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ÚSTAV JAZYKŮ

INDUSTRIAL TESTER FOR PHOTOMETRIC VALUES OF LED DIODES USED IN AUTOMOTIVE SIGNAL LIGHTING

PRŮMYSLOVÝ TESTER FOTOMETRICKÝCH HODNOT LED DIOD POUŽÍVANÝCH V AUTOMOBILOVÉ SIGNALIZACI

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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RECOMMENDED LITERATURE:

1. Max Born,Emil Wolf: Principles of optics.CUP 1999.

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Abstract

Headlamps in cars have been passing through an enormous technical development in recent years, and with the development comes complexity. Various technologies are employed in order to deliver progressively safer and more efficient light output, to satisfy drivers and customers alike. Companies strive to minimize losses in production in order to be economical and environment-friendly. For the sake of the minimalization, this thesis aims to research the lighting technology and design a simple, but effective device to help with determining of faulty LED PCBs in headlamps. Another objective is to research the possibilities of construction of such a device from technological standpoint.

Keywords

LED diode, tester, spectrometer, programmable power supply, VB .NET, lighting, optics, photometry

Abstrakt

V posledních letech zažily světlomety v autech obrovský technický rozvoj, který se podílel na jejich současné složitosti. Aby řidiči i zákazníci byli spokojeni, je využíváno různých technologií pro neustálé dosahování účinnějších a bezpečnějších světelných zdrojů. Společnosti usilují o minimalizaci ztrát ve výrobě ve snaze šetřit životní prostředí a konat ekonomicky. Tato práce se zabývá výzkumem osvětlovací techniky a návrhem jednoduchého a efektivního zařízení pro testovaní chyb LED plošných obvodů ve světlometech, to vše za účelem minimalizace ztrát. Dalším cílem je výzkum možností konstrukce takového zařízení z technologického hlediska.

Klíčová slova

LED dioda, tester, spektrometer, programovatelný zdroj, VB .NET, světlomet, optika, fotometrie

Rozšírený abstrakt

Automobilový priemysel neodmysliteľne patrí k jednému z najvýznamnejších odvetví produkcie nielen na Slovensku, a v ostatných rokoch sa jeho dôležitá pozícia iba posilňuje. Moderné automobily v súčasnosti disponujú najnovšími technológiami nielen zo sveta strojníctva, ale aj elektrotechniky či informatiky. Jedným z mnoho komponentov, ktorý prešiel takouto modernizáciou, je určite aj svetlomet. Svetlomet už nie je iba spôsob manuálneho osvetlenia cesty, po ktorej sa automobil pohybuje; svetlomet je inteligentné zariadenie, ktoré funguje na báze nainštalovaných prednastavení a využíva rozličné technológie na to, aby zabezpečil efektívne, bezpečné a šetrné osvetlenie.

Letná stáž v spoločnosti Hella Front Lighting Slovakia mi umožnila byť súčasťou výrobného procesu svetlometov, kde sme na oddelení elektrooptického testingu riešili ich elektrické a optické vlastnosti a charakteristiky a problematiku vo výrobe spojenú s nimi. Podľa legislatívnych noriem a požiadaviek objednávateľa má každý svetlomet spĺňať isté kritériá a pri množstve vyrobených kusov pohybujúcom sa v tisícoch denne môže nastať chyba vo výrobnom procese. Táto práca sa zaoberá problematikou elektrických a optických vlastností plošných obvodov v svetlomete t.j. kontrolou týchto hodnôt. Ak plošný obvod nevyhovuje kritériám, musí prejsť opravou, pri ktorej je potrebné diagnostikovať chybu a následne skontrolovať, či oprava túto chybu vyriešila. Cieľom tejto práce je poskytnúť spoločnosti návrh zariadenia resp. konfigurácii viacero zariadení, ktoré umožňujú jednoducho a efektívne vykonať takúto kontrolu. Bakalárska práca sa skladá z dvoch častí: pohľad na problematiku z teoretického a fyzikálneho hľadiska a praktický návrh a popis zamýšľanej aplikácie.

Prvá časť bakalárskej práce sa venuje svetlu ako fyzikálnemu javu. Stručný prehľad historického vývoja chápania svetla ľuďmi slúži zároveň aj ako uvedenie jeho základných vlastností. Nasleduje charakteristika svetelnej radiácie a klasifikácia podľa rôznych kritérií. V kapitole „Photometry" diskutujeme o svetle ako o fyzikálnom jave popísanom a meranom ľudským pozorovateľom, k čomu slúži aj poukázanie na rozdiel medzi rádiometriou a fotometriou. Definujú sa tu základné pojmy a fyzikálne veličiny spojené so svetlom ako napríklad svetelný tok či svetelná intenzita. V nasledujúcej kapitole sa venujeme ústrednému prvku v meraní – LED diódam. Okrem základných vlastností LED diód je tu vysvetlený aj fyzikálny princíp prechodu PN, ktorý stojí za žiarením týchto diód. Obsiahnutý je aj vzťah medzi materiálom použitým pri výrobe diód a jej finálnym svetelným výstupom. Kapitola je

uzatvorená klasifikáciou diód a stručný prehľad širokej škály ich využitia v rôznych oblastiach. Posledná kapitola prvej časti obsahuje podrobný rozbor spektrometra, zariadenia merajúceho optické vlastnosti LED diód. Popisujeme tu jednotlivé súčasti spektrometra ako sú napríklad detektor či drážkovaná plocha a zároveň s nimi uvádzame aj kroky merania svetelného vstupu. Tiež sa tu nachádza aj objasnenie problematiky z hľadiska fyziky a spôsoby, akými môžeme spektrometer prispôsobiť v závislosti od charakteru meraného svetelného výstupu.

Druhá časť bakalárskej práce sa zaoberá prechodom z teoretickej roviny do praktickej. Je dôležité podotknúť, že cieľom bakalárskej práce bolo poskytnúť návrh konfigurácie zariadení, ktoré budú merať svetelné a elektrické vlastnosti LED diód plošných spojov. Na začiatku sa teda nachádza uvedenie presnej funkcie a operácie týchto zariadení a aplikácie, ktorá slúži ako rozhranie ovládania merania, jeho jednotlivých komponentov a nastavení a spracovania výsledkov merania. Ako už z textu vyplýva, musíme použiť viacero zariadení. Každé zariadenie (programovateľný zdroj jednosmerného napätia, analyzér/spektrometer LED diód) je v tejto kapitole popísané či už z hľadiska technických špecifikácií, jeho funkcií a nami zvolených rozhraní, s ktorými pracujeme až po odôvodnenie výberu daného modelu. Taktiež je vysvetlený systém merania farieb a intenzity, k čomu sú využité poznatky z teoretickej časti venujúcej sa fotometrii.

Nasleduje podrobný rozbor jadra bakalárskej práce – aplikácie samotnej. Jej hlavné časti sú databáza, používateľské rozhranie a procedúry a funkcie zabezpečujúce meranie. Postupne rozoberáme každú časť tak, aby bolo vysvetlenie merania čo najzrozumiteľnejšie a s nadväznosťou na predošlé kroky. Prejdeme tak najskôr prehľadom databázy, v ktorej sú uložené zdrojové údaje dôležité pre inicializáciu testu a prvotné nastavenie aplikácie tak, aby bola pripravená na meranie. Pokračujeme elektrickým testom, ktorý zahŕňa zabezpečenie obojsmernej komunikácie medzi aplikáciou a programovateľným zdrojom. Sú tu popísané procedúry a funkcie, ktoré umožnia nastaviť prúd a napätie na výstupoch zdroja a následne namerať tieto veličiny a poslať výsledky späť do aplikácie, kde sú spracované. Podobný princíp je uplatnený aj pri ovládaní spektrometra, kde však musíme použiť aj logiku, ktorá berie do úvahy, že nie všetky vlákna budú pri danom meraní použité. V závere práce ešte diskutujeme o možnostiach zlepšenia aplikácie v budúcnosti.

Prohlášení

Prohlašuji, že svou bakalářskou práci na téma Průmyslový tester fotometrických hodnot LED diod používaných v automobilové signalizaci jsem vypracoval samostatně pod vedením vedoucího bakalářské práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne .... …................................ (podpis autora)

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Contents

1. Introduction

Automotive industry has been an undeniably large and sprawling portion of Slovak production in the recent years. The total yearly sum of cars produced in the country has been comfortably reaching over 1 million, which is a disproportionally high number compared to only 5.4 million inhabitants, and with the arrival of Land Rover, it will continue to rise. Hella corporate is ranking 4th in this branch of industry, despite manufacturing lighting used in cars only. During the process, a lot of new approaches and methods are being used, alongside with cutting-edge technologies and prototypes already in usage. My summer internship took place at Hella Front Lighting Slovakia, a branch that focuses on, as the name suggests, the manufacturing and testing of headlamps. The department I was interning at is called Electro-optical testing, where the employees examine the electrical and optical properties of the headlamps, and based on the results, tweaks and small improvements are made in either the automatization or manufacturing process. Based on my experience and the needs of repairing workspace, this thesis' aim is to provide the company with a solution for economical and reliable testing system that determines whether the LED diodes located on a printed circuit board have sufficient enough results to be used in another headlamp piece for a second time. In order to be successful, I will research the problematics that arise with creation of such a tester, whether it is physical phenomena, construction blueprints or choosing the most suitable components for the project.

2. Light

Light is a concept that is accompanying the humankind since its very first steps. A prehistoric man must have found out fairly soon that he will not be able to accomplish even the most basic tasks without the help of light. Our lives are closely intertwined with light and it impacts our physiological functions and cycles, the prime example is sleep. The man functions this way naturally, since there is no light to assist his vision at night, which from a primal standpoint is a disadvantageous situation to be found in, and an ideal solution is to simply wait it out. As the man advances, so does the need of being able to fortify his vision when the natural light from the Sun is not sufficient or present. The way of evolution from a torch enlightening the cave to LED diodes being used in nearly every household was long, but nevertheless a rewarding process.

