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COLOUR MEASUREMENT

Dissertation in Master of Biomedical Engineering

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ABSTRACT

As humans we sense colour by the amount of red, green and blue which are the cone cells present in our vision system. A colour can be described by three values, because of the existence of three types of cones - tristimulus data, or by reflectance values - spectral data. Tristimulus data characterizes how a human viewer or a sensor perceives colour, or how a particular device reproduces a colour. Spectral data describes a colour in terms of the intensity reflected in each wavelength.

In order to compare the colour of different objects, a measurement and mapping system is required. The colour spaces mostly used for colour measurement are CIE XYZ, $L^*a^*b^*$ or $L^*u^*v^*$. To have the difference of one colour to another computed it is necessary to measure the distance between the colours in the colour space. A colour sensor quantifies colour in RGB components (similar to the human eye, a monitor, or a scanner).

In this project, it was used the MTCS-C2 Colorimeter Board. It was tried four different configurations in order to achieve accuracy and repeatability. Despite a non-standard light source was used, all the measurements were taken under the same circumstances.

Despite spectrometers remain the Golden Standard for colour measurement, in applications where repeatability is critical, instead of accuracy, colour sensors are an option. Therefore, the aim of this document is to prove that colour sensors are capable of measuring colour repeatedly, and that they can be integrated in different devices.

The results discussed are the ones given by the last experimental setup, since it had produced the best results, being repeatability successfully achieved.

RESUMO

Como seres humanos o nosso cérebro quantifica a cor em vermelho, verde e azul, que correspondem aos cones presentes no nosso sistema visual. Uma cor pode ser descrita por três valores, pela existência de três tipos de cones - valores triestímulos, ou pela sua reflectância - dados espectrais. Os valores triestímulos caracterizam a percepção de um observador humano ou de um sensor sobre a cor de um objecto, ou de como uma cor é reproduzida por um dispositivo. Os dados espectrais descrevem a cor pela intensidade reflectida em cada comprimento de onda.

De modo a se poder comparar a cor de diferentes objectos, é necessário um sistema de medida e de mapeamento. Os espaços colourimétricos mais utilizados na medida da cor são CIE XYZ, $L^*a^*b^*$ *e* $L^*u^*v^*$*. A diferença entre uma cor e outra pode ser calculada medindo a distância entre as cores num espaço colourimétrico. Um sensor de cor divide a luz nas suas componentes RGB (semelhante ao olho humano, monitor, ou scanner).*

Neste projecto, foi utilizado o MTCS-C2 Colorimeter Board, tendo sido experimentadas diferentes configurações de modo a se atingir a repetibilidade e a exactidão de resultados. Apesar de se ter utilizado uma fonte de luz não-standard, todas as medidas foram efectuadas sob as mesmas circunstâncias.

Na medida da cor os espectrómetros são considerados os dispositivos padrão, embora em aplicações onde seja necessário a repetibilidade e não a exactidão, os sensores de cor são considerados os melhores dispositivos. É, portanto, objectivo deste estudo provar que os sensores de cor são capazes de medir cor com repetibilidade, e que podem ser integrados em diferentes dispositivos.

Os resultados discutidos foram obtidos pela última unidade experimental, pois era a que apresentava os melhores resultados, tendo sido atingido com sucesso a repetibilidade.

ACRONYMS

A/D Converter	Analog-to-digital converter
CCD	Charge coupled device
CIE	International Commission on Illumination
CMOS	Complementary metal-oxide-semiconductor
CMYK	Cyan, magenta, cyan, and key
CCT	Correlated colour temperature
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EEPROM	Electrically Erasable Programmable Read-Only Memory
FWHM	Full width at half maximum
GFC	Goodness-of-fit coefficient
HSL	Hue, saturation, and lightness
HSV	Hue, saturation, and value
InGaN	Indium gallium nitride
IR	Infrared
LED	Light-emitting diode
NTSC	National Television System Committee
PAL	Phase Alternating Line
PCS	Profile Colour Space
RGB	Red, green, and blue
RMSE	Root mean square error
SECAM	Sequential Colour with Memory
SD	Standard deviation
SNR	Signal-to-noise ratio
sRGB	Standard RGB
TAG	Terbium aluminum garnet

