000** camera with **Nikkor** and **Sigma** lenses was used to create the first set of tests. These lenses had different focal distances, more specifically *60mm*, *85mm*, *105mm*, and *150mm*. Both lenses have a *Micro/Macro* ratio of **1:1**. This ratio indicates that a 1mm physical object is projected exactly as 1mm on the camera chip, as can be seen in the example 5.4. Therefore, there is no reduction, so the image is not distorted and the necessary data is not lost. There is also the possibility of using Macro lenses with an **X:1** ratio, which allows further magnification and detail enhancement.[17] However, such lenses are expensive. Fortunately, they can be substituted - more in chapter 5.2.

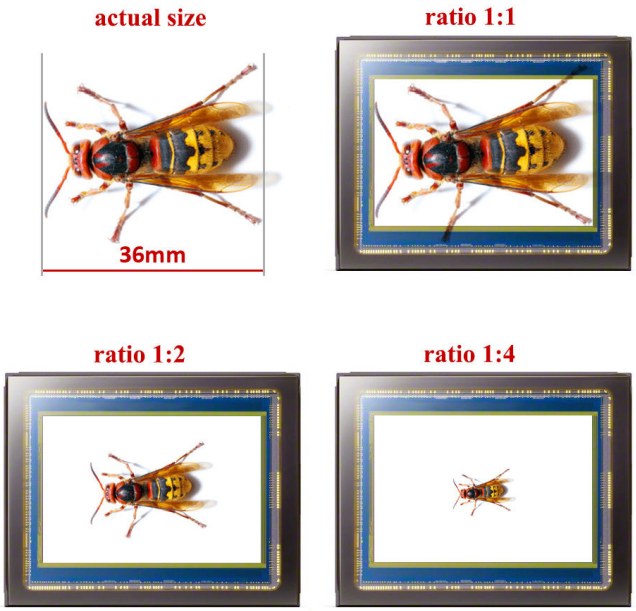


Figure 5.4: Chip magnification ratios taken from [15]

Then, it was found that the camera corpus, with its parameters, was insufficient. The chip is an **APS-C** chip. In the case of the Nikon, this means that the chip size is **1.5x** smaller than classic **35mm** film of dimension **24x36mm**. Such a chip reduction ratio is called the **crop factor**.[16] The advantage of chips with a crop factor is in the mentioned reduction, compared to film, in our case by 1.5. This factor increases the focal distance of the objects. This results in a narrower viewing angle of the camera while maintaining the declared minimum focusing distance. This phenomenon could then be described as digital zoom, without loss of data quality and without noise in the resulting image. The chip in the camera used by the camera then has a resolution of only **16.2Mpx (i.e. 4928x3246)**. This significantly reduces the amount of data in the resulting image. Generally, APS-C chips suffer greatly from noise in dark parts of the image at higher **ISO values**, which also significantly reduces image quality. This fact is especially noticeable when a **1:1** image is enlarged (i.e. the full depiction in its real resolution).

The main specification for the choice of lens, apart from the focal distance that indicates the lens shot, was also the minimum focusing distance. This indicates at what minimum distance to the object that the lens can focus. This, together with the first specification, creates what amount of data is displayed on the resulting image. For example, using a lens with a focal distance of 150mm and a minimum focusing distance of 10cm may cause a problem. The lens would be so close to the iris that, at that distance of 10 cm and a focal distance of 150mm, part of the iris would be beyond the boundary of the sensor and would not be scanned. A state has to be reached, where the entire iris and the sclera are displayed on the sensor. This condition must be achieved at a distance that is indicated by the minimum focusing distance and at the appropriate focal distance of the lens. It would be ideal that other unnecessary parts of the face would not be seen, such as the arch of the eye or the root of the nose. This would be the perfect situation so as to obtain the maximum amount of information from the image. Therefore, in the initial phase, a number of lenses with varying focal distances were tested. The best images were provided by the **Sigma 150mm F/2.8 Macro** lens, with a focal distance of **225mm** after compensation for crop factor, and a minimum focusing distance of **38cm**. However, as can be seen in picture 5.5, there is still quite a bit of free space and the amount of acquired data is rather average.

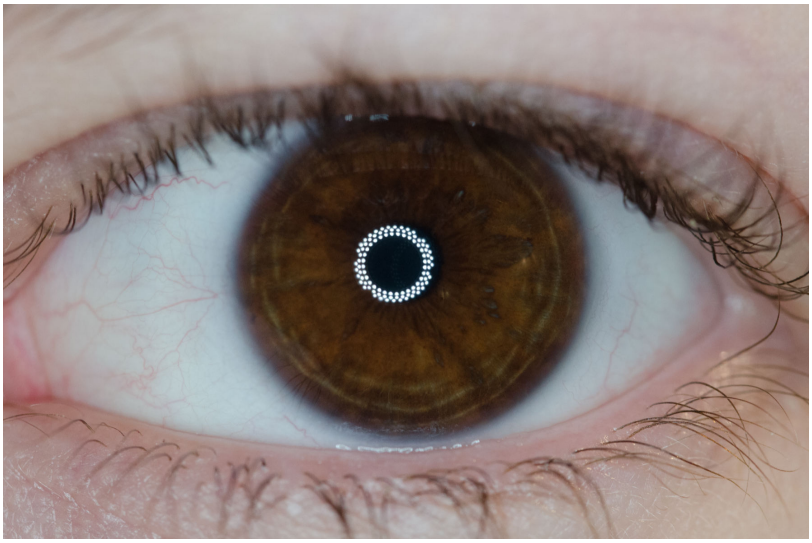

Figure 5.5: Image taken with a Sigma 150mm lens

### Camera

As was mentioned earlier, it was necessary to find a more suitable corpus for the camera. Nowadays, there is a wealth of camera models to choose from. Each of these models has its advantages and disadvantages and therefore it is not possible to explicitly identify the most suitable model. However, as a starting point, the requirements set by the specifications for the model should be taken into account. The first specification to be satisfied was that the new camera be **FullFrame**, or ***„FF“***. FullFrame has a chip size equal to the size of 35mm film. With this specification, a lot of models were eliminated as well as ensuring a higher quality of images, because FullFrame chips do not tend to create excessive noise in images.

Another specification was the size of the resolution. There was an effort to choose the model with the highest resolution and thus the greatest amount of information. The resolutions of such models range from **12Mpx** to **100Mpx**. 100Mpx models are usually quite hard to come by and very expensive. The last specification was good, low-noise image quality at higher ISO values. Only very few models matched these parameters, one of them being the **SONY A7R II**. It is a FullFrame, **42Mpx** camera with excellent, high ISO image quality. This high resolution would allow us to make cut-outs from the resulting image without worrying about the loss of a large amount of data.

### Lens

As a new corpus had been chosen, new lenses were also required, both because it is a completely different system, and therefore the previously used lenses cannot simply be fitted into the new corpus, and also because there is already a different sized chip mounted in it. The lens used, whose real focal distance after crop factor conversion was 225mm, should have, on this type of chip, its original value of 150mm. The choice of lens has narrowed only to lenses compatible with Sony systems. As mentioned above, it is impractical and unnecessary to mount third-party lenses through reductions if suitable native solutions exist. It was therefore necessary to find all suitable lenses labelled *Macro*. One of the few lenses then met all the required specifications was the **Sony FE 90mm f/2.8 Macro**. As its name suggests, its focal distance is 90mm and the minimum focusing distance is **28cm**. In addition, it allows the focusing distance to be reduced, which contributes to the precision of focusing at a very short distance. The magnification ratio for this lens is then **1:1**.