2.1. A brief historical introduction

The historical timeline of evolution of perception of light and vision by man is nearly as complex as the concept of light itself. As it is closely related to function of an eye, the oldest known origins of observing the phenomenon are traced back to ancient Greek era. Leno and Frank Pedrotti (1998) compile a brief overview, and start with a philosopher named Aristotle(384-322 BC.). In his “tentacle theory”, he claims that visual rays(tentacles) come from the eye itself and point to the objects it sees, but dismissed the theory with a profound reasoning that in that case a man should be able to see in the dark as well as in the broad daylight. Although a lot of anatomic advances were made during the Hellenic and Roman era, this theory was still falsely believed. Many great minds during the Middle Ages made a progress on understanding reflection and refraction. They also were aware of *camera obscura*, a pinhole camera with no lens that creates an inverted image. This led to discovery that the eye has to be similar to this camera, but the inverted image remained an unsolved mystery. Renaissance came with theories of purpose of single parts of the eye, namely Leonardo da Vinci(1452-1519), who recognizes that retina is in fact essential in eye’s vision, instead of lens as was believed at that time. On top of that, he delves deeper into nature of peripheral vision and depth perception. Da Vinci also touched on the problem of inverted image, stating that the eye must have a way to invert it for a second time before it is processed in the brain. The first to prove this theory was Johannes Kepler (1571-1630), alongside observing function of lens and retina. For what it is worth, the most important discovery as far as this thesis is concerned, was made by Thomas Young in his 1799 paper *Sound and Light*, where he proposes a theory that light is propagating in waves and discusses topics such as interference, color of thin films and double-slit experiment, say Max Born and Emil Wolf (1980). Man had a substantial amount of knowledge on the eye and its interaction with light, but to come up with definitions of the light's nature itself was proven to be more of a delicate task. Up to 20^{th} century, it was believed that light be either waves or particles, but not both at the same time. Descartes provided a foundation, continue Pedrottis, on which other great minds would build e.g. Huygens, Newton and aforesaid Young. Maxwell presents a set of four *Maxwell equations*, describing an electromagnetic wave. However, it was in 1900 that the theory of particle emerges, with Planck's discovery that proves atoms emit lights not continuously, as was thought at the time, but discretely in ”packets of energy”, today known as quanta. Planck's constant is defined as a proportionality between the energy and frequency of radiation. In 5 years' time, Einstein says that the radiation of light is a stream of particles called *photons*, and their energy results from the Planck's equation. The ending of the duality of theories is attributed to Luis De Broglie, who presents in his 1924 publication a theory that the photon itself has wave properties, thus claiming that light behaves like a wave when propagating, while in interacting with matter it behaves as particles. Niels Bohr elaborates on the true nature of photons and electrons, Fermi and Bose statistics build upon it even further. What we end up with is *quantum electrodynamics,* a scientific standpoint which is nearly fully sufficient to describe phenomena that we deal with in modern physics.

2.2. Definition of light

Radiation is a phenomenon, when energy is transferred through space in form of either particles or electromagnetic waves. For the sake of exactness, emitting of light will be called visible (electromagnetic) radiation. Albert Einstein has established a *quantum theory*, describing radiation either as a stream of particles or an electromagnetic wave. In modern physics, we do not make an exact boundary between these two characteristics. When the subject is of a technical nature, we are not attempting to define the nature of light. Rather, the primary property of radiation that interests us is the distribution of individual streams of energy in discrete time intervals while propagating continuously between any two points in the space. Thus, any arbitrary type of radiation can be divided into a number of sinusoidal waveforms. Each of these waveforms can be defined by frequency (Hz) and wavelength (mm) (Habel, Dvořáček, Dvořáček, Žák, 2013).

Depending on this knowledge, we can, according to Leno and Frank Pedrotti (1998), call an electromagnetic disturbance either monochromatic (single wavelength) or polychromatic (many wavelengths). It is possible to create a spectrum of the radiation depending on the energy distribution across the individual waves. The most common method is to determine the spectrum according to the wavelength and frequency of the wave, which are both related to the speed of wave c. Thanks to this distribution, we can divide the waves into many categories e.g. ultraviolet, cosmic, gamma, radio waves etc. The wavelengths we are concerned about are located in optical radiation, which is approximately 1nm – 1mm. Any type of such a radiation that can evoke a reaction in human eye is called visible light. The exact boundaries cannot be defined precisely and depend on the individual's eye, the most common range is from 360 – 400 nm to 760 – 830 nm. Radiation in this region is monochromatic, because each wavelength delivers a definite color of the spectrum. Ultraviolet and infrared radiations are at the boundaries of visible light spectrum (Habel et al., 2013).

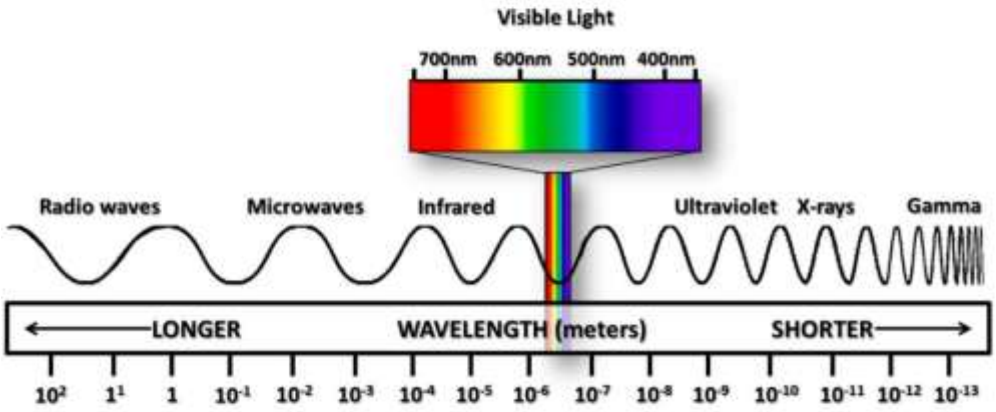

Figure 1. Wavelength spectrum.

(retrieved from www.ces.fau.edu)

3. Photometry

In the previous chapter, we established that light is a visible radiation, a stream of photons that causes a reaction in human eye. Light, on the contrary to electricity, is a much older concept that man attempts to describe and evaluate its properties, therefore first methods and terms developed to measure light are accustomed to human eye. Here comes a major distinction between two disciplines that measure light – radiometry and photometry.

In measurement of all electromagnetic radiation, we apply radiometry and radiometric units. The difference radiometry makes, is that we use standard SI units to express the radiant transfer of energy, in other words, radiometry is a measurement of light from non-human perspective. On the other hand, photometry considers a human observer in its measurement, whereas radiometry works strictly on physical plane. This distinction is in fact quite logical, due to the fact that human eye does not have a flat (universal) response to different kinds of wavelength (Leno and Frank Pedrotti, 1998). From a historical standpoint, it is possible to say that photometry was in use prior to radiometry, for the sake of being an “art of making visual comparisons of light” (Wittels, 1997)

Nevertheless, radiometry and photometry are not two ultimately separated disciplines, on the contrary, they were united by expressing the preceding photometric units by means of the SI standard radiometric units. Since every eye has a distinct response to the visible light, a standard response had to be established by the Commission on Illumination (CIE). Nowadays, it is possible to describe the direct relation of the two disciplines by a CIE luminous efficiency curve, say Pedrottis.

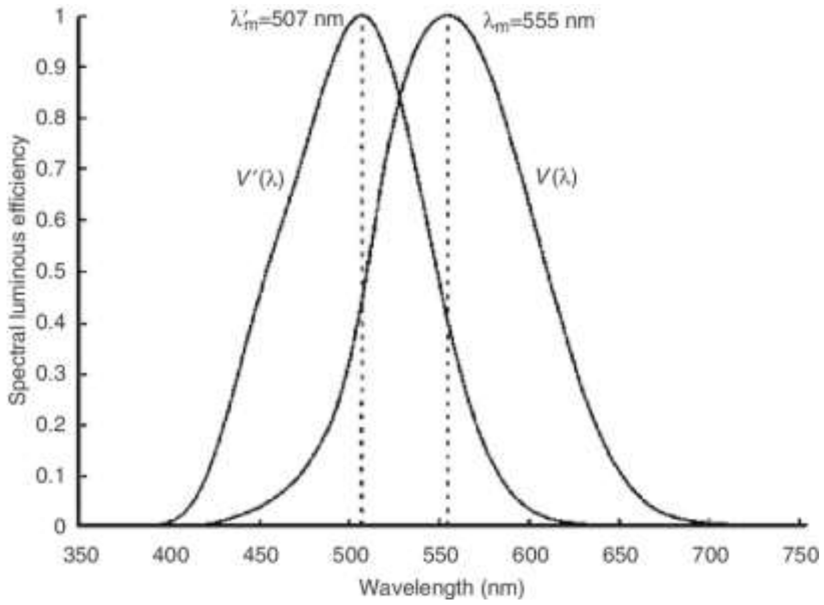

Figure 2. CIE luminous efficiency curve.

(retrieved from www.researchgate.net)

Although the usage of earlier and seemingly more inconsistent approach seems problematic, it is well justified. When it comes to visible light, people are more interested to response based on the eye rather than unnatural sensor, i.e. broadband light is easier explained with usage of broadband system that is photometry. Wittels perfectly describes another advantage of photometric system over the radiometric one – Photometry helps us answer questions such as "Which fabric sample is more reflective, the red one or the blue one?". Radiometry does not provide us with units that would make the answer to people easily understandable. Even cameras are designed with having the same wavelength response as human eye in mind, in order to make the results comprehensible to us, people. Hence, photometry is used in machines, although it may sound irrational without preceding explanation.

3.1. Definition of the quantities

From the previous chapter, it is very clear that radiometry and photometry go hand in hand, and physical quantities follow the same manner. It is of great importance to distinguish them correctly, as it may often appear there are similarities between them.

Radiant energy is simply the amount energy radiated from the source of light. Radiant flux and radiant energy density, as their names suggest, denote the amount of energy radiated with respect to time or volume, respectively. We talk about radiant emittance when we desire to express radiant flux density "emitted, scattered or reflected from a surface". On the other hand, radiant flux density emitted *onto* surface is called irradiance. This quantity can be often mistaken for radiant intensity, which describes the amount of radiant flux emitted by the source of radiation per unit of solid angle. The major difference is that where irradiance takes area into consideration, radiant intensity deals with an angle. The following picture illustrates the relation changing area with respect to distance.