USB	Universal serial bus
UV	Ultraviolet
ΔE, or dE	Colour difference

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CONTENTS

ABSTRACT i
RESUMO ii
ACRONYMS iii
ACKNOWLEDGMENTS v
LIST OF FIGURES ix
LIST OF TABLES xi

1. INTRODUCTION 1
1.1. MOTIVATION 1
1.2. OBJECTIVES 1
1.3. DOCUMENT'S STRUCTURE 2

2. THEORETICAL BACKGROUND 3
2.1. INTRODUCTION 3
2.2. STANDARD OBSERVER 5
2.3. ILLUMINANT 6
2.4. COLOUR SPACES 7
2.4.1. CIE XYZ 8
2.4.2. CIE L*a*b* 9
2.4.3. CIE L*u*v* 11
2.4.4. Other Colour Spaces 12
2.5. COLOUR DIFFERENCE 13

3. COLOUR MEASUREMENT DEVICES 16
3.1. INTRODUCTION 16

3.2. COLOUR SENSORS 16
3.2.1. State of the Art 17
3.3. SPECTROMETERS 19
3.3.1. Colour Sensors vs. Spectrometers 19
3.4. RGB DIGITAL CAMERAS 20

4. COMPONENTS OF THE SYSTEM 21
4.1. MEASUREMENT SYSTEM ARCHITECTURE 21
4.2. IMPLEMENTATION 22
4.2.1. Experimental setup A 22
4.2.2. Experimental setup B 24
4.2.3. Experimental setup C 25
4.2.4. Experimental setup D 26

5. COLOUR SENSOR 29
5.1. INTRODUCTION 29
5.2. MTCS-C2 BOARD COLORIMETER 29
5.3. JENCOLOUR 31
5.3.1. Illuminant 31
5.3.2. Calibration 36

6. RESULTS 40
6.1. REPEATABILITY 41
6.2. ACCURACY 42

7. CONCLUSIONS AND FUTURE WORK 46

7.1. CONCLUSIONS 46
7.2. FUTURE WORK 47

8. REFERENCES 48

APPENDIX A 52
APPENDIX B 54
APPENDIX C 56
APPENDIX D 68

LIST OF FIGURES

Figure 1 – Electromagnetic spectrum (2).. 3

Figure 2 – The wavelength sensitivities of the different photoreceptor types in the retina (4).... 4

Figure 3 - Colour matching functions: on the left the CIE 1931 RGB colour matching functions, and on the right the CIE Standard Observer colour matching functions (8)................................ 5

Figure 4 – 2 versus 10 degree Standard Observer (9). 6

Figure 5– The CIE 1931 colour space chromaticity diagram (12). 9

Figure 6– CIE LAB colour space (13).. 10

Figure 7– CIE LUV chromaticity diagram (14). 11

Figure 8 – Operation principle of the system. 21

Figure 9– Different views of the experimental setup A: on the left, a top view, and on the right, a lateral view showing the different light sources. 22

Figure 10 – Schematic diagram of the current regulator of Experimental setup A. 23

Figure 11- Schematic diagram of experimental setup B (31). 24

Figure 12 – Schematic diagram of experimental setup C. 25

Figure 13 – General view of experimental setup C.. 26

Figure 14 – General view of experimental setup D. 26

Figure 16 – The different light sources used in experimental setup D....................................... 27

Figure 15 – The different measuring heads used in Experimental setup D. On the left, a measuring head with a configuration of 0°/0°; in the middle, a configuration of 45°/45°; on the right, a configuration of 45°/0°. 27

Figure 17 - Schematic diagram of the circuit used for the RGB LED in Experimental setup D..... 28

Figure 18 – MTCS-C2 Colorimeter Board (33).. 29

Figure 19 - Typical (relative) sensitivity (XYZ) of the colour sensor (MTCSiCS), and Standard Observer function (34)... 30

Figure 20– Jencolour system configuration.. 31

Figure 21 – USB4000 Miniature Fibre Optic Spectrometer (35).. 32

Figure 22- The high intensity LED spectrums: one given by its data sheet, and the other given by the spectrometer. 34
Figure 23 – The spectrums shifts in order to match the wavelengths where the first peak occurs. 35
Figure 24– Colour Checker chart (37). 36

LIST OF TABLES

Table 1 – The chromaticity coordinates given by the spectrometer and data sheet, and their shifts. 36

Table 2 – The RGB offsets obtained for each calibration. 38

Table 3 – The repeatability of results for different chromaticity coordinates of the light source. 41

Table 4 – The goodness-of-fit coefficient of results for different chromaticity coordinates of the light source. 42

Table 5 – The root mean square error of results for different chromaticity coordinates of the light source. 43

Table 6 – The colour difference ΔE^*_{ab} for each patch. 44

Table 7 - The colour difference ΔE^*_{00} for each patch. 45

1. INTRODUCTION

1.1. MOTIVATION

In order to measure colour, spectrometers remain the golden standard and are capable of providing the most complete description. This device quantifies the reflectance or transmittance of a sample at discrete wavelengths. With a few calculations, spectral data can be converted into colorimetric data. Despite spectrometers are the most accurate, colour sensors are the most appropriate when price-performance ratio is considered.