### Settings

As with the prototype for the light source, it was necessary to properly test the new corpus and lens and establish the basic camera settings so that the images would be consistent. This will be done by ensuring four key settings:

- **White Balance Settings:** With this setting, we can compensate for the colour shift that arises due to the different light temperature (more in the Light Colour chapter). We know that the temperature of the LEDs used in the prototype is given within the range of **6000 – 6500K**. So we set the white balance to *6300K*. This ensures colour stability and credibility of all images taken independent of time, without the need for additional post-production. In picture 5.6 below, identical photos can be seen with different settings of the white balance settings.

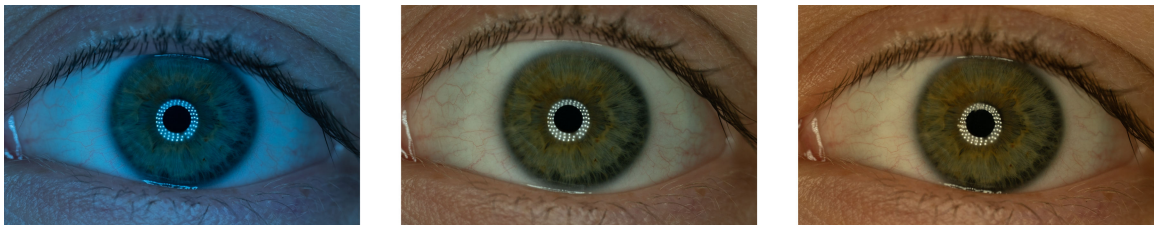

Figure 5.6: Different white balance values – *left*: 3000K, *middle*: 6300K, *right*: 9000K

- **Shutter speed (exposure time):** It indicates the time that the shutter, located in front of the chip, is open so that the camera chip is exposed to light. This greatly affects the amount of incident light and thus how light or dark the photo is. Setting the shutter speed to **1/100** means then means that the shutter will only open for one hundredth of a second. This exposure time will not allow in much light. On the other hand, a **15s** exposure time means that the shutter will open for a whole fifteen seconds, which is too long and allows a huge amount of light to reach the chip. When using the light prototype, we were forced to use an exposure time of **1/50**. This particular time, because the voltage that flows into the LEDs has a frequency of 50Hz, which is similar to that used for in high-speed flashes and so flickering is not seen in the images. Alternatively, it is possible to use multiples of this synchronization value, where it is then possible to see minute traces of flickering, but it is not as significant as in other values.

- **Sensitivity:** Also called **ISO** in digital photography, is another aspect that determines the exposure (lightness) of the resulting image. In general, it is the ability of light sensitive material to capture a certain level of light. The basic ISO value starts at 100 and the next value equal to twice the previous value, so 200. Each such value is then equal to half of the time needed to properly expose the image. In addition, the lower the ISO value, the better the image. Since at higher ISO values, typically from **3200**, there is a large amount of noise in the images (visible in picture 5.7), they significantly reduce the resulting quality. Due to the fact that the exposure time is more or less fixed, the sensitivity will be significantly modified. Since the last specification also affects the overall exposure of the image, namely the aperture, ISO will have a relatively limited range of setup options. It will therefore be necessary to set the ISO to a higher value. However, for the selected Sony corpus, this is not such a problem as the noise level at higher ISO values is not as significant as with other manudacturers. The values used are roughly in the range of 800 to 3200.

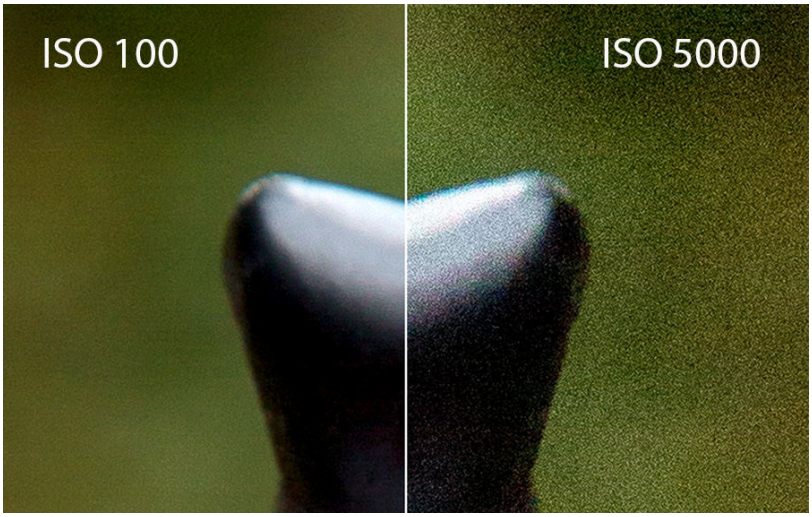


Figure 5.7: Visible noise at higher ISO parameter settings (taken from [20])

- **Aperture and aperture number (F):** This works along a similar principle to the pupil in the human eye. It controls the amount of light that passes through the lens to the camera sensor. Just as a pupil regulates the amount of a stream of light by widening or constricting. The system of expanding and constricting stops, arranged in a circle within the lens, works in a similar manner. Furthermore, the number of stops in the system depends on how the lens was constructed. This number only affects the image cosmetically and in places outside the depth of field (in parts of the image without detail). So then, it is not necessary to pay particular attention to the number of stops. The aperture is the last aspect to influence the exposure of the image [8]. However, it does not only affect the exposure of the image, but also the overall depth of field [9]. This significantly affects the amount of detail in the image. As a general rule, the smaller the aperture number, the greater the depth of field and thus the smaller the amount of detail in images at different distances. The aperture size is given by the aperture number, F, which is written as follows: **F/2.8**. The digit after the slash then indicates the smallest possible aperture. Also, the smaller the digit, the larger the aperture we can create, and the more light that passes on the camera chip. The size of the aperture can then be expressed by the formula 5.1 where **F** is the aperture size, **f** is the focal length of the lens, and **d** is the diameter of the aperture opening.

$$F = \frac{f}{d} \tag{5.1}$$

A double aperture number means a quarter of the light let through. For this reason, apertures are designated as multiples of the square root of two. This corresponds to half the amount of light each time.