When we move onto photometric units, the principles of evaluating the individual properties of light remain the same, however, the perspective switches to human eye. Since human eyesight does not require being exposed to visible radiation for a certain period of time to stimulate a response in the brain center, in photometry we focus rather on power and spatial distribution of light than the total amount of energy over time emitted by the source. Therefore, when determining the qualities of light, we use photometric quantities that take sensitivity of the eye into account. As was previously mentioned, CIE luminous efficiency curve shows a relation between radiometric and photometric quantities. In case of speaking about photometric quantities, we use term luminous (Leno and Frank Pedrotti, 1998).

Luminous flux (power) is a photometric counterpart to radiant flux that denotes ability of the flux to invoke a response in the eye, say Habel et al. It is also possible to say that it represents a certain number of transmitted photons per second. The unit is called lumen. Let us have a monochromatic radiation with a wavelength λ and radiant flux Φ_e, its luminous power will be defined as

$$\Phi(\lambda) = K(\lambda)\Phi_e(\lambda) = K_m V(\lambda)\Phi_e(\lambda)$$

K(λ) is called the luminous efficacy, V(λ) is luminous efficiency. We can denote K(λ) as

$$K(\lambda) = K_m V(\lambda)$$

where K_m is a maximal value of spectral progression of K. For more practical purposes, we can express luminous flux with a general equation

$$\Phi_v = \frac{\Delta Q_v}{\Delta t}.$$

Here we can see that lumen is the amount of emitted energy per second.

Where radiant energy uses joules, luminous energy Q_v uses lumen second (talbot). When we divide the energy in lumen seconds with time in seconds, we get lumens.

3.2. Luminous flux

By the number of photons emitted by the source, we can determine spectral content of light i.e. color (Wittels, 1997). One watt of orange monochromatic light with wavelength of 610nm has only a half of spectral luminous efficiency as watt with wavelength of 550nm, that produces green light. This function was established based upon experimenting with a considerable amount of people, and it fundamentally is a function tabulated over the range 380 – 780 nm. With spectral luminous efficiency, we can find a value of the flux in lumens by multiplying it by spectral energy distribution, however, in reality this method is nearly unusable by being inaccurate and difficult. Rather, we can measure it by putting two sources – unknown and standard, inside an integrating sphere, which is hollow and painted matte white from the inside. Habel et al. state that the light will distribute uniformly along the surface of the sphere's inside, despite not radiating in a uniform manner. There is a small hole in it, through which the light combined from both sources passes. An electronic sensor with corresponding filters measures the flux that is passing through the hole, and since we know the flux of the standard source, the difference between the total flux and flux of the standard source is equal to the unknown source's luminous flux. From that, we can obtain luminous efficiency if we divide the flux by the electrical power consumed by the source (Leno and Frank Pedrotti, 1998).

3.3. Luminous intensity

Another crucial quantity is called luminous intensity, the standard unit of which is candela (cd). It denotes luminous intensity of radiation source of frequency ν = 540×10^{12} Hz and radiant intensity in the given direction of 1/683 $W.sr^{-1}$. The frequency is directly related to standard wavelength in neutral conditions.

$$\lambda_m = \frac{c}{v} = \frac{2.997\,086\,40 \cdot 10^8}{540 \cdot 10^{12}} = 555\;nm$$

Candela describes a relation of radiation to solid angle. In photometry, we call this quantity luminous intensity I_v. It is very efficient in dealing with sources with uneven distribution of radiation in space. According to equation

$$I_v = \frac{\Delta\Phi_v}{\Delta\omega},$$

luminous intensity is expressed in a peak of angle ω, where the luminous flux is Φ_v, thus taking into consideration only a single point. Therefore, luminous intensity is applicable only to point sources, in other words, sources where we can neglect their radiation area with respect to the distance of control point and the peak of angle.

4. LED diodes

LED diodes are the target subject of measurement in this thesis, and the reason of it is their almost exclusive employment in modern automotive industry.

LED is an abbreviation for Light Emitting Diode. The principle of LED diode operation was discovered in 1920s, but the first methods of a practical usage were not being applied till 1962. Ever since, these components have seen a notable development in terms of production process and different material choices, that enabled us to change the lighting output, whether it be color, higher efficiency and longer lifespan, describe Habel et al. (2013).

4.1. Operation of LED diodes

Electroluminescence is the name of the principle, by which the semiconducting material converts the electrical energy into light energy. LEDs are semiconductor components comprising a PN junction emitting a radiation of visible light, provided it is polarized by electrical current passing through it.

A PN junction consists of P and N types of materials that do not conduct an electrical current under typical conditions. When they are conjoined, a movement of electrons to one region creates holes in the other, in other words, donors and acceptors are created by diffusion. There is a barrier formed between the two regions called depletion region, that lacks either of.

In order to overcome this barrier, a threshold voltage must be applied to both ends of the junction to make the particles carrying the free charge in the material overcome the potential of the electrical field created by the diffusion process. The acceptors and donors recombine and an electric current will flow through the junction now, and based on the bias of voltage, the polarization of it can be either forward or reversed (Hadley, 2014).

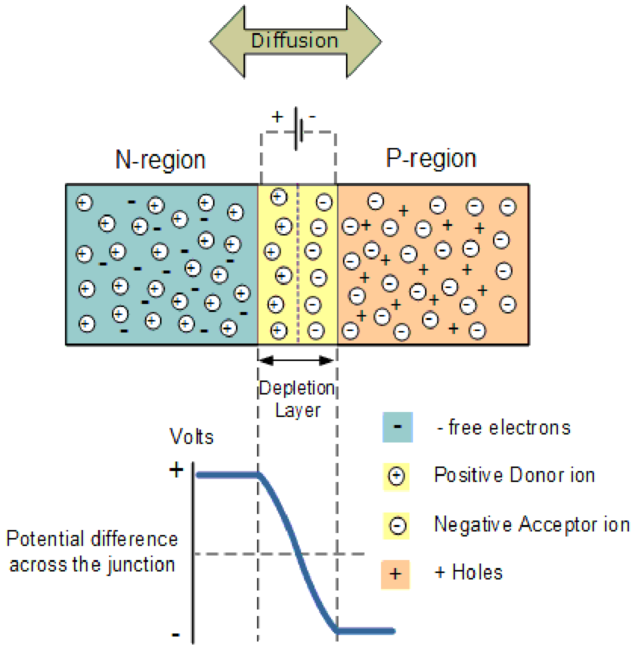

Figure 3. Diode functioning principle.

(retrieved from www.electronics-tutorials.ws)

Whether the diode will emit light or not depends on the band gap of the semiconductor i.e. energy difference between the conductive band and valence band (p-type and n-type region). If the band gap is direct, the electrons in valence band have only a minimal difference in momentum compared to conductive band's holes. In this case, no momentum has to be transferred in recombination of donors and acceptors, and the energy resulting from it takes form of a photon. If we use a material with indirect band gap, the momentum has to be transferred, which results in a vibration in the lattice - phonon. Based on this knowledge, we establish that the LED diodes must use a material with the direct band gap (Hadley, 2014).

4.2. Luminous and electrical properties of LED diodes

The first colors to be emitted by a LED were red and green, hence the narrow and incomplete spectral range. In sphere of automotive industry, a diode with these properties could be used in turn indicators and rear signal lamps. Contemporary semiconductors use highly complex materials, mixed from multiple chemical elements. Choice of the material used for chips stems from the preferred color spectrum. Materials used in chip manufacturing were made of Aluminum Indium Gallium Phosphide – AlInGaP. Using this simple, but useful technology, we can achieve colors from red to amber. Its disadvantages lie in a small band gap and high level of thermal degradation of the output. The most utilized materials are zinc, indium and gallium nitrides or selenides in green, blue and violet diodes. Recent materials in creating red, orange and yellow color are made of indium, gallium and aluminum arsenides and phosphides. (Habel et al., 2013)

Only after addition of blue it was possible to create a full spectrum of colors, white included. Such an innovation also broadened the applications of diodes immensely. However, developing a white color emitting LED diode is a slightly complicated task. The first method solely mixes all three of the RGB elements to create a white. Application of this method has high requirements on both hardware and software and the diode may start emitting a different color later on throughout its lifespan, since the degrading of chips is not uniform for each of them. Another downside is the diode having lower brightness.

A different way of achieving a white color output is using a LED with short wavelength together with phosphors. If we illuminate a phosphor material used in LEDs by blue light, it will emit yellow light. Coating the diode with this material and illuminating it constantly with a light of peak wavelength in range between 450 and 470 nm will result in portion of the light being converted into yellow, while the remaining blue light will mix with the resultant yellow again, specifies John D. Bullough (2003). Ultimately, a white light is emitted by this composition of multiple portions.

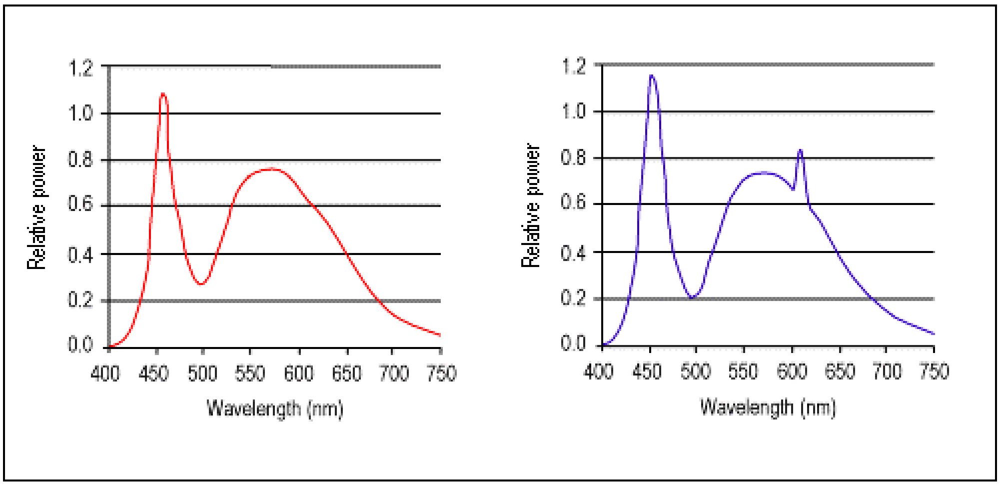

Figure 4. Difference in output wavelengths changing with material.
(retrieved from www.lrc.rpi.edu)

We can spot the difference between spectral power distributions of an older and more recent phosphor material used in white LED (Figure 4). As is manifested, the output between wavelengths of 600 and 650 nm was increased.