Colour sensors typically use three filters (red, green, and blue - RGB), producing a response similar to that of the eye. In order to simplify calculations, a conversion between RGB to XYZ is necessary. This procedure is important to avoid negative quantities. From XYZ values, a proper colour space can be computed, dependent on the application.

As the prices of spectrometers and colour sensors differ in two orders of magnitude, is important to keep searching and developing the actual technology of colour sensors in order to make them accurate.

1.2. OBJECTIVES

The aim of this project is to get repeatable measurements with a low-cost sensor. Colour sensors aim to replace spectrometers in applications where accuracy is not critical, and this documents is intended to give a contribute. The greatest advantage of colour sensors over spectrometers is their low-cost.

It is also an objective the accuracy inspection of the colour sensor: whether the results are or not accurate.

1.3. DOCUMENT'S STRUCTURE

In this section, it will be summarized each of the eight chapters that are present in this document.

In the second chapter, it will be referred the colour theory. This chapter is divided into six sub-chapters. Firstly, it is introduced the vision system and the problematic of Colourimetry. Then it is discussed the Standard Observer and the Illuminant, being two decisive factors of how a colour will be perceived by a subject or a device. Afterward, are described some colour spaces related to measure reflective light, to emissive light and to printing inks. Finally, are enumerated different procedures in order to quantify the colour difference.

The third chapter is intended to describe three measuring colour devices. The first is colour sensors where is made the state of the art of these devices. After that, it is described the spectrometers and is made a comparison between colour sensors and spectrophotometers. Then, is mentioned a new technique to measure colour: RGB digital cameras associated to image processing software.

In the forth chapter is described the different experimental setups made through the project. First is delineated the operation principle of the measurement system. Afterward, the experimental setups are explained in detail.

The fifth chapter is dedicated to the colour sensor used in the project. At the beginning, it is mentioned the hardware, and in the second sub-chapter is referred Jencolour, the application software. In this sub-chapter is mentioned the problematic of illumination and calibration.

In the sixth chapter is presented some results taken with the high intensity light emitting diode (LED) in Experimental setup D, taking into account repeatability and accuracy.

The seventh chapter is dedicated to present some conclusions and to delineate some future work that would be relevant in the consequence of this project.

In the last chapter is referenced all the sources used for the writing of this document.

2. THEORETICAL BACKGROUND

2.1. INTRODUCTION

Colour is the sensation produced in response to selective absorption of wavelengths from visible light (1). The human eye only perceives a small part of the electromagnetic spectrum, ranging the wavelength of the visible light from about 380nm to 780nm. A colour produced by a single wavelength is known as spectral colour, being the colours of the rainbow an example: violet, blue, green, yellow, orange and red. The other colours are characterized by a spectrum with different wavelengths. Brown and pink are examples of non-spectral colours, which are produced by a mixture of various wavelengths.

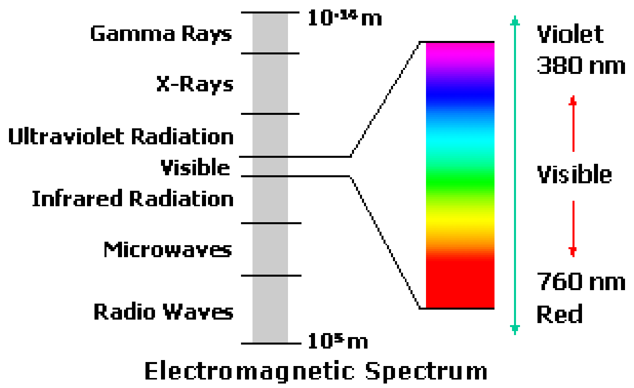

Figure 1 – Electromagnetic spectrum (2).

Colour vision begins with the activation of the photopigments in the cone photoreceptor cells. Human eyes have three types of cones differing in the pigment they absorb, responding optimally to light of different wavelengths (3).

The photopigments have their peak sensitivities at 420nm, 534nm, and 564nm, and have a bandwidth on the order of 100nm. These three cases are commonly known as blue or short wavelength, green or medium wavelength, and red or long wavelength, respectively.