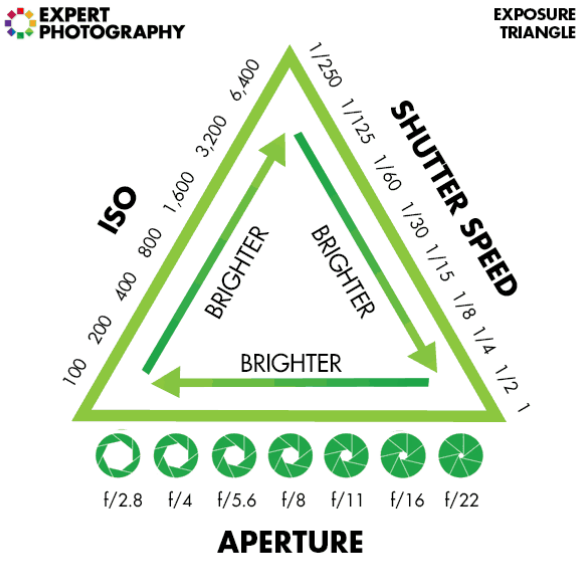


Figure 5.8: ISO parameter dependency, aperture and shutter speed (taken from [11])

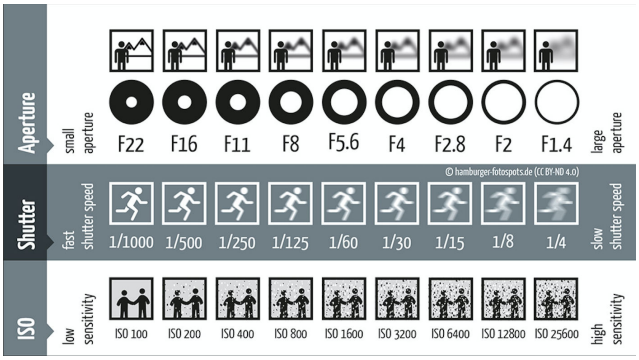


Figure 5.9: Image changes when setting individual parameters (taken from [10])

- **Depth of field** is the distance range (near distance for acceptable sharpness a far distance for acceptable sharpness) dividing the focus plane, which is determined by the focusing distance. However, depth of field cannot be seen as a physical phenomenon, but rather as a subjective range of deviations from the plane of focus. Thus, the expression of the principle on the human eye works, within the perception of detail, depending on the distance of the object. The extent of the depth of field is then influenced by 3 factors: **aperture**, **focal distance**, **distance**. Closing the aperture (increasing the aperture number) causes the light rays to be more parallel, and thus the deviation from the focus plane is not so large, by which the depth of field increases. Conversely, when opening the aperture, the depth of field becomes smaller as the deviation from the focus plane increases. The shorter the focal length of the lens, or its focus, the greater the depth of field. Longer focal points then reduce the depth of field. For very long focal points, or even telephoto lenses, the size of the depth of field range can only be **1 cm**. Last but not least, distance plays an important role. Here, the closer we are to the object, the smaller the depth of field and vice versa. Long-focus macro photography has its own specific features, where it reaches a very small aperture of **milli-to-micrometer** range depth of field. The size of the chip is such, that it does not have the depth of field. However, the crop factor can significantly increase the focus of the lens and significantly reduce the depth of field. A light spot passing through an unfocused lens appears on the sensor as a blurry circle. This circle is known as the **Circle of confusion (CoC)** and by its diameter, the size of the blur on the sensor can be measured. In an A4-sized image, the blur can be with in the tolerance of 0.25 mm, which is the resolution of the human eye. Thus, if we reduce the size from A4 to a 35mm film size, which is 8.5x smaller, we obtain a CoC value for the FF sensor that comes to **0.0294mm** (0.25/8.5). Applying the same formula will also give the APS-C sensor value, which is **0.0195mm**.[22] In the case of the lens used at its highest possible depth of field, at an **F/2.8** aperture and a **28 cm** distance from the lens, this depth-of-field plane is only 1 millimetre. Gradual testing revealed that the ideal depth of field, at that distance of 28 cm, moves around the aperture number **F/6.3**. This is a depth of field of **2.5 millimetres**. The size was calculated using the formula 5.5 for which we needed formulas 5.2, 5.3 and 5.4. Where: **H** – hyper-focal distance [mm], **f** – focal lens distance [mm], **s** - focusing distance, $\mathbf{D}_n$ – the nearest sharp distance (is the nearest distance for acceptable sharpness), $\mathbf{D}_f$ – the furthest sharp distance (is the furthest distance for acceptable sharpness), **N** – aperture number ($f$ – *number*), **c** – circle of confusion [mm] taken from [5]

$$F = \frac{f^2}{N * c} + f \tag{5.2}$$

$$D_n = \frac{s * (H - f)}{H + s - 2 * f} \tag{5.3}$$

$$D_f = \frac{s * (H - f)}{H - s} \tag{5.4}$$

$$DoF = D_f - D_n \tag{5.5}$$

- **FullFrame vs. APS-C mode:** As mentioned earlier, a camera with a 35mm film size chip, i.e. FullFrame, was chosen. This has indisputable advantages in better control over depth of field. Generally, it generates a higher resolution and has much less noise in images taken. Noise level and, subsequently, its reduction are both an essential factor since scanning takes place under laboratory conditions where no other light source is present, except for the developed prototype. Therefore, the images show a higher degree of noise. However, the selected camera corpus can also be switched to APS-C mode, which causes a crop factor of 1.5 to be activated and the resulting 42Mpx image resolution to be reduced to just 17.8Mpx. The software then records the data that would fit in the chip and discards the rest of the data. This mode allows us to extend the focal length of the lens from the original 90mm to 135mm along with a reduction in resolution. As a result, the coverage of the iris image is much greater than would be without using APS-C mode. However, there is more noise in the images. In picture 5.10 a difference can be seen in photos with APS-C switched on and without. In picture 5.11, a greater degree of detail can be observed in the case with APS-C mode switched off. When compared, the cut-out from the photo taken from the FullFrame chip is enlarged 1:1 in proportion to the image taken with APS-C enabled mode.

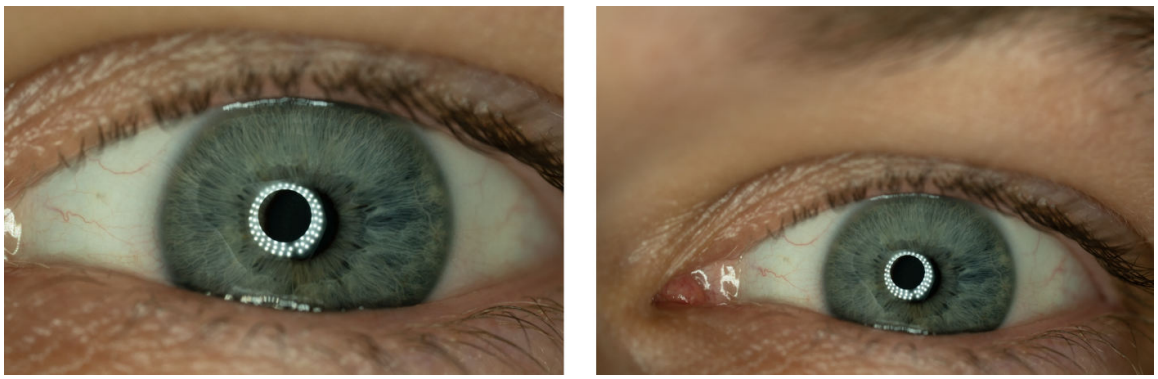

Figure 5.10: Return mode images comparison. *Left:* APS-C mode, *Right:* Fullframe mode