The semiconductor, which is a LED in itself, is of a miniature size. The first diodes had a chip with a surface of bare 0,05 mm^2. Thus, the voltage, current and emitted luminous flux were of low values, too. It was only with further development that the LED diodes were capable of delivering more substantial light effect, thanks to higher current, now in tenths of milliamperes, flowing through the chip. In recent past, diodes with current in units of amperes and power consumption up to 10W were introduced. Hence, the luminous flux emitted by them reaches almost 1000 lumens. From the consumer standpoint, Habel et al. (2013) divide LED diodes into three categories:

- Low-power diodes, current from 1 to 2 mA.
- Standard diodes, current greater than 20 mA.
- High-power diodes, current greater than 350 mA.

4.3. Practical use of LED diodes

LEDs have a great deal of advantages, many of which justify their use in the environment this thesis is focused on, automotive engineering. Firstly, they have an extremely efficient output and high brightness, compared to light bulbs and tubes. This goes hand in hand with the convenient size of the diodes, and on top of that, smaller size of LED does not necessarily mean lower luminous intensity at its output. The variety of sizing gives freedom to constructing technicians in terms of power and shape design. This enables us to create printed circuit boards with multiple diodes on them, which is of high importance in this research. Furthermore, the desired color is easier to achieve than with other light sources, which resort to various filters. Habel et al. (2013) add that in majority of cases they create almost a monochromatic color, a very important trait in signaling, where the colors must be definitive, and in no way interchangeable. In state-of-the-art diodes, there are theoretically infinite variations of shades. LEDs are also economically viable choice, and their lifetime is much longer than that of a light bulb. According to the US Department of Energy, they can achieve from 35.000 to 50.000 hours of useful lifetime, which is in comparison to a light bulb's maximum of 2.000 hours an enormous difference. Other sources suggest even longevity up to 100.000 hours with 30-40% decrement of luminous flux. Last but not least, the environmental impact is almost non-existent, both during their operation and after its end. Many materials used in manufacturing process are recyclable, which is a factor becoming gradually more important to massive producers. Ultimately, the lifetime is significantly dependent on temperature, in which the diode operates (Habel et al., 2013). The utilizations of LED diodes are countless. To name a few, traffic signs and signaling, outdoor and indoor lighting, medical equipment. Thanks to their high brightness and ergonomic values of observation distance and angles, they are used as panels for advertisements. In smaller scale, their applications are as UV check of authenticity of bank notes, light source in optic fibers, barcode scanners and mobile phone displays.

Figure 5. A high-power diode.

(retrieved from www.tinytronics.nl)

5. Spectrometer

Now that we know the behavior and details about LED diodes, we can proceed to the measuring process itself. In order to measure the LED diodes on printed circuit board, we have to use a highly sophisticated device capable of such task.

A spectrometer is an optical device responsible for processing spectral components of light by taking it in, digitizing the input signal of radiation as a function of wavelength and send the results to a PC Firstly, we need to direct the measured light to the slit in spectrometer, which then vignettes the light. It is possible to do so with a fiber optic cable. Light is then collimated by a concave mirror and reflected onto a grated surface inside the spectrometer. Grating can disperse the lighting components at different angles for efficient processing of spectral portions of the radiation. Next, light is focused by another mirror and projected onto a detector. At the end of the physical part, the photons projected onto detector are converted to electrons, which are digitized and sent through the communication port to device of choice (“Spectrometer Knowledge”, 2019).

According to B&W Tek (2019), “The processing software interpolates the signal based on the number of pixels in the detector, and the linear dispersion of the diffraction grating to create a calibration that enables the data to be plotted as a function of wavelength over the given spectral range.”

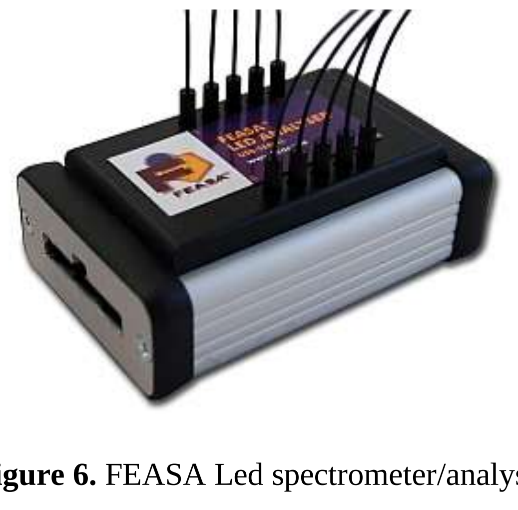

Figure 6. FEASA Led spectrometer/analyser.

(retrieved from www.feasa.ie)

5.1. Slit

Slit is one of the most crucial parts of the spectrometer, since it determines the amount of photon flux entering the spectrometer, and together with that the spectral resolution. It also controls the angle under which the light enters the spectrometer. As mentioned previously, the light enters the slit through the optical fiber.

The slit comes in various width sizes from 5 µm to 800 µm, although the most common sizes are 10, 25, 50, 100 and 200 µm. Height is usually in the range of 1 to 2 mm. Width is the factor that determines the spectral resolution of spectrometer, if it is greater than width of the detector.

5.2. Grating

The grated surface in the inside of spectrometer defines its wavelength range and to some extent also the resultant optical resolution. Diffraction grating can be divided into two types: ruled and holographic grating. A ruled one, the less expensive choice, is created by stamping numerous grooves onto the substrate surface in parallel, and coated with a highly reflective material. However, this method can contribute to several flaws, causing a decent portion of reflected light to be stray. Holographic grating, on the other hand, is made by modifying a piece of optical glass with UV beams to reflect light with "sinusoidal index of refraction variation" (B&W Tek, 2019). This solution is less efficient, but more reliable.

5.3. Groove frequency

Under this term, we understand it is the number of grooves per millimeter on the reflective surface. It greatly affects the spectrometer's coverage of wavelength and spectral resolution. A rule, according to which we choose the grating, states that the higher the dispersion of the grating is, the lower the wavelength frequency will be. On the contrary, the resolving power of the spectrometer will be higher. In other words, one can increase wavelength range in exchange the resolution and vice versa.

5.4. Blaze angle

The grated surface does not diffract the incoming light with constant efficiency across the surface, continue the websites of B&W Tek company. This characteristic can be denoted as a diffraction curve and its shape revolves around the angle of the groove edge. We can calculate the blaze wavelength i.e. predict which blaze angle has the highest efficiency corresponding to what wavelength the light incoming to the surface has. The efficiency will decrease by roughly 50% at 0.6x and 1.8x multiplier of the most efficient wavelength, hence the noticeable bias to the weaker side of the spectrum to improve signal to noise ratio of the spectrometer (Figure 7).

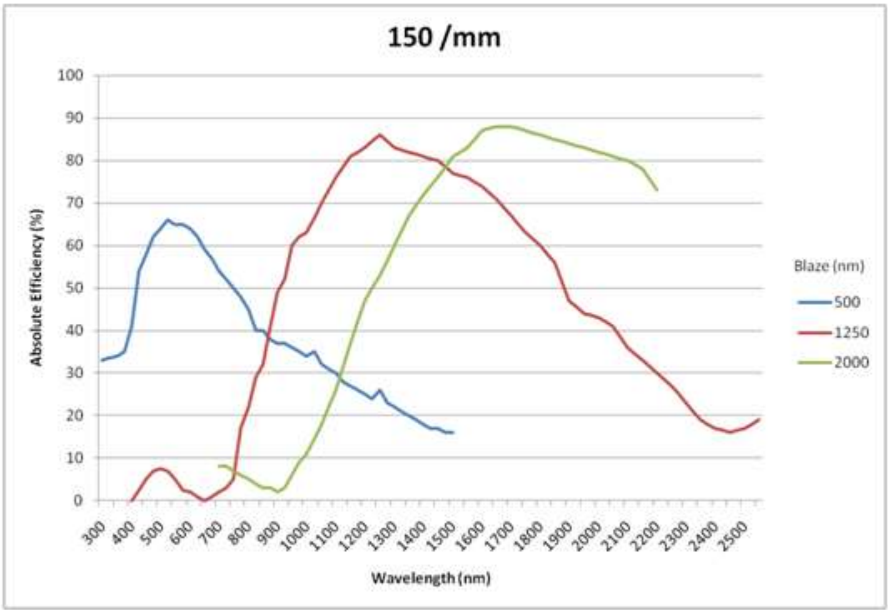

Figure 7. Blaze wavelength.

(retrieved from bwtek.com)

5.5. Detector

Detector, formerly an exit slit, is an element that measures the intensity of the light. An array of detectors is illuminated by the light, and then translates each pixel as a portion of spectrum to the computer, where it is subsequently displayed. For this task, a special software is used (“Spectrometer Knowledge”, 2019).

The most important aspect of categorizing detectors is the material they are made of. “The bandgap energy in a material determines the maximal wavelength detectable. Based on this, among the frequently used materials are Si and InGaAs, whose bandgap energy values are 1.11 eV and 0.73 eV, respectively.

However, the lower limit of detection is not easy to define. It revolves around the absorbance characteristics of the semiconductor material, thus, the limit can vary substantially also with thickness of it.

“Another common method of lowering the detection limit of the detector is to place a fluorescent coating on the window of the detector, which will absorb the higher energy photons and reemit lower energy photons which are then detectable by the sensor” (B&W Tek, 2019).

Contemporarily, the InGaAs detectors are in only one configuration, and the Si are in three; charge coupled devices, back-thinned charge coupled devices and photodiode arrays.

5.5.1. Noise sources in detector

Various noises in the detector affect the results of measurement. We distinguish handful of noises, such as readout, shot, dark and fixed pattern noise. If we know the corresponding values of them, we can calculate the total noise of the array detector by summing the square roots of the respective values. Noise, mainly the dark one, can be reduced by cooling the detector by a built-in thermoelectric cooler (TEC). However, during a measurement of high levels of light, such as LED diodes, the cooling can reduce only a minimal portion of the dark noise for the sake of the integration period being short.

5.6. Fiber optic cable

When we discuss the ability of the spectrometer to evaluate the light parameters efficiently and precisely, we must not neglect the high importance of directing the light into the spectrometer flawlessly.