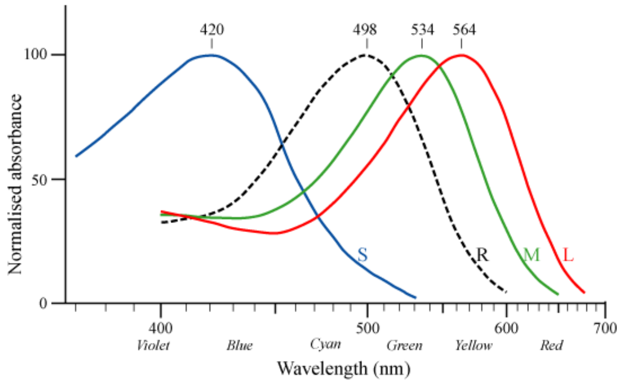

Figure 2 – The wavelength sensitivities of the different photoreceptor types in the retina (4).

By having three types of cones, a simplified spectrum can be represented by three independent variables, a concept known as trichromacy. This model is the underlying basis for RGB video monitors and colour television (5).

There is another type of photoreceptor cell in the retina that is called rod. They function in less intense light than the cone cells, being responsible for night vision, conferring an achromatic vision.

Colourimetry, the measurement of colour, attempts to quantify the perception of colour (6). This method depends on two basic principles: any colour can be matched with an appropriate mixture of three selected beams of light with a few exceptions, and two colours when matched in turn by such mixtures will be matched by the sum of their separate matching combinations similarly mixed (7).

In order to bring uniformity to the colour measurement, in 1931 was created the *Commission Internationale d'Éclairage* (International Commission on Illumination, CIE). This organism established numerical specification of colours that provided a common basis for all colour measuring methods which is independent of the colour vision of any particular individual, so that results may be interchangeable between different methods and between different instruments using any one method (7).

For the perception of colour there are three components that need to be understood: the object, the observer, and the illumination. These three factors are taken into account when is carried out a measurement and expressed in a colour space.

2.2. STANDARD OBSERVER

In order to make an establishment between the physical stimulation and the visual sensation, W. David Wright and John Guild independently carried out experiments. They used various primaries at various intensities, a number of different observers, and the results were obtained using three monochromatic primaries at wavelengths of 435,8nm (blue), 546,1nm (green), and 700nm(red). By knowing the intensities of each colour, it is possible to calculate the amounts of primaries needed for an observer to adjust the colour correctly. These results were called RGB colour matching functions.

Afterward, the CIE has delineated and adopted a new colorimetric system based on the primaries colours red, green and blue. This new system was defined in terms of three new colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, and is known as XYZ colour matching functions. These are theoretical and unreal primaries, being impossible to produce.

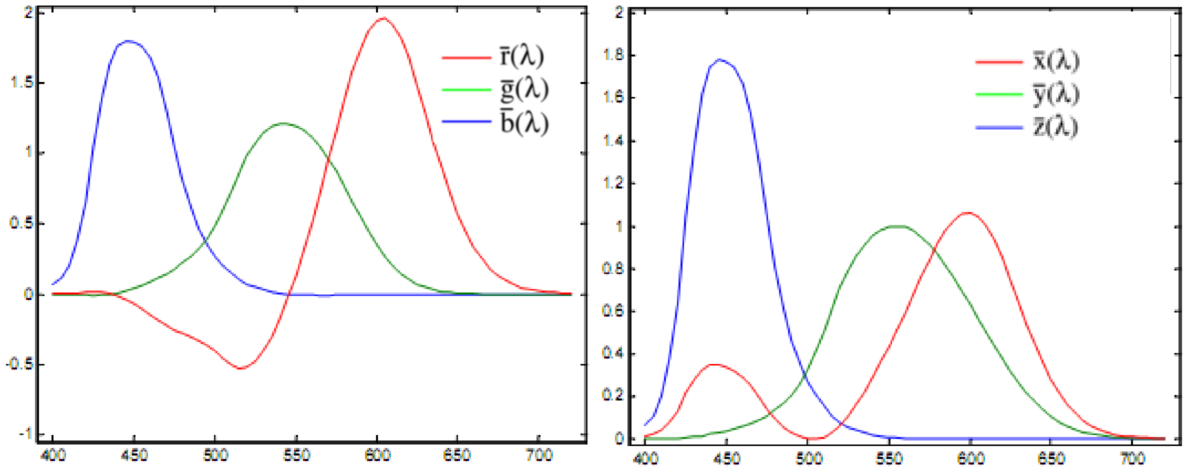

Figure 3 - Colour matching functions: on the left the CIE 1931 RGB colour matching functions, and on the right the CIE Standard Observer colour matching functions (8).