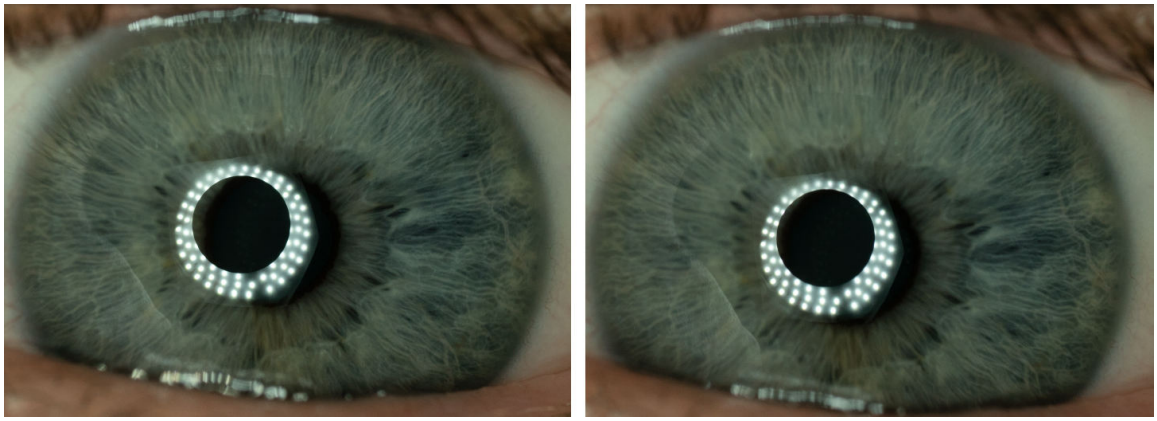

Figure 5.11: Comparing detail in a 1:1 ratio. *Left:* APS-C mode, *Right:* Fullframe mode

- **Focusing and magnification:** The original idea was to use autofocus. However, this proved to be a bad solution. Not even the most advanced system was unable to focus on such a small distance as required. Another option was to use step-by-step sequential focusing of the lens focusing ring. However, the necessary cameras API software from the manufacturer was not provided. The last method, and the one that was used, is manual focusing. Focusing is on at the minimum focusing distance and the iris is positioned exactly within this distance. The camera then allows the display to control the focus plane, which must be projected onto the iris. Due to the very shallow depth of field, only the iris and sclera are focused. Image quality is more than satisfactory, but at a **1:1** magnification it can be seen that some of the markers in the eyes are so small that their difference disappears and therefore it is not possible to properly separate them selectively. Nevertheless, they should interfere with far distance for acceptable sharpness. The laws of physics come into play here and the lens would need to be expanded to some extent. This reduces the minimum focusing distance and allows for better detail capture. Thus, it is possible to enrich the lens with a conversion lens, more precisely with a macro-lens or intermediate rings. The macro-lens works on the principle of a magnifying glass, which precedes the lens itself, allowing magnification greater than **1:1** mentioned in chapter 5.2. The amount of magnification is then given in the **dioptres (+1, +2, +4, +10)**. Unfortunately, the macro-lining has its ailments and the fact that in the final image a significant reduction of the drawing can be observed. As it is another optical element in the assembly, it brings with it a number of optical defects. The second option is the extension tubes. They look like a metal tube consisting of smaller sub-parts – an extension tube. The larger the extension rings (ie the lens distance from the chip), the closer the focusing distance of the lens is. Here it is possible to get to the minimum focusing distance in the order of cm. However, this also drastically reduces depth of field and is very difficult to focus on very small points. Just like a macro-lens, it allows greater magnification than **1:1**, but at the expense of reducing the flow of light to the chip, which, in such difficult light conditions, creates another complication.

# Chapter 6

# Post-production adjustments

As in chapter 5 suggested, the very small depth of field leads to the fact that the necessary details are in the iris outside the boundaries of the near and far focal plane causing loss of detail. Thus, it is necessary to refocus and thereby move this plane closer to the desired details. This procedure creates a set of images with a different focal plane and detail level. After that, the set of images have to be merged into one resulting image with a continuous depth of field. There are many ways to achieve such a picture, from fully manual methods to automatic modifications with differing output qualities. Stacking images can contribute significantly to improving the quality of the images because optical defects may not manifest themselves in all sub-frames. Merging the pictures allows for complete or partial elimination.

Individual filters or their variations can then be applied to the resulting image then a series of images can be obtained from it that have only one key property, mainly any of the markers found in the iris. This is, for example, a colour map or an image that shows only the edges detected in the image. These images can then serve to create a multimodal system that can be widely used in bio-criteria or in ophthalmology.

Alternatively, the possibility of using special filters and functions, for example, to eliminate defects or optical defects in the image, is offered. An example of such filters can be filters removing noise, focusing the image, removing vignettes or automatically trimming the image exactly to the iris.

## 6.1 Composition of macro photography

Before using any of the various methods for macro photography stacking, manual intervention in the set of images is needed. Specifically, the images have to be sorted. One that are out of focus or poorly exposed images have to be deleted and images that have any optical or technical defect, such the subject winking or with a half-closed eye, should be removed. It is also necessary to check that the photos are not duplicated, so there won't be two sets of photos with the same depth of field and the same focal plane. Also, if any of the images had not been deliberately moved, thus being out of the iris frame. Either of two basic approaches to stacking macro photography can be applied to such a set and these are:

### Manual stacking

this approach requires a raster graphic editor that can work with layers. Typical representatives of such editors are *Adobe Photoshop*, *GIMP*, *Zoner Photo Studio* and others. Such programs take each frame containing a different focal plane, placing it in a separate layer and any trimming with the subsequent shift to ensure that the individual layers overlap each other and are placed exactly over each other. Some of the more modern editors can do these actions semi automatically. The next procedure then differs depending on the particular editor and its options. The first option is to gradually delete parts of the images that do not have sufficient detail (do not have the necessary depth of field), throughout all the layers. As a result, individual layers are formed in which there are only fragments of correctly sharpened images. Together, these form the resulting stacked image. However, this is a so-called *„destructive“* method, which means that when deleting part of the images, data is irreversibly lost, even if it contains a lot of useful information. Editors such as the above mentioned *Adobe Photoshop* can work over layers with the help of masks. Thanks to these masks, unnecessary frames of the images become invisible, creating the impression that they had been removed. Thus, the result is the same as when using the first method, but all the information remains available from all the images and can be used if needed. In general, the advantage of manual stacking is having full control over details and, most importantly, in what places can be viewed. The disadvantage is the slow production of images, even with the use of semi-automatic scripts that compare the images and load them into the appropriate layers. In addition, it is a generally known fact that any manual intervention leaves open the the possibility of errors and applying the method twice to the same set of images may not produce the same results.

### Automatic stacking

Thanks to various fields of science that make use of stacking macro images (for example, imaging beetles using specialized microscopes), an entire range of software has been created that allows automatic image stacking. In general, most of these programs uses an edge detection approach that indicate that the image to be converted to a layer is correctly focused for the particular detail. Subsequently, the edges thus detected in each layer are blended into one common result. However, as has already been mentioned previously, a few rules must be observed and, the more of these rules kept, the better the result that can be expected from automatic stacking. For example, ensure that the iris images is always in the same place or that in the set of photos contain only images that are correctly focused. In this approach, the **Helicon** software package is by far the most advanced. The package includes two programs: **Helicon Remote**, which offers the ability to help in the actual imaging and can also remotely control the camera's focusing interface. This will automatically provide a set of images that meet all the conditions and rules for macro composition. **Helicon Focus**, the second program, then takes care of the very stacking of the beforehand prepared images from the first program. This solution, however, is strictly commercial, and unfortunately does not work properly on the chosen camera and lens right now. When testing this software, the individual focusing steps between transitions were too big so the resulting set of images lacked important, properly-focused parts of the iris.