It is possible to say that light can travel through the fiber medium in the same fashion as water travels through the piping. Guiding of light is done, instead of twists and turns, by a process called total internal reflection.

The speed of light c changes accordingly to the interface through which it travels, more specifically to its property called refracting power n

$$n = \frac{c}{v}.$$

We can define a relationship between the refracting powers of two materials by Snell's Law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2.$$

Clearly, it is possible to create a medium in which the light will reflect back and forth across the whole medium, while it travels point to point. Based on the equation, we choose materials with properties that provide us with suitable angles of reflection. From the picture, we can deduce that the cladding index will be low, and conversely, the core index high.

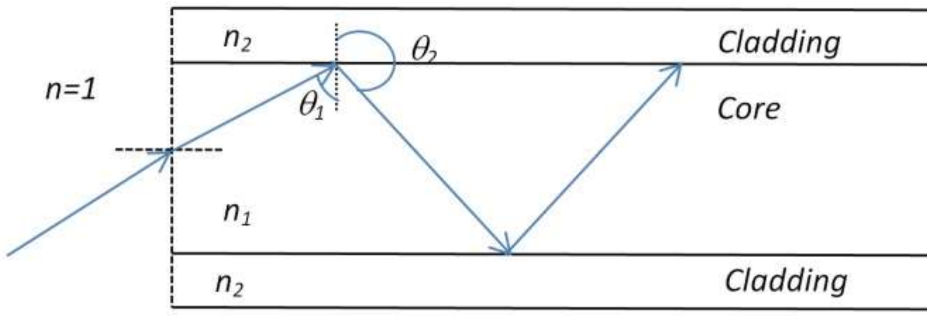

Figure 8. Light travelling through the fiber optic cable.

(retrieved from bwtek.com)

The crucial properties of the fiber optic cable are absorption and diameter of the core. For measuring a visible portion of light, UV fiber optics are suitable in terms of absorption. It is not a rule that the bigger core diameter, the more accurate the measurement, in fact, the limiting factor is the area of detector. If the light is passing through a diameter bigger than the height of detector, the portion of light that does not illuminate the detector is redundant. However, it is possible to focus the redundant portion to be projected onto the detector by using a cylindrical lens, which is a highly effective method ("Spectrometer Knowledge", 2019).

6. The project

The project that we deal with in this thesis is aimed to fulfil the company's needs in terms of applicability, efficiency, easy operation for layman and economical viability. All these aspects will be examined throughout this chapter.

The main function of the designed application and the accompanying interconnection of necessary devices is to measure the basic electrical and photometric properties of LED diodes of a printed circuit board (PCB), process the acquired data and subsequently evaluate the results. We will use multiple components picked in a highly specific manner as to meet the requirements of a precise and effective measurement. In order to understand the measuring procedure better, each part of the project will be introduced.

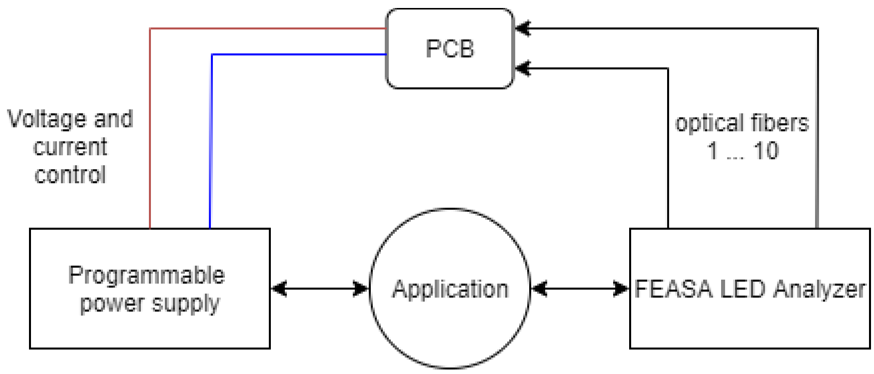

Figure 9. Diagram of the project.

According to the diagram of the project, we have to choose each part of the project: programmable power supply, LED Analyzer and coding language.

6.1 Programmable power supply

Programmable power supply (onwards PPSU) is a multifunctional electrical device that is able to provide an intelligent supply of electrical power at its outputs. It is provided with display and buttons with which it can be easily controlled locally. However, the major advantage offered by the PPSU for our needs is a both way communication with a computer based on a terminal.

Among the main functions of PPSU belong setting the output values of voltage and current, measurement of the output values, fuse linking, overvoltage protection and sequencing of various commands. Our choice of the supply is a quality high-performance model of HMP4030 by ROHDE&SCHWARZ, with the total output power of 384W. The instrument includes three identical channels, that can be fed with a voltage range of 0 V to 32

V, and depending on the voltage, the current can range from 0 to 16 A. The outputs are short circuit proof and galvanically isolated, thus enabling the combination of connecting in series or parallel. Due to the PCBs requiring higher voltages, we were forced to choose a 3-channel version with a broader range of output values, despite measuring a maximum of two boards at the same time. Nonetheless, it provides a convenient possibility of extending the testing capacity for this project, should it be needed in the future. The power supply was chosen primarily because it is the standard choice for the company, and this particular instrument is already used in numerous workspaces every day and deemed itself reliable and precise.

6.1.1 Controlling the power supply

The IEEE 488.2 (IEC 625-2) standard allows for communication between the PPSU and the controlling device. According to IEEE Standards Association, this standard is meant for application in measurement performed by small to medium scale of instruments. It also defines the communication protocols needed to exchange the messages between the devices and basic commands and characteristics (e.g. error handling and syntax of the commands and their respective responses). However, even though the protocol 488 and its additional layer .2 were established, no universal set of commands was assigned as another layer of the protocol, which lead to inconsistencies. Therefore, a SCPI standard, bearing uniform commands, was introduced in 1990 as additional layer. (ROHDE&SCHWARZ, 2020). We distinguish between two types of commands, set and query. Set command serves as a one-way instruction for the instrument whereas the query expects a return value from the instrument.

In our testing sequence, we will use both types of commands. The first command "*IDN?" serves as a query to the instrument to send its identifying parameters to the COM port. Following commands are "REMOTE" and "RWLOCK", which enable the remote control and lock the manual control from the panel, respectively. Setting the desired values on the output consists of several commands. The first step is to select, which output should be controlled. The manual says that the command "INST" belongs to the INSTRument node of commands. However, each output of the power supply is considered a separate instrument, therefore we have to select for example output 1 by issuing a command "INST OUT1".

After we have selected the channel, we can change the voltage and current by commands "VOLT" and "CURR". We have to add an empty space and either round or decimal value, e.g. “VOLT 4” or “CURR 1.25”. Once the circuit is closed by feeding the PCBs with current, we need to measure them in order to determine their electrical capabilities. Every circuit board has to manifest the exact voltage and current draw according to the legislation norms and requirements of the customer ordering the headlamps. Moreover, they are being supplied from a unit with exact set rates of the electrical values being fed to them.

Once we have our output fed with desired voltage and current, we have to conduct a test of electrical capabilities of our circuit boards. This procedure is quite simple – measure the voltage and current drawn by the circuit board and then compare it to the predetermined tolerance values saved in the program’s database. The measurement is done by query commands sent to the power supply: “MEAS:CURR?“ and “MEAS:VOLT?”. However, it is necessary to remember to switch between the measured outputs with already introduced commands “INST OUT1” and “INST OUT2”.

Figure 10. Programmable power supply R&S HMP4030
(retrieved from www.rohde-schwarz.com)

6.1.2 Technical specifications

These commands can be simply sent through various interfaces such as Ethernet (LAN), USB or RS-232 serial communication. For the specific needs of this project, we opted for the usage of USB interface. It offers a conventional way of connection with nearly every device being equipped with it. Other advantages are higher bitrate as well as no need to have additional hardware compared to the outdated RS-232. LAN connection would be a viable but redundant solution, as we have no need of interconnecting multiple instruments or a remote controlling for this project.

One hardware wise problem accompanying the choice of USB interface arises as soon as we connect the instrument to the PC that is supposed to control it. A special interface card HO732 with LAN and USB options needs to be fit into the power supply. Even though it recognizes the HMP4030 as a connected device, we can only control it with the programs and terminal provided by ROHDE&SCHWARZ. The guide says that "the traditional version of the VCP allows the user to communicate with the instrument using any terminal program via SCPI commands once the corresponding Windows drivers have been installed." In other words, such scenario does not allow us to control the power supply as a universal COM port that is accessible by almost any programming language that can send commands into hardware communication ports. In order to overcome this obstacle, we have to install a Virtual COM port driver for the Windows operating system. The installation is rather simple and fast, and a detailed guide is attached to the driver files. Despite the requirement that the application be portable, this procedure must be done on every computer that is designated to operate the instrument and the power supply. Resulting connection is USB type B connector in the instrument to type A in our computer.

6.2 The spectrometer used for the project

The proposed LED testing device in this project is the Feasa LED Analyzer. One of the main reasons for the choice of this analyzer is the fact that HELLA Front-Lighting Slovakia has several years' experience with products of this Irish company. Furthermore, this device was developed in mind with specific application in numerous fields and industries, one of them being automotive industry.

6.2.1 Technical specifications

"Analyzer is an instrument that tests the HSI (Hue, Saturation, Intensity), RGB (Red, Green, Blue Color content of a single LED), XY Chromaticity, Dominant Wavelength and CCT Color temperature of Light Emitting Diodes (LEDs) in a test process." (FEASA, 2019)

For more demanding measurement procedures, it is able to provide us with values of luminous flux, luminance or luminous intensity. One individual analyzer can use up to 20 fibers for the measurement. These are in practice light guides placed above the diodes that are supposed to be tested. The raw data is then saved into the Analyzer and can be interpreted in various methods and formats by using the interfaces of the device – Serial or USB. The daisy chain interconnection is very useful in great scale measurements, it allows to connect together up to 30 LED analyzers. The time needed for the measurement depends on the intensity of the tested LEDs, in general, the brighter the LED the shorter the time necessary to evaluate its light output. A very crucial feature of the capturing device is that the measurements of the individual threads are done in parallel, therefore they can be conducted at the same time, which drastically reduces the time of measuring. FEASA claims the fastest capturing of the brightest LED diodes can reach times as short as 102 ms. Once this data is captured by the thread, it is read back by the analyzer at the rate of approximately 5 ms per fiber.