The greatest particularity of this new system is that any colour can be matchable only by positive mixtures of the primaries, without any negative quantities. This led to a simplification in computations.

The Standard Observer defined in 1931 by the CIE contemplates a 2° field of view, which means that an observer is able to use only the region of the retina that is more sensitive to colour, known as fovea. Around the years 60, it was discovered that the cones are not only present in the fovea. There are subtle differences when a wider area of view is used, particularly in the blue-green region of the spectrum. Despite this, studies showed that there is a better repeatability when is considered the 10° observer.

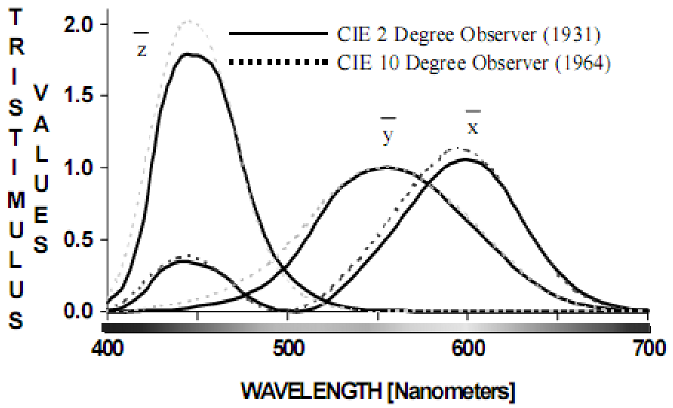

Figure 4 – 2 versus 10 degree Standard Observer (9).

The 10° Standard Observer is accepted nowadays to be the best fitting of the average spectral response of human observers, although the 2° Standard Observer is still considered for measurement of objects at long distance.

2.3. ILLUMINANT

The illumination influences directly the colour: when the objects are submitted to different light sources the perception of colour changes significantly. Sometimes, different colours when submitted to different light sources appear to be the same colour. This is called metamerism – apparent colour of objects matchable when having different spectral power distribution. Therefore, the CIE has defined standard illuminants which are characterized by their spectral power distribution.

Illuminant and light source are not the same thing: while a light source is a physical light, an illuminant has its spectral power distribution defined, but may not really exist.

Illuminant A represents an incandescent light, illuminant B represents the sunlight with a temperature of 4900k, and illuminant C represents the average daylight with a temperature of 6800k. These illuminants were introduced in 1931.

Illuminants D represent phases of daylight. The number in the illuminant of D series represents the Correlated Colour Temperature (CCT) of the light, for example, illuminant D50 has a CCT of 5000k. In 1963, CIE recommended the Standard Illuminant D65, which has a temperature of 6504k.

Illuminants F represent fluorescent lamps of various compositions: F2 is the cool white fluorescent source, F7 is a broad band daylight fluorescent day light, and F11 is a narrow band white fluorescent source (10).

2.4. COLOUR SPACES

As mentioned before, the human eye has three types of photoreceptors: blue, green and red. In principle, a colour needs three parameters to be defined. A method consisting in the association of three numbers, or tristimulus values, to each colour is called a colour space. The most known colour space is CIE XYZ.

2.4.1. CIE XYZ

The corresponding XYZ tristimulus values for a colour with a radiance or spectral power distribution $R_e(\lambda)$ are given by:

$$X = \int_{\lambda_{min}}^{\lambda_{max}} \bar{x}(\lambda)\, R_e(\lambda) d\lambda \qquad Y = \int_{\lambda_{min}}^{\lambda_{max}} \bar{y}(\lambda)\, R_e(\lambda) d\lambda \qquad 2.1$$

$$Z = \int_{\lambda_{min}}^{\lambda_{max}} \bar{z}(\lambda)\, R_e(\lambda) d\lambda$$

where λ_{min} and λ_{max} represent the limits of the visible light in terms of wavelengths.

An interesting property of this colour space is that Y represents the luminance factor for quantity.

When a specimen colour is matched by certain proportions of the primaries R, G and B lights, as measured on the colour sensor, these proportions can be converted arithmetically, using the known X, Y and Z values of the primaries, into the CIE tristimulus values for the colour (7). This linear transformation defines the Standard Colorimetric System CIE XYZ 1931 and it can be expressed by means of the following matrix:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad 2.2$$

It is convenient to have a representation of "pure" colour in the absence of luminance. The CIE standardized a procedure to normalize the tristimulus values XYZ to obtain two chromaticity values x and y (11). These new chromaticity coordinates are known as CIE xyY and are represented in the following chromaticity diagram, on figure 5. They are computed by the following equations:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} \qquad 2.3$$

In the chromaticity diagram, the outer curved boundary is known as the spectral locus and it corresponds to monochromatic light, with wavelengths shown in nanometres. The line in the lower part of the spectral locus is called the line of purples and represents the pure purples or magentas, which do not occur in the spectrum being non-spectral colours.