Another option out of the range of available software is the already mentioned *Adobe Photoshop*, which, besides being of service in manual stacking, also has its own the auto-stacking feature. However, this is not its primary function and the images have to be significantly adjusted beforehand, or after stacking, manual correction has to be applied on the resulting image. Conversely, software such as *Zerene Stacker* or *CombineZM* were created specifically for making macro stack images or panorama shots. Besides these bespoke software solutions there is also a large number of scientific publications that cover the *Depth of field synthesis* topic, which exclusively focus on automatic stacking macro photography.

### Testing

In the framework of testing it was necessary to apply all possible and even the above-described methods to the sets of images. However, all the tested approaches gave the same error and so the results could not be used. As mentioned earlier, macro focus stacking methods require a prior sorting out of the images. First of all, sort non-valid images out of the set and then evaluate the position of the iris. However, not even such preparation helped. In general, these methods count with images in the set not changing, which does not apply to the iris of the eye. Over the period of imaging time the iris size and structure change, for instance, as a result of winking. Therefore, it is not possible to ensure that this won't happen during refocus on another focal plane. The change in the structure after re-focusing can be seen in Figure 6.1 where the manual stacking method is employed. Then, the automatic methods can correctly stack images into each other. However, the result 6.2 shows the inconsistencies of the individual images, in particular the transitions between the individual images, both the individual parts of the iris do not attach to each other. This phenomenon is most pronounced in light eyes, where in detail there are a lot of microscopic fragments, which, just by the movement of the iris, very often contract or dilate. This phenomenon was observed across all test sets. The phenomenon can only be transitioned using a method which at one point could take three different images with varying focal planes. The solution is not to create a set of images with a small depth of field, but by increasing the aperture to create an image with a depth of field that sufficiently covers the depth of the iris, as described in chapter 5.2. However, the disadvantage of this solution is a greater ISO value, which will then show up in the picture as slight noise. It also cause a loss of detail. The latter, however, is negligibly. Both these flaws can be solved by applying appropriate filters, more precisely to eliminate colour noise. This can cause unwanted blur and subsequent fine focusing of images with the desired depth of field, which in turn can add more noise to the image. Because of this, a suitable compromise has to be reached between the application of both filters.

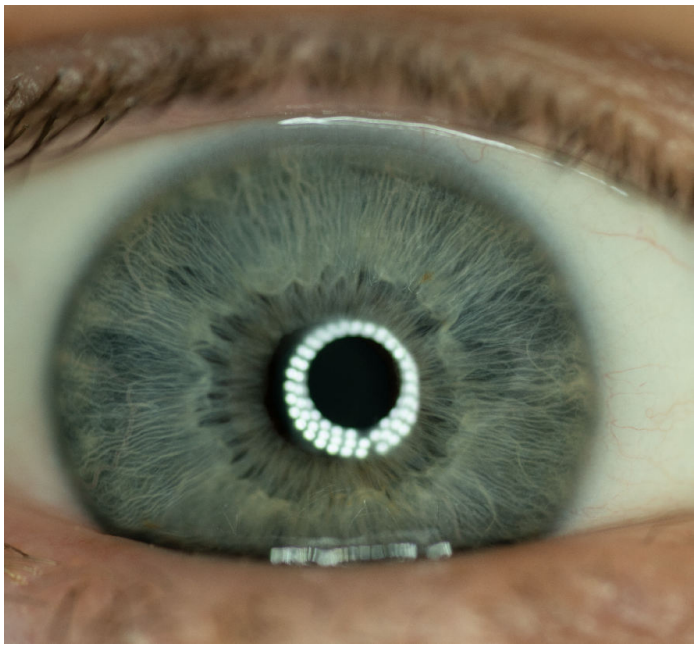

Figure 6.1: Manual stacking

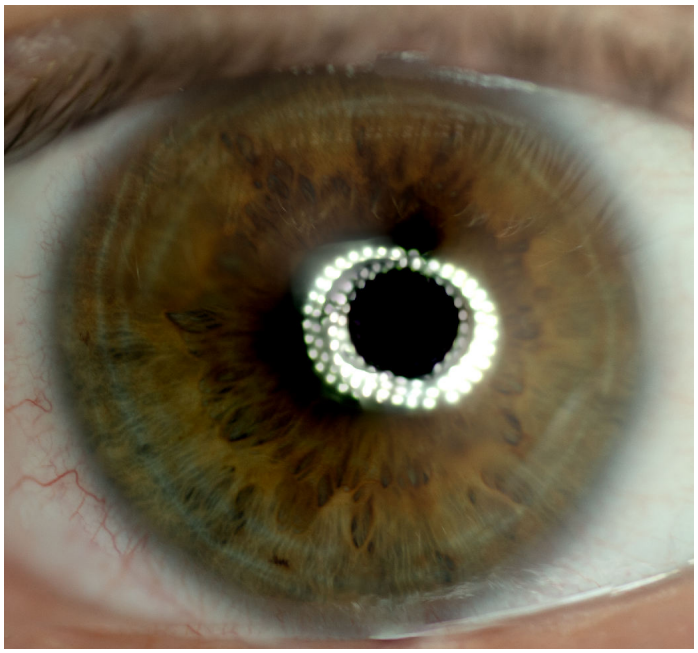

Figure 6.2: Automatic stacking

## 6.2 Filters

As a result of the change in the method of taking the resulting images, it was necessary to add post-production filters that would eliminate the flaws of the newly selected method. These were mainly are filters for the elimination of colour noise, for example, a **Low-pass filter**, a **Gaussian filter** or one of the **Nonlinear filters** were used. Then there was the fine focusing of important parts of the image that contain the depth of field needed. This, for example, was a variation of the **High-pass filter**, which only allows through high frequencies that define in and image detail and proper space. This release of high frequency, however, is precisely the reason noise gets back into the image. Therefore, it was necessary to test and verify to what extent individual filters should be applied to the image in order to achieve the desired results. Experimenting with these filters led to the idea to apply other suitable filters, which could significantly contribute to highlighting the depth or pigment maps in the iris of the eye, and thus ensure a better readability of the minutiae in the iris, independently of the colour of the iris. The first experiment was conducted on the above-mentioned high-pass filter. This was not applied directly to the image, but a mask was created using the filter visible in picture 6.3.

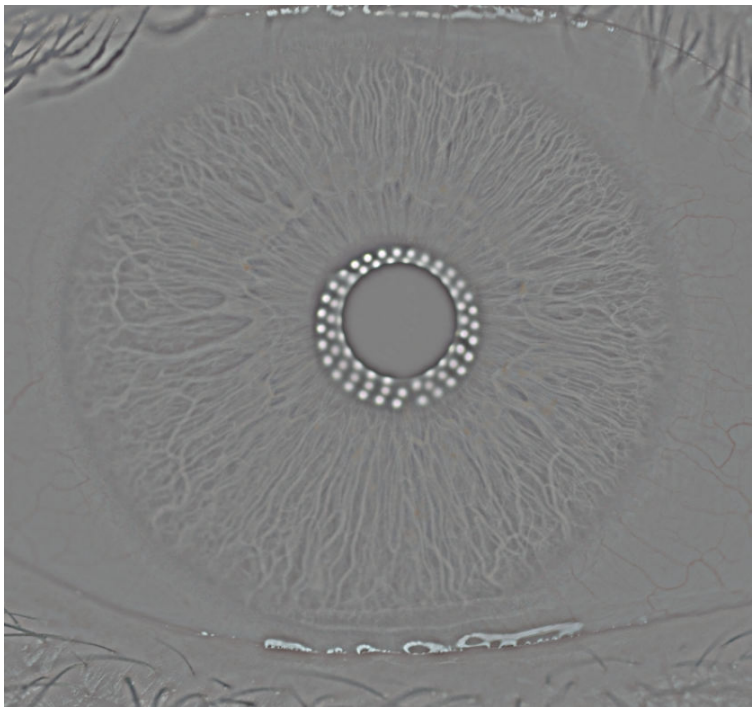

Figure 6.3: Creating an iris mask using a High-pass filter

Due to the fact that the images are taken in the visible spectrum, thus they contain information about the colour structure of the iris, it is possible to experiment with filters and methods that influence the colour channels in the image. Depending on the colour of the iris, colour channels can then be removed that do not affect the colour and thus achieve cleaner and more readable markers in the iris. For example, removing the green and red channels, in the case of blue eyes and, in the case of brown eyes, removing the blue and green channels as shown in the picture 6.4.