The examples for the test times listed by Feasa:

- Ultra High Brightness LED: 1 LED Capture Time – 2 ms, Read Back – 5ms; resulting total time – 7 ms. In case of 20 LEDs, the capture time remains 2 ms and the read back is $20 \times 5 = 100$ ms; resulting in 102 ms.
- Dim LED: 1 LED Capture Time – 650 ms, Read Back – 5ms; resulting total time – 655 ms. In case of 20 LEDs, the capture time remains 655 ms and the read back is $20 \times 5 = 100$ ms; resulting in 755 ms.

Our specific model is FEASA 10-F. The name indicates the number of channels (measuring optical threads) is ten, and the F stands for functional model. In the table below we can see the main differences between the industrial (I) and functional (F) models outlined.

	Feasa I	**Feasa F**
USB	No	Yes
RS232	Yes	Yes
20 Pin Port - Frequency Out	Yes	No
20 Pin Port - Synchronous Out	Yes	No
Daisy Chain	No	Yes
External Trigger	Yes	No

Table 1. Technical properties of FEASA Led Analyzers (retrieved from https://www.feasa.ie/ledanalyser.html)

In the same fashion as in the power supply's case, we opted for USB interface again. Compared to the RS232, it offers very high baud rate up to 460800 baud, while the former offers only 115200 baud. On top of that, the RS232 requires an external power supply, whereas USB is already powered from the computer's power supply and can be connected to any computer with the application.

6.2.2 Color measuring

The term color is purely human invention, simply a perception of the visuals in our mind. In order to objectively classify, store and compare colors with the use of digital devices, we must code them in some way. Perhaps the most common method is using RGB method. This method builds on the principle of combining three basic portions (colors) – red, green and blue – to create almost any color. Each of these colors have their individual value from 0 to 255, denoting the extent to which the portion is represented in the final color. Therefore, the number does not represent any physical quantity. In total the RGB method makes the number of colors that can be created and encoded by this model equal to 256^3 = 16 777 216. The higher figure of the portion, the lighter the corresponding color will be in the final result. However, we can also use the location of the color on the RGB color wheel in degrees and call it the hue of the color e.g. hue of yellow color will be around 60. (Gerald Bakker, 2020).

"A pure color will be represented on the color wheel as a point near the outer edge. White will be represented by a point near the center of the wheel. The degree of whiteness in a LED will affect its position on the wheel – the greater the amount of white the closer it will be to the center." (FEASA, 2019)

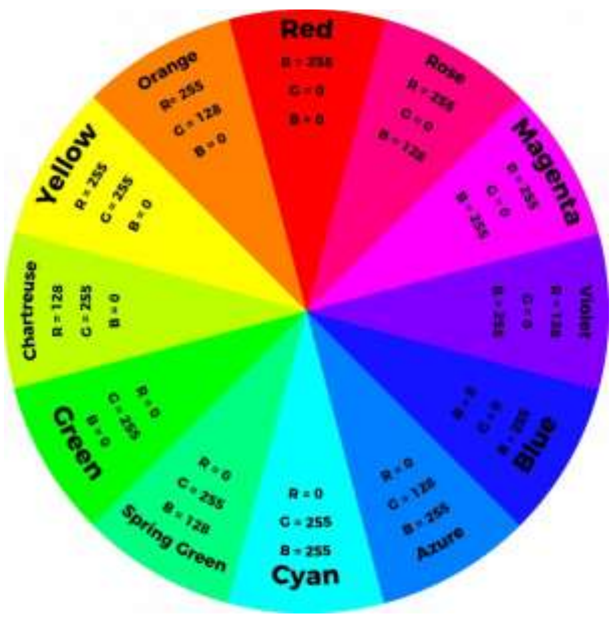

Figure 11. RGB color wheel.

(retrieved from https://learn.sparkfun.com/tutorials/lilypad-protosnap-plus-activity-guide/3-custom-color-mixing)

Another quality of LED measured by the analyzer is its intensity, which is the amount of light it emits. Similarly to RGB color measuring, each diode is first measured and the value is then transmitted to the output. The value can range from 0 to 99 999, and once again, it does not belong in the International System of Units (SI), nor it can be traced to color measurement.

“The analyzer is calibrated to a fixed standard and all measurements are relative. The intensity output reading is not a part of the International System of Units and is not an absolute or traceable unit of color measurement. In this case, this portion of radiation is described by the HSI (Hue, Saturation, Intensity) system.” (FEASA, 2019, p.10)

Factory settings are defaulted to logarithmic mode of measuring the intensity, but linear mode is also available. With appropriate commands, we can check the current mode of measurement or change it.

According to FEASA (2019), the factors influencing the measurement of intensity are:

- the position of the fiber in relation to the LED,
- offset from the optical Centre of the LED,
- the gap between the end of the fiber light guide and LED to be measured,
- the condition of the Fiber end,
- whether is the LED static or flashing
- External Influences (ambient lighting, proximity of other diodes)

6.3 Application

The application is undeniably the most crucial part of this project. It serves as a communicating and data processing hub of all the devices used for the measurement. Also, it is arguably the most complicated and customized component of this thesis, as it was developed for the specific requests and requirements of the company. The application’s major tasks are:

- to successfully establish connection with the devices,
- to send and receive data accordingly to the measurement step,
- to conduct the measurement in a meaningful and logical sequencing,
- to correctly evaluate the measured values,
- to provide an easy to operate interface for a practical use for a layman.

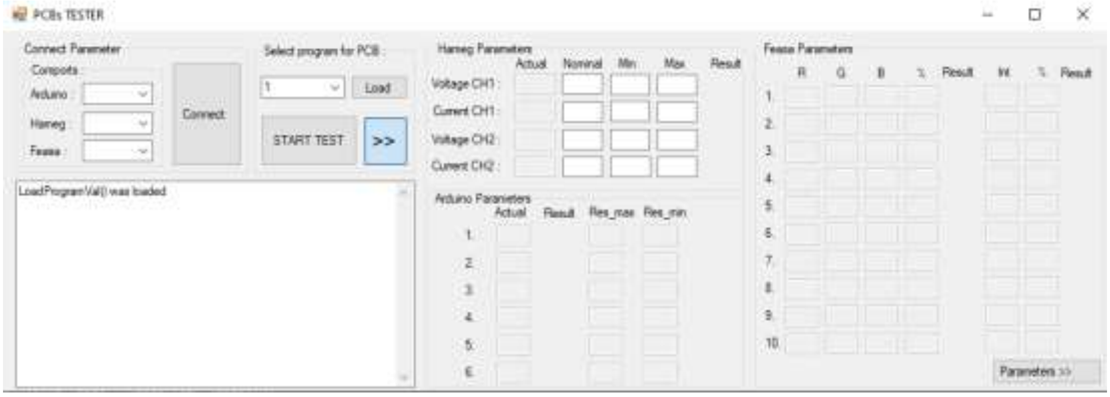

Figure 12. User interface of the application.

6.3.1 Programming language

The programming language of our choice for this project is Microsoft's Visual Basic .NET (VB.NET). The website Stack Overflow defines it followingly:

“[VB. NET] is a multi-paradigm, managed, type-safe, object-oriented computer programming language. Along with C# and F#, it is one of the main languages targeting the .NET Framework. VB.NET can be viewed as an evolution of Microsoft's Visual Basic 6, but implemented on the Microsoft .NET Framework. This is reflected in VB.NET's version numbering, which continues from VB6. Although Microsoft decided to drop the ".NET" portion of the language's name in 2005, it is still often referred to that way in order to differentiate it from its predecessors.”

The reason for choosing this option is easy programming for amateur coders and simple and easy to understand operation for layman. Moreover, the operating system Windows is the standard used in the company and our application (Windows form) is fully compatible with devices running it.

6.3.2 Structure and function of the application

The application consists of several main and crucial parts contributing to the overall operation:

- database, in which all the data tied to the tested printed circuit board is stored,
- module, which correctly reads and transfers the data in the database into the program,
- procedures, that control the programmable power supply, FEASA Analyzer and (hypothetically) Arduino Mega 2560 and send them appropriate commands

- procedures, which read the data received in the communication ports (incoming from all three measuring devices)
- procedures, which process all the measured results, store them into the program and determine whether the results are satisfactory and comply with the norms.

6.3.2.1 Database

Firstly, we need to employ a simple module that connects the database which stores the data about the PCBs to the program. The module starts a new SQL-based connection, locates the database file and transfers the data to the program. It also checks whether the transfer has succeeded. The database is currently located in the application folder, but it can be changed easily to any location of user's choice.

The database is loaded into the main program simply by picking a PCB name from the dropdown menu. There are attached four different tables bearing various values to the name of the PCB. The first table "Arduino" provides us with values for the resistance tolerances for each measured thermistor on the circuit board. E.g. there are columns named "R1_min" or "R2_max", in which are stored values for the minimal resistance of the first thermistor and maximum resistance of the second thermistor, respectively. Another table, named "Feasa", bears nominal values of each color portion and intensity for each LED diode on the printed circuit board, which makes it the most extensive and complicated part of the table. Furthermore, it is also supplied with tolerance values for color and intensity for each LED.
An example of employing those values into use is to take the measuring thread number 6. The columns R6, G6 and B6 contain the nominal values for red, green and blue portion of the measured light. With the use of the value in column Tcol6 we can simply calculate the minimum and maximum of each color using a basic formula. Such calculation is done in the program itself upon the loading the database into it. The identical process applies to the intensity values.

```
Private Sub txtInt6_TextChanged(sender As Object, e As EventArgs) Handles
txtInt6.TextChanged
        If txtInt6.Text = "0" Or txtInt6.Text = "" Or txtTint6.Text = "0" Or
txtTint6.Text = "" Then
        Else
            txtInt6Max.Text = Int6 + ((Tint6 / 100) * Int6)
            txtInt6Min.Text = Int6 - ((Tint6 / 100) * Int6)
        End If
End Sub
```

Figure 13. Procedure: Computation of tolerances

The table “Hameg” is filled with values for electrical measurement, denoting the minimal and maximal values of current and voltage of the PCB. The fourth and last table Program has indicators for the LED analyzer and Arduino which are needed to determine which optical threads (or channels) will be used in the measurement, since not every single one will be used during the measurement. It is a means of improving the speed and efficiency of the measuring procedure. This will be elaborated upon later.