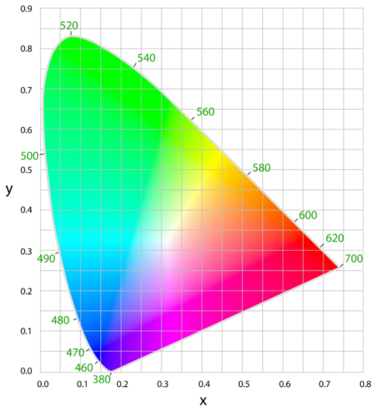

Figure 5– The CIE 1931 colour space chromaticity diagram (12).

All colours that can be formed by adding three sources of light, lie inside of a triangle formed by the source points in the spectral locus. An important fact that can be concluded is that there are no three points that can cover the entire chromaticity diagram. A limitation of this colour space is that it isn't perceptually uniform.

The dominant wavelength is the wavelength of the light that would be equivalent to the colour, if it was a pure colour. The purity tells how close a colour is from the pure spectral colour represented by its dominant wavelength.

2.4.2. CIE L*a*b*

Since the chromaticity diagrams only consider tristimulus values, they merely show colours with the same value of luminance. In 1976, the CIE specified a colour space in which would be contemplated the variations of tristimulus values and the luminance. This colour space is known as CIE LAB 1976 and is exclusively projected to relate to reflective "colour".

This system is based on the fact that a colour cannot be simultaneously black and white, nor red and green, and nor yellow and blue. L^* defines lightness, a^* denotes red/green, and b^*

denotes yellow/blue. The L* coordinate ranges from 0 through +100, and the last two coordinates range from -500 through +500, being only used the range from -128 through +127. The three coordinates are computed from the tristimulus values according to the following equations:

$$L^* = 116\, f\left(\frac{Y}{Y_0}\right) - 16 \qquad 2.4$$

$$a^* = 500\left[f\left(\frac{X}{X_0}\right) - f\left(\frac{Y}{Y_0}\right)\right] \qquad 2.5$$

$$b^* = 200\left[f\left(\frac{Y}{Y_0}\right) - f\left(\frac{Z}{Z_0}\right)\right] \qquad 2.6$$

where $f(t) = \begin{cases} 7{,}787 * t + \frac{16}{116}, & t \leq 0{,}008856 \\ t^{1/3}, & t > 0{,}008856 \end{cases}$.

The X_0, Y_0 and Z_0 are the CIE XYZ tristimulus values of the reference point.

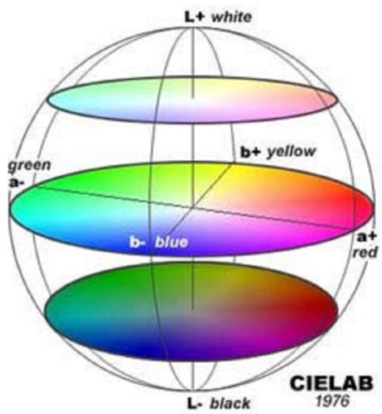

Figure 6– CIE LAB colour space (13).

This colour space has a greater importance because it is approximately uniform, which means that the distance between two colours corresponds roughly to the colours' perception difference.

Since the response of the eye is nonlinear, the coefficient 1/3 is optimized to correspond. The linear piece of the function is to avoid complications when converting L*a*b* to XYZ because in the inverse function the slope of the function becomes infinite at the origin.

When a colour is attenuated, all the three coordinates decrease.

The colour space L*C*H* is a different system of measuring the colour space L*a*b*. It is a polar coordinate colour space, where L* stands for lightness, C* stands for chroma (the distance between the point and the lightness axis), and H* stands for hue (the angle in degrees between the point and the lightness axis). The coordinate L* is the same for these two colour scales, and C and H are computed from the a* and b* of the CIE L*a*b* colour space.

$$L = L \quad 2.7$$

$$C = \sqrt{a^2 + b^2} \quad 2.8$$

$$H = tg^{-1}\left(\frac{b}{a}\right) \quad 2.9$$

2.4.3. CIE L*u*v*

In the CIE L*u*v* colour space the colour differences between the coordinates are approximately equivalent to the perceptible colours. It was defined in 1976 by the CIE, and it is one of the most uniform colour spaces (10).