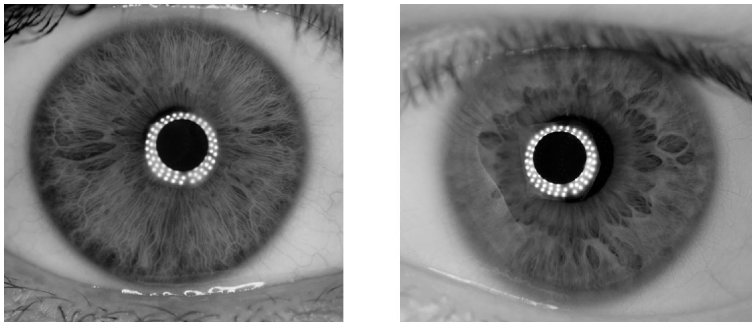

Figure 6.4: An example of the elimination of colour channels to highlight the structure of markers

Experiments can also be done with masking the main iris colour. This creates an inverted image on which the structure of the markers can be observed, which is normally hidden just below the colour part of the iris. However, masking cannot be applied to all iris colour iris types. The best inverse map is achieved when applied to monochrome irises as shown in Figure 6.5.

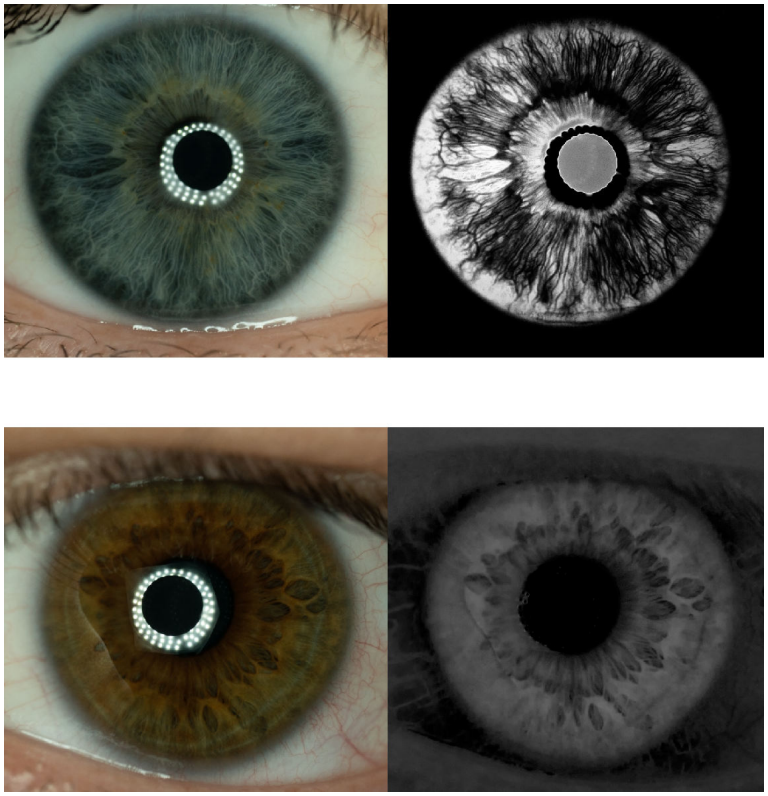

Figure 6.5: Selective masking of the main colour of the iris. *Top*: Masking the blue colour in blue eyes. *Bottom*: Masking the yellow colour in brown-green eyes.

By variations and layering of individual filters and methods, countless new possible filters can be obtained, but most of the resulting filters do not meet the needs of the research and rather degrade the informative value of the image. Another possible modification of images is, for example, creating colour maps.

Because of their high resolution, the images offer a great opportunity to experiment as they contain a lot of source data. Even when applying extreme or invasive local filters, modifying portions of the image does not only result in degeneration or in data loss. Filters and image manipulation can be applied without loss of quality, because the data is available in the **RAW format** that retains all the necessary source data, so there is no problem to recover part of the information if needed.

# Chapter 7

# Evaluation

Before comparing individual methods and approaches, criteria that are important to the project have to be defined. Since each method has its own specifics, they cannot be compared directly. The primary aim of the work was to create methodology to capture and subsequently create a depth map. The first criterion, then will be the **quality of the depth map**, specifically, the degree of detail that can be read from the images. Another important point was also the design of a lighting source to be used in taking the pictures. The aim, then, was to develop a source of lighting that would causes the least possible **physical stress** to the eye. The last important criterion is the difficulty of taking pictures in relation to the amount of information obtained. These three criteria should serve as the main indicator of the fulfilment of the potential of the described methodology in comparison with already existing or emerging methods. An additional factor may be the individual incomparable advantages and disadvantages of each method, such as the processing time or the time it takes for the imaging itself and other nuances. Since the iris is considered to be personal information, it is also protected, so most databases are not publicly available. Therefore, for comparison, we will only use available data.

## 7.1 Infrared systems

Generally, systems using this principle do not have a colour component in the resulting image, thanks to the use of a near-infrared beam. On the other hand, this should illuminate the iris better and the markers in the eye should be seen more clearly in the image. Moreover, the beam is not visible to the human eye, so there is no conscious exposure of the eye to physical stress. In addition, as can be seen in the images from the database created by the *Computer Vision Laboratory* at *The Chinese University of Hong Kong* (available from [9]), the pupil is not always dilated to its maximum. This means that in some images the structure of the iris is not fully seen and so there is a significant loss of information. Although there is no visible colour in the images, according to typical markers and iris shapes it can be assumed that the system has a problem with darker iris colours that contain almost no information, as seen in the sample picture 7.1 from the database. In addition, the images reach the maximum resolution of only **300x420px**. The *IIT Delhi Iris Database* (available from [13]) has a similar resolution. However, compared to the first database, the sample data shows a greater degree of detail, primarily in light irises. It can also be observed that the pupil is not sufficiently contracted for the images, so information is lost again for some of the images.

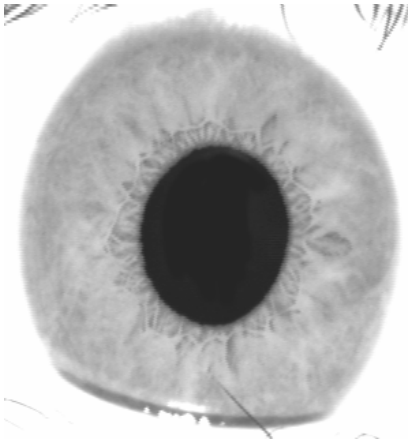

Figure 7.1: Sample image from *The Chinese University of Hong Kong* database available at [9]

Thus, it can be said that methods that use the NIR principle are the most appropriate for the perceived stress factor for the eye. However, in terms of quality, it is not sufficient. Images taken with this method are not constant, considering the different pupil size in each image. The image also lacks colour information, which for us is important. The image quality is consistent with system complexity. The imaging itself can then be performed anywhere indoors, using only special, portable camera technology.