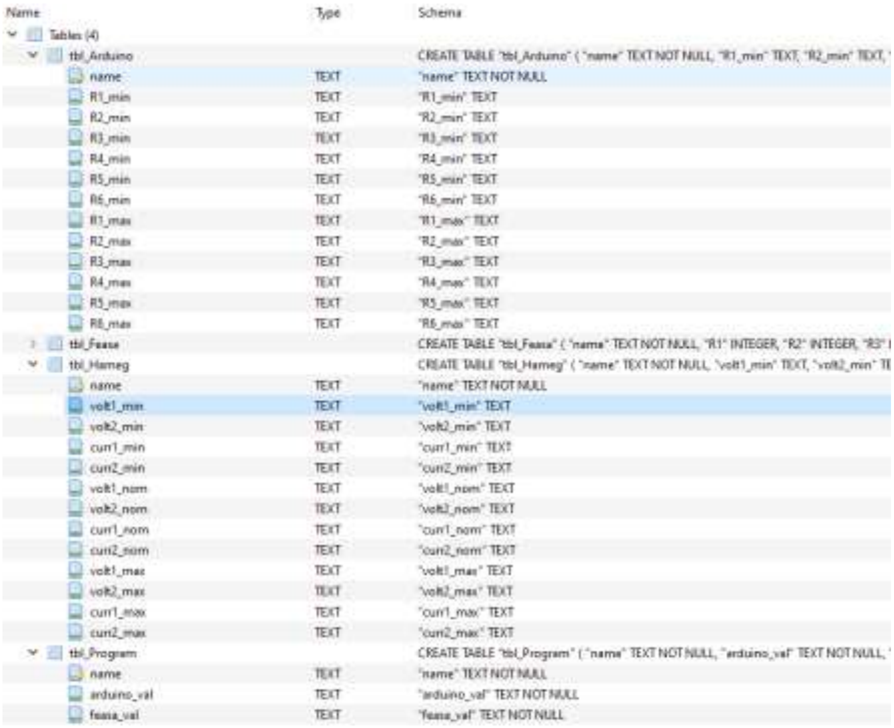

Figure 14. Layout of the database.

6.3.2.2 Initialization

Upon the launch of the program, all the values stored in the database are loaded into the program. The individual values are available to check in the very right side of the program window, but are not necessary to be displayed during the runtime. The very first step is to choose the COM ports for each of the three devices used for measurement. When we have picked the communication ports, we can simply press the button “Connect” to establish a suitable connection with the computer.

The procedure “ConnectButton_Click” attempts to establish all three connections and warns us should it not be possible. The logic behind is to firstly check whether there has been picked any COM port whatsoever and then proceed to attempt opening the port for communication. Before that, correct properties for the communication are already preset in the code e.g. for the LED analyzer the baud rate is 57 600, no parity bits and one stop bit. Naturally, there are different values in the program for different connections.

```
Try
           If (String.IsNullOrEmpty(cmbFeasaComport.Text)) Then
                MessageBox.Show("The COM port for FEASA LED Analyzer has not
been chosen", MessageBoxButtons.OK, MessageBoxIcon.Warning)
            Else
                FeasaPort.PortName = cmbFeasaComport.Text
                FeasaPort.BaudRate = 57600
                FeasaPort.Parity = IO.Ports.Parity.None
                FeasaPort.StopBits = IO.Ports.StopBits.One
                FeasaPort.Encoding = System.Text.Encoding.Default
                FeasaPort.DataBits = 8
                Try
                    FeasaPort.Open()
                    Timer2.Start()
                Catch ex As Exception
                    MessageBox.Show("The FEASA LED Analyzer COM port could not
have been opened", MessageBoxButtons.OK, MessageBoxIcon.Warning)
                End Try
            End If
Catch ex As Exception
MessageBox.Show("The FEASA LED Analyzer COM port could not have been opened ",
MessageBoxButtons.OK, MessageBoxIcon.Warning)
End Try
```

Figure 15. Procedure: Establishing a connection with COM port.

After opening all three ports, the application is ready to start the measuring process. However, it is possible to adjust the application in the future to use only power supply and one other device of choice. Perhaps the most crucial command in the example above is starting a timer ("Timer2.Start"). This starts the whole process of receiving incoming messages and symbols for the given port, which will be explained later.

6.3.2.3 Electrical test

Upon the pressing of the "START TEST" button, we start a sequence of numerous procedures which contain additional procedures in themselves. The first we describe here is named "ElectricalTest", and by the name of it we can safely assume it covers the testing of electrical properties of the PCB.

The first function of the procedure is "wait", which suspends any threads in the application for a specified number of seconds in the bracket. The reason for implementing this function is to let the programmable power supply process the commands sent to it with appropriate delay between the messages in order to not overload the communication channel. The function has to be custom as the VB .NET does not offer any default function to delay the actions of program.

Next, the "HamegDefault" sets the PPSU into the default state e.g. 0 volts and 0 amperes on all the outputs. The power supply seemingly stores the commands in its memory and upon restarting it, the values set onto the output channels stay the same. Thanks to this procedure, we can easily prevent it.

```
Private Sub HamegDefault()
        HamegPort.WriteLine("INST OUT1")
        HamegPort.WriteLine("APPL 0,0")
        HamegPort.WriteLine("OUTPUT 0")
        wait(0.05)
        HamegPort.WriteLine("INST OUT2")
        HamegPort.WriteLine("APPL 0,0")
        HamegPort.WriteLine("OUTPUT 0")
End Sub
```

Figure 16. Procedure: Setting the PPSU into a default state.

We already know that the command "INST [OUT1/OUT2]" will change the output that is being controlled. As we can see, the delaying function explained recently is employed upon switching from channel 1 to channel 2 to ensure the correct execution of the "APPL" command. This is a combination of "VOLT" and "CURR" commands into one, where the first value is voltage and the second one is current. However, this command did not function properly with using the values loaded into variables from the database, therefore we only use it with this procedure. The command "OUTPUT" sets the channel on or off, depending on the number following it, which can be 1 or 0 respectively.

The following functions, "SetChannel1" and "SetChannel2", use strings loaded into the program from database to set the channel values accordingly. In order to make setting the output channels universal, we use a function which sets them according to the input parameters. Next, these parameters are simply added to the commands which creates a single string which works as a command understandable by the power supply. Once again, we have to delay the sending of the commands upon the change of physical quantity. For the function "SetChannel2", the process is identical except for using command "INST OUT2" instead.

```
Private Sub SetChannel1(ByVal Volt As String, ByVal Curr As String)
        HamegPort.WriteLine("INST OUT1")
        HamegPort.WriteLine("VOLT " & Volt)
        wait(0.05)
        HamegPort.WriteLine("INST OUT1")
        HamegPort.WriteLine("CURR " & Curr)
End Sub
```

Figure 17. Function: Setting the voltage and current of a channel.

Furthermore, the procedure “HamegOutputOn” simply sets the channels from OFF to ON state with using the previously explained command “OUTPUT”. This part of the electrical test leaves us with the power supply feeding the connected circuit boards with appropriate voltage and current and ready for testing the electrical properties.

In the following section, we start using the query commands i.e. commands which return value from the measuring instrument. Every time we change from channel to channel, a variable named “Channel” changes its value accordingly. Once the query command is sent to the power supply, we are notified in the log window. As the code suggests, the measuring procedure is designed in such a fashion that we group together physical quantities and not channels, which may come as unusual and unreasonable. However, we observed that the voltage and current are measured with different accuracy, and the procedures which process the incoming messages have to be set exactly for the anticipated number of characters. Still, the procedure “HamegMeasure” serves only as one-sided communication with the PPSU.

```
HamegPort.WriteLine("INST OUT1")
Channel = 1
txtLog.Text += "Starting voltage measurement of channel no." & Channel
HamegPort.WriteLine("MEAS:VOLT?")
wait(1)
HamegPort.WriteLine("INST OUT2")
Channel = 2
txtLog.Text += "Starting voltage measurement of channel no." & Channel
HamegPort.WriteLine("MEAS:VOLT?")
wait(1)
```

Figure 18. Measurement of voltage.

Followingly, when all of the commands have been sent, we need to have a way of processing them in a meaningful way. Now we can trace our steps back to the beginning when we let a timer tick with establishing a connection to the measuring devices. Our procedure “Timer1_Tick” serves as a method of capturing the characters received from the power supply.

```
Private Sub HamegPort_DataReceived(sender As Object, e As
SerialDataReceivedEventArgs) Handles HamegPort.DataReceived
        Thread.Sleep(100)
        HamegInputData.Enqueue(HamegPort.ReadExisting())
End Sub
```

Figure 19. Procedure: Reading the incoming characters 1.

The variable “HamegInputData” is a queue of string which is filled by incoming characters which are then saved into “HamegString”. Thanks to SyncLock, we prevent the data reading process from being interrupted by any other thread, according to Microsoft. We use the condition that the variable will be filled only if we have any characters to fill it with. Then we proceed to determining what type of data we have received by a sizable if condition. Firstly, it distinguishes between the numerical data and an identification message which is sent automatically upon establishing the connection with the power supply by finding out if the first character of the incoming message is letter “R” as the beginning of the message reads “ROHDE&SCHWARZ”. When we are assured that we receive in fact numerical values, we test the length of the string. As was mentioned above, the voltage and current measurements have different degrees of accuracy, which serves as a simple method of telling the two quantities apart. The incoming string and quantity are displayed in the log window and based on the quantity, another simple procedure starts.

```
Private Sub Timer1_Tick(sender As Object, e As EventArgs) Handles Timer1.Tick
    HamegString = ""
    SyncLock HamegInputData
        While HamegInputData.Count > 0
            HamegString &= HamegInputData.Dequeue
        End While
    End SyncLock

    If HamegString.Length > 1 Then
        If HamegString(0) = "R" Then
            txtLog.Text +=
            "Measuring instrument identification: " & HamegString & vbCrLf
        Else
            Try

                If HamegString.Length = 6 Then
                    txtLog.Text += "Received a string: " & HamegString & vbCrLf
                    feedbackHameg = HamegString
                    txtLog.Text += "Starting voltage measurement... "
                    HamegMeasureVoltage()
                ElseIf HamegString.Length = 7 Then
                    txtLog.Text += "Received a string: " & HamegString & vbCrLf
                    feedbackHameg = HamegString
                    txtLog.Text += "Starting current measurement... "
                    HamegMeasureCurrent()
                Else
                txtLog.Text +=
                "Incoming string could not be identified: " & HamegString
                End If

            Catch ex As Exception
                MsgBox(HamegString)
            End Try
        End If
    End If
End Sub
```

Figure 20. Procedure: Reading the incoming characters 2.