This colour space and CIE L*a*b* were accepted simultaneously by the CIE when it was not figured out a consensus behind simply one or the other of these two colour spaces.

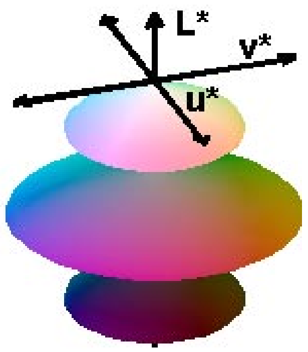

Figure 7– CIE LUV chromaticity diagram (14).

The coordinate L* refers to the lightness and is defined by a nonlinear function, ranging from 0 through +100. The coordinates u* and v* are chrominance values and are defined by linear functions. These variables are defined by the following equations:

$$L^* = \begin{cases} 116 * \left(\frac{Y}{Y_0}\right)^{1/3} - 16, & \frac{Y}{Y_0} < 0{,}008856 \quad 2.10 \\ \left(\frac{29}{3}\right)^3 * \left(\frac{Y}{Y_0}\right), & \frac{Y}{Y_0} \geq 0{,}008856 \quad 2.11 \end{cases}$$

$$U = 13 * L^*(u' - u'_0) \quad 2.12$$

$$V = 13 * L^*(v' - v'_0) \quad 2.13$$

$$u' = \frac{4X}{X + 15Y + 3Z} \quad 2.14$$

$$v' = \frac{9X}{X+15Y+3Z} \quad 2.15$$

$$v = \frac{2}{3} * v', \qquad u = u' \quad 2.16$$

where u'_0 and v'_0 are the reference point chromaticity coordinates.

2.4.4. Other Colour Spaces

The colour spaces discussed so far are intended to relate to reflective "colour". There are other colour spaces which have their purpose to relate to emissive light sources (15).

For computer graphics the most widely used colour spaces are RGB, HSV and HSL. The RGB space quantifies a colour in terms of red, green, and blue. HSV and HSL are simple conversions of RGB. The HSL coordinates are hue, saturation and lightness, and the HSV coordinates are hue, saturation, and brightness. Although "hue" in both colour spaces stands for the same attribute, "saturation" is different.

For television images the colour spaces used are Yuv, YIQ, YP_BP_R, and YC_BC_R. Yuv is used in the American NTSC TV System, in the European PAL TV System, and in the SECAM, and it derives from the RGB model. Y is the luma component, and u and v are the chrominance components. YIQ is used in the analog NTSC TV System. Y stands for luma, and I and Q stand for chrominance. If we think that in Yuv, u and v components are x and y axes, in YIQ, I and Q components will be a second pair of axes on the same graph, rotated by 33°. YP_BP_R is used in consumer electronics, being the analog video signal carried by the component video cable. Y is the luma component, P_B is the difference between blue and luma (B-Y), and P_R is the difference between red and luma (R-Y). YC_BC_R is used in digital video.

For photographic images the colour spaces used are sRGB, Adobe RGB, sYCC, and PCS. sRGB derives from the RGB colour space and is widely used in digital cameras, LCD displays, printers and cameras, being its greatest advantage a larger gamut. PCS (Profile Colour Space) is an intermediate language between two different colour spaces, and is never used as an "output".

For the printing process it is used CMYK which is a subtractive colour model. C stands for cyan and is the combination of blue and green; M stands for magenta and is the combination of blue and red; Y stands for yellow and is the combination of green and red; and K stands for black and is the combination of cyan, magenta, and yellow. The black ink was introduced in order to produce low-reflectance colours.

2.5. COLOUR DIFFERENCE

The difference between two colours is a concept of interest in colour science, being represented by ΔE, or sometimes dE. It is used to predict how far off has a device floated from the original, and to eliminate subjectivity. ΔE is an important indicator since it evaluates the performance of the estimation method (16).

In theory, the least colour difference the human eye can see is a ΔE of 1,0, when the samples are separated. However, the human eye is more sensitive to certain wavelengths, being some differences of 1,0 between two colours perfectly acceptable and for others do not.