## 7.2 Systems using visible spectrum

The main idea of imaging, in the visible spectrum, is to capture iris colour information that is completely missing from the NIR systems mentioned above. Due to the low resolution rate, NIR imaging time is much better. Now, with the advent of more modern technologies and, above all, the increase in resolution, images in the visible spectrum, in terms of detail, have significantly improved. A continuing problem is the need for intense lighting in this type of imaging. This is both a technological problem and also the imaged iris is exposed to a higher rate of more physical stress than when using NIR. Systems that use this principle can be divided into two basic types according to the imaging technology used:

### Camera

These systems use a standard **CCD** or **CMOS** chip to capture images, either embedded in a commercially available corpus or embedded in special hardware. The sensor is then connected to a special instrument that resembles a lens housing that consists of a system of lenses, mirrors and interior lighting. This device in ophthalmology is called a fundus camera 7.2. However, it is used primarily to capture the retina.


Figure 7.2: Canon Fundus Camera (taken from [29])

However, the device can also be modified to to capture the iris, which is can by seen by the Iris database, created at *Palacký University in Olomouc*, with the help of a similar device. In sample 7.3, a very good level of detail can be seen irrespective of the iris colour. Moreover, the quality of the database is constant, but all the images suffer from a strange colour haze. Thus, when using iris colour as another marker, distortion may occur. The size of the images depends on the imaging sensor used. Here, it is **768x576px** which is very good value.

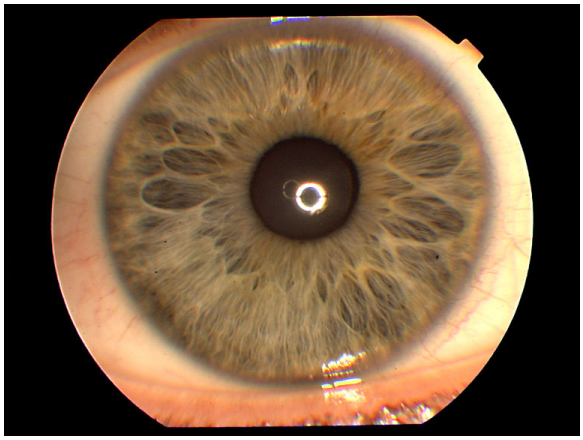

Figure 7.3: Sample image from database available at [4]

In general, systems using CCD or CMOS chips have the best results. In contrast to the system described in the work, however, a few details can be observed. The fundus camera system allows the imaged person more comfort in the form of a head rest and, generally, faster imaging. However, the colour contamination of the frames and also the high level of eye stress factor play a detrimental role, as the lighting system uses a lighting discharge that is short but an extreme strain to the eye. Fundus cameras or a similar system are not very portable.

### Digital Microscope

Systems operating on a similar principle to those using cameras. However, here the digital chip scans the image magnified by a special optical system. With this magnification, it achieves the best detailed result of the iris. However, handling is demanding and the whole process of iris imaging is the most demanding of all presented methods. It is also necessary to properly illuminate the iris and, because the microscope is placed in the immediate vicinity of the iris, there is a very high exposure to eye stress. Moreover, from such a distance, the reflection of the light is not only reflected in the pupil, but also in the iris, and data is lost, as can be seen in the left side on picture 7.4. The eye can be imaged even without suitable lighting. In this case, however, other light sources are reflected in the iris, as shown in the right side on picture 7.4. Although the microscope gives the most detailed iris image, thanks to the surprisingly high resolution of **1280x1024**, its manipulation and physical stress caused to the eye greatly reduces its ability to be used in a practical environment.

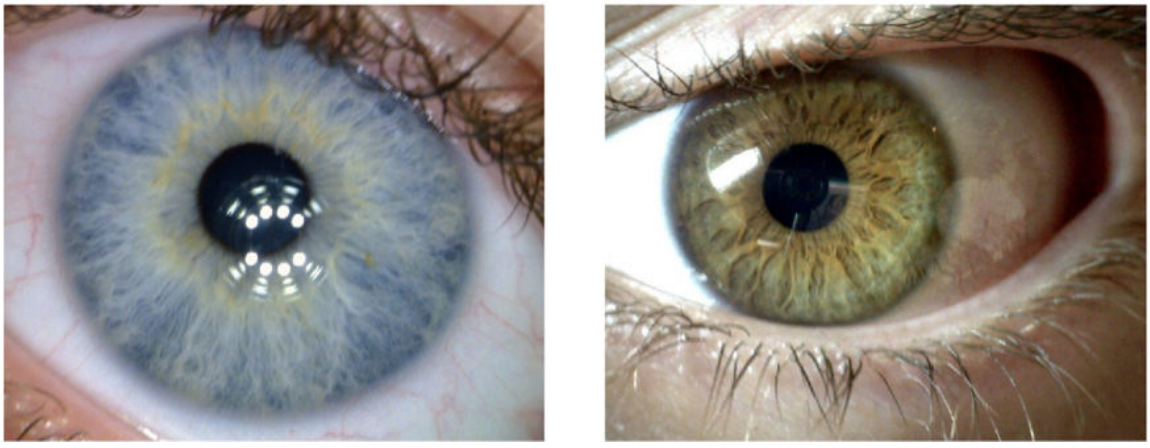

Figure 7.4: Example of images taken with a digital microscope in a biometric lab **STRaDe**

## 7.3 Results

The proposed methodology shows very good results in all selected criteria. However, these can be improved, in part, thanks to the results of imaging and later analysis of the images and the questionnaire that the imaged people received. Therefore, the criteria can be summarized as follows:

- **Quality of the depth maps:** Thanks to the high resolution images, the depth maps very detailed and contain a high degree of information. At maximum zoom, some of the marker microscopic structures can be seen to not have sufficient detail drawing. This is due to the physical limits of the lens and to get an even more detailed structure a macro converter lens or magnifying rings would be needed.

- **Stress factor:** According to respondents who have experience with other ophthalmic devices, the stressed factor was several times lower than with other devices. However, they suffered from a relatively long exposure to the light source. The problem occurred in people, whose optic systems or optic nerves were sensitive to greater light intensity. Even at the lowest possible light source, they tend to close their eyes or turn their eyes away from the light source. One solution is to increase the diffusion layer at the light source, without using the guide tunnel from the lens. This will ensure that there is no space for dispersion and the full intensity will be directed to the iris. As a result, it will be possible to significantly reduce the emitted light intensity, which will not be disperse to the environment.

- **Imaging process:** the whole process of imaging one eye takes about 5 minutes. All the time, the eye is exposed to a source of light, which for some was not pleasant. There are several reasons why the process takes so long. There is the need to localize the eye, done in such a way that the camera is set to a suitable position, also taking in the sides and height of the subject being imaged. The lens had to be set to the desired distance in order to focus on different planes. With each new focusing, it was necessary to position the iris so as to have it as much on the same plane as the previous image as possible. Using the head rest as needed to see into the fundus camera 7.2 would speed up the process considerably. With the lens set to the desired distance, special sliding rails can be used to position the camera corpus. The rails will then provide a faster and more accurate setting of the required minimum distance and stillness of the camera after finding the appropriate position. Another factor that contributed negatively to increasing the total imaging time was making multiple versions of the images, for instance, with different aperture sizes.