The procedure “HamegMeasureVoltage” simply reads the variable “Channel” used back when sending the query commands and based on that, it saves the according voltage values into the program and also displays them into the program’s window. The value is made of individual characters combined together into a single string. Almost identical process is repeated with the current processing.

```
Sub HamegMeasureVoltage()
        If Channel = 1 Then
            txtLog.Text += "Channel: " & Channel
            Voltage1Act = feedbackHameg(0) & feedbackHameg(1) & feedbackHameg(2)
& feedbackHameg(3) & feedbackHameg(4)
            txtLog.Text += "Voltage1Act value is:" & Voltage1Act
            txtVoltageAct1.Text = Voltage1Act
        ElseIf Channel = 2 Then
            txtLog.Text += "Channel:" & Channel
            Voltage2Act = feedbackHameg(0) & feedbackHameg(1) & feedbackHameg(2)
& feedbackHameg(3) & feedbackHameg(4)
            txtLog.Text += "Voltage2Act value is:" & Voltage2Act
            txtVoltageAct2.Text = Voltage2Act
        End If
End Sub
```

Figure 21. Procedure: Processing the results.

All of the above procedures cover the electrical measurement, which is now almost finished. The last task left is to determine whether the values are in the accepted range, which is done by the procedure “HamegEvaluation”, which uses a simple logic of comparing the value to the minimal and maximal value in the range. Firstly, it has to use “CDbl” function to convert each value from type string into numerical type double. Based on the result of comparison, we set the picture signalizing the result next to the value to a tick or cross. In this phase, we have completely executed the electrical test and we can proceed to the optical test.

```
Volt1 = CDbl(txtVoltageAct1.Text)
If Volt1 >= Volt1Min And Volt1 <= Volt1Max Then
            Voltage1Result.Image = ImageList1.Images(0)
            Else
            Voltage1Result.Image = ImageList1.Images(1)
End If
```

Figure 22. Evaluating the results.

6.3.2.4 Optical test

The optical test is once again built of multiple different procedures completing various tasks. When we look at the physical state of the test, ideally, the circuit board should be fed with defined voltage and current which will results in the LED diodes emitting a light. Under such circumstances, the optical test will perform and evaluation of the optical properties of the LED diodes, namely split the emitted spectrum into red, green and blue portion and measure intensity. This stage of measurement is perhaps the most complicated, as it works with the highest volume of data.

Firstly, the “FeasaMeasure” procedure’s task is to send a definite number of commands requesting the LED Analyzer to measure the given diode. For example, command “getrgbi03” orders the device to measure the radiating output flowing into the optical thread number 3. The variable "TestString" is used as an identification whether the loaded measuring program uses the given thread for measurement or not, based on 1 or 0 at the index position of the thread. The indicator, which was already mentioned previously in the introduction, is a simple string consisting of zeroes and ones, the latter indicating the use of the channel or thread in the measurement. For example, the content of feasa_val (which is in this procedure "TestString") equal to "0110000101" tells us that the numbers of optical threads used for measuring the LED diodes in the particular program will be 2, 3, 8 and 10. The procedure uses two integer counters, one lagging behind the other one. The reason for this solution is because the indexing of the individual threads ("FeasaCounter") in the commands starts at 1, but the indexing of the strings in the programming language starts at 0. Therefore, the command will be sent to the device only under the condition we actually need the measured data from the given thread. In both cases are the counters increased by one until we reach the last thread – number 10.

```
Private Sub FeasaMeasure()
        FeasaCounter = 1
        Counter = 0
        While FeasaCounter < 10
            If TestString(Counter) = "1" Then
                FeasaPort.WriteLine("getrgbi0" & FeasaCounter)
                wait(0.5)
            End If
            Counter += 1
            FeasaCounter += 1
        End While
        If TestString(9) = "1" Then
            FeasaPort.WriteLine("getrgbi10")
            Counter += 1
            FeasaCounter += 1
        End If
End Sub
```

Figure 23. Procedure: Color and intensity measurement.

Similar to upon receiving the measurement results from the power supply, another procedure handling timer is in use for processing the data incoming from the LED Analyzer. Once again, the same string and queue are used for the initial message to be stored. After that, we check if the data incoming is in a complete format i.e. the message is 19 characters long. Simultaneously, the counter for the optical threads from the previous procedure is being checked in order to keep the sending and receiving of the same data in synchronization. The message is then split accordingly into the portions of red, green, blue and finally intensity. In this procedure, the variable "FeasaCounter" is also used as an indexing counter for storing the measured values in an array. Followingly, the measurement results are printed onto the screen in the log window. The last action is the conversion of the results from the string format into the integer to enable them to be numerically compared.

```
If FeasaString.Length = 19 And FeasaCounter < 11 Then

FeasaRed(FeasaCounter) = FeasaString.Substring(0, 3)
FeasaGreen(FeasaCounter) = FeasaString.Substring(4, 3)
FeasaBlue(FeasaCounter) = FeasaString.Substring(8, 3)
FeasaIntensity(FeasaCounter) = FeasaString.Substring(12, 5)

txtLog.Text += vbCrLf & "Values for thread no." & FeasaCounter
txtLog.Text += vbCrLf & "Red: " & FeasaRed(FeasaCounter) & " Green: " &
FeasaGreen(FeasaCounter) & " Blue: " & FeasaBlue(FeasaCounter) & " Intensity: "
& FeasaIntensity(FeasaCounter)

RedTextbox(FeasaCounter).Text = Convert.ToInt32(FeasaRed(FeasaCounter))
GreenTextbox(FeasaCounter).Text = Convert.ToInt32(FeasaGreen(FeasaCounter))
BlueTextbox(FeasaCounter).Text = Convert.ToInt32(FeasaBlue(FeasaCounter))
IntensityBox(FeasaCounter).Text = Convert.ToInt32(FeasaIntensity(FeasaCounter))
End If
```

Figure 24. Processing the color and intensity measurement results.

Procedure “FeasaColorEvaluation” simply navigates the array of the windows of the program in which are the results stored and subsequently compares these values. Furthermore, the result images are also arranged in an array. With the use of the same logic as before, we can easily determine whether the red, green and blue values are within the allowed limits. According to the results of comparation a tick or cross appears next to the row corresponding to the given optical thread. Another procedure “FeasaIntensityEvaluation” conducts the evaluation process in identical fashion. Thus, all the measurement steps are completed and the application informs us about the results graphically.

6.3.2.5 Economical prospect

One of the aims of the bachelor thesis was to offer an economically viable solution. Although the suggested project is not in a final form, we can safely assume that in the case of implementation into the production process, it is a considerably inexpensive tester that is capable of the tasks required by the company. The total sum of the project in the current phase amounts to around 3 000 EUR. The programmable power supply is the most budget heavy part, with its cost around 2100 EUR. The cost of FEASA LED Analyzer is approximately 910 EUR. The other options might vary in their price, but in both cases, we opted out for these devices to match the company’s standards. Furthermore, both types of devices have already been in use in the factory for several years. Comparing multiple choices that could have been used for this project is rather complicated, as there are hardly any accurate numbers provided by the manufacturers and the prices demonstrate a substantial fluctuation due to the high degree of modification.

6.3.2.6 Further possibilities and improvements

One of the possible ways to expand the measuring application in the future would be to add a simple resistance measurement of the thermistor which is located on the printed circuit board. This is a quite essential step in allowing the PCB to be put back into the manufacturing process. The proposal is following: we connect Arduino board to the PC with the application and establish the connection with the assets which are already in use. Hypothetically, the application will use the same approach with the procedures sending the commands to Arduino and a timer ticking to ensure two-way communication between the devices. The programmable board would run a program waiting for the incoming command to measure the resistance and send the result back to the program. The processing and printing of the measured values would follow nearly identical steps as we used in the previous procedures. A concept is already present in the application, however, it could not be completely finished.

Efficiency is another side in need of improvement in the application. Due to inexperience and amateurish programming done in the development process of the application, it cannot be in any way concealed that the code is in need of polishing and it is fully understandable the code could be deemed as inefficient by a professional. On the other hand, it is reliably working, tested and ready to use for the company's needs.

7. Conclusion

This bachelor thesis' aim was to conduct a research of light and its measurement, mainly from the standpoint of physics and electrical engineering, and afterwards provide a layout of the hypothetical device that can accomplish the task of measuring LED diodes.

Light is a phenomenon which is greatly utilized by man. However, we need to follow different methods when we try to describe light from the view of a subjective, human observer. Photometry is a scientific discipline which is concerned with evaluating light by human means. We then employ our knowledge of photometry and RGB color coding to measure the light output in the given task, which is radiated by LED diodes. LED diodes are chips with diodes working on a principle of electroluminescence of a PN junction. We learn many ways of using the LED diodes and specific details about numerous materials and colors of them. The device measuring the light output is spectrometer and it consists of multiple parts such as grating or slit that have to be chosen appropriately according to the type of radiation we attempt to measure.

Solution of the task of measuring the LED diodes is done in a fairly lightweight and simple manner. We use power supply to feed the voltage and current to the printed circuit boards with integrated LEDs and subsequently, a highly specific spectrometer for automotive purposes (LED Analyzer) is followingly used to measure the radiating diodes. The whole process of measuring is conducted by an application created specifically for this project, and the computer running the application serves as a node interconnecting all parts of the project. The programming done on the application and its specific procedures and functions are detailed and illustrated in the practical part of this thesis. We discovered there are multiple methods in approaching this task e.g. the color measuring done by the LED Analyzer has an option to measure white color based on CIE Chromaticity index instead of RGB model used in the project.

We have tested the application and deemed it fairly stable and reliable, although some minor improvements could be welcome. In the current state, the application is not yet completely ready to use, but the implementation in a company workplace is not out of the question in the future. Further improvements examined in the last part of the bachelor thesis list adding a programmable board Arduino to measure the resistance of the thermistors on the PCB or making the code more efficient.

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9. List of figures