Certain recurrent patterns seen during imaging lead to the creation of theses that would be worth investigating on a larger statistical sample to see, if it was just a statistical error or a mistake in the methodology. These theses will also be consulted with ophthalmologists and any resulting findings will be incorporated into the methodology.

- **Eye defects:** One of the thesis talks about possible manifestations of eye defects in healthy, imaged subjects. This is based on the fact that during imaging, a healthy subject focuses on the centre of the lens. As a result, the pupil is also directed toward the centre and thus the light source is accurately projected into it. For some, however, there was a phenomenon that, when focused on the centre of the lens, the pupil was outside the centre and the light source reflected in the iris structure. If the subject focused in the opposite direction to the pupil, it was centred and the light source reflected correctly. As shown in Figure 7.5, the right image of the lens focuses on the centre of the lens, and in the left image there is then correction and the imaged subject then focused on the right corner of the lens. Similar behaviour was seen in subjects diagnosed with *Amblyopia*.

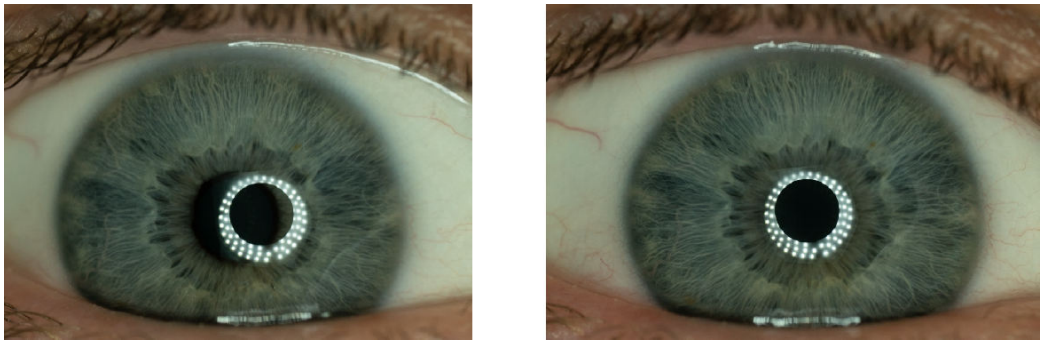

Figure 7.5: Possible hint of Amblyopia. *Right*: eye focusing on the centre of the lens, *Left*: eye after focus correction at the edge of the lens.

Another side issue of imaging is the veins found in the sclera. The notes illustrated by picture 7.6, where, in the first picture can be seen an eye that has not been exposed to any physical stress during the day. In the second picture, there is an eye that has been exposed to normal physical stress, i.e. sitting at a monitor or other aggressive light sources. The last picture shows an eye that has been exposed to extreme stress and damage in the form of intensive, persistent radiation. It is therefore provable that the veins of the eye too are variable. This significantly reduces their identification ability.

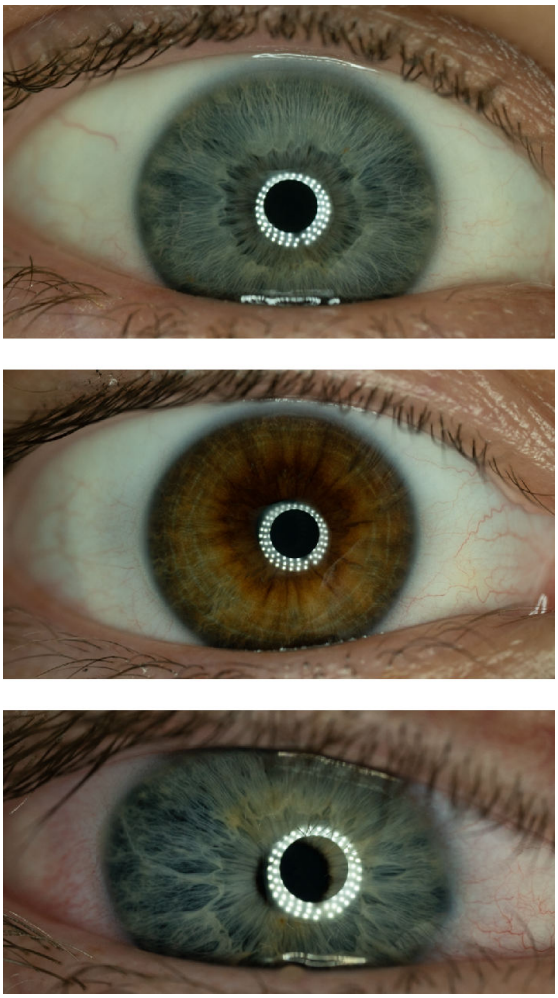

Figure 7.6: Veins in the sclera. *Top*: Eye without physical stress, *Middle*: Eye exposed to normal physical stress, *Bottom*: Eye exposed to extreme physical stress.

After analysing the images taken and applying some post-production adjustments, it became clear that it is better to have the image slightly overexposed to achieve better visible details in dark eyes, especially pure brown. If necessary, during imaging, increase the intensity of brightness in such irises.

# Chapter 8

# Conclusion

Thanks to the theoretical foundations mentioned in 5.1, 5.2 and to the experimental images taken, it was possible to lay the foundations for the creation of the methodology. The methodology itself was then altered on the go due to a change in the technology used. Because to this change, it was necessary to significantly adjust and, in particular, to reconsider some of the conclusions that arose from the experimental testing.

Real imaging then showed some deficiencies in the methodology, but these were soon incorporated without the need to significantly modify the existing methodology. Then, gradually, towards the end of the work and processing, the resulting database was developed as needed.

When producing final depth map images, none of the proposed technologies proved to be usable because the technologies used work with a coherent set of images. However, it was not possible to create it in the case of the eye and its micro movement. Although the images were normalized, the macro stacking itself showed a state where the eye changes its shape with each blink and actually every micro movement, and the muscles forming the minutiae are differently shaped in each photo set. Thus, a different scanning approach was chosen to achieve the desired image quality.

Experimentally, a few images were created using a variety of filters, which would in the future be able to serve in the framework of any multimodal biometric systems, where appropriate, to serve for the further development in the field of processing of human irises, in high resolution. Experimental filters also showed possible development within the next iterative procedure on the methodology.

Analysis of the questionnaire, which was administered to the subjects, together with a comparison of other, already existing solutions, has led to proposals, which should sweeten the feeling when imaging and also to increase the quality of the resulting images.

The resulting high-resolution Iris database can have a significant impact on the two main sectors. For bio-criteria, where it will serve as a reference database, on also serve for research purposes, as demonstrated that you can get the detailed minutiae of the iris without requiring the use of special devices. The analysis revealed hidden details in the iris and in its functioning, which can also be subjected to further examination. In the second sector, ophthalmology, the database will be subjected to a deeper examination of the doctors and mainly the knowledge on the health status of the visual system, as in the following images, as appropriate to serve the consultations and subsequent improvement for medical purposes.

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# Appendix A

# CD Content

*samples/:* Dataset,

*tex/:* LaTeX source of this document,

xkubic34-dip.pdf: PDF file of this document.