In 1976, the CIE has defined colour difference as the Euclidean distance between two points, which represents the two colours, in a chromaticity diagram. This ΔE is defined in the L*a*b* colour space and is given by the following equation:

$$\Delta E^* = \sqrt{(\mathrm{L}_2^* - \mathrm{L}_1^*)^2 + (\mathrm{a}_2^* - \mathrm{a}_1^*)^2 + (\mathrm{b}_2^* - \mathrm{b}_1^*)^2} \quad 2.17$$

where L_1^*, a_1^* and b_1^* are the coordinates of standard colour, and L_2^*, a_2^* and b_2^* are the coordinates of comparison colour. When ΔL* is positive it means that the sample is lighter than the standard, and if it is negative the sample is darker than the standard; when Δa* is positive it means that the sample is more red (or less green) than the standard, and if it is negative the sample is more green (or less red) than the standard; when Δb* is positive it means that the sample is more yellow (or less blue) than the standard, and if it is negative the sample is more blue (or less yellow) than the standard.

The same ΔE* can be given by different colour variation in different colour areas of L*a*b*, which means that this colour space is not perceptually uniform, against to what its creators pretended. Consequently, ΔE* can only be used for basic calculations.

In 1994, the CIE has defined another colour difference, ΔE_{94}^*, from the L*C*H* colour space. This colour difference is given by:

$$\Delta E_{94}^* = \sqrt{\left(\frac{L_2^* - L_1^*}{K_L}\right)^2 + \left(\frac{C_2^* - C_1^*}{1 + K_C * C_1^*}\right)^2 + \left(\frac{H_2 - H_1}{1 + K_2 * C_1^*}\right)^2} \quad 2.18$$

where the k factor is dependent on the application.

The colour difference ΔE_{94}^* is recommended to use in graphic arts.

In 2000, CIE has defined another colour difference, ΔE_{00}^*, since the last one did not solve effectively the perceptual uniformity problem. There was a compensation for lightness (S_L), for chroma (S_C), for hue (S_H), and for neutral colours.

$$\Delta E_{00}^* = \sqrt{\left(\frac{\Delta L'}{K_L * S_L}\right)^2 + \left(\frac{\Delta C'}{K_C * S_C}\right)^2 + \left(\frac{\Delta H'}{K_H * S_H}\right)^2 + R_T * \left(\frac{\Delta C'}{K_C * S_C}\right) * \left(\frac{\Delta H'}{K_H * S_H}\right)} \quad 2.19$$

R_T is a hue term to treat the blue region, around the angles of 275°. The rest variables will be defined in Appendix B.

This colour difference at this time is still under consideration, but seems the most complete and the most accurate.

3. COLOUR MEASUREMENT DEVICES

3.1. INTRODUCTION

Common colour measurement devices are densitometers, spectrometers, colour sensors, and RGB digital cameras. A densitometer measures and computes how much of a known amount of light is reflected from-or transmitted through-an object (17). A spectrometer measures spectral data, which means that measures the amount of light in a specific range of the electromagnetic spectrum. These values are represented as a spectral curve. A colour sensor quantifies colour in RGB components (similar to the human eye, a monitor, or a scanner). RGB digital cameras need image processing software in order to obtain the tristimulus values.

3.2. COLOUR SENSORS

Our brain interprets the red, green and blue signals as one colour. Colour sensor is a device which uses three or more filters (RGB) to produce a response similar to that of the eye (18). The combined response of the filters is designed to match the CIE standard observer. A colour's numeric value is determined using CIE XYZ, L*a*b* or L*u*v*.

Colour sensors measure reflected and emitted light. In managing a colour system, a device-independent colour description is important.

The repeatability and lower cost of these devices make them very popular in the industry. Compared with other measurement devices, colour sensors offer less accurate results but are highly repeatable. If a colour sensor's spectral response exactly matches the observer matching functions, its measurements will be accurate (19).

A typical approach is the combination of three photodiodes with red, green, and blue filters applied to the photodiode surface. Sometimes it can be used two photodiodes with blue filter in order to compensate a lower sensitivity of silicon to blue light. The output of each photodiode is fed by separate trans-impedance amplifiers to A/D converters. The resolution of the A/D converters is typically 8 to 12 bits and their output is fed to a microcontroller or other type of digital processor.

A second approach results on the arrangement of a photodiode, a colour filter, and a trans-impedance amplifier on a single die for each colour band. The output of three of those arrangements is fed to an external three-channel A/D converter followed by digital processing. This approach is a converter light-to-voltage and requires fewer components than the first one.

Another approach converts light intensity to a pulse train with a frequency proportional to the intensity of the red, green, and blue components of the light on each of the red, green, and blue channels, respectively (20). The trans-impedance and A/D converters are not needed since this arrangement provides a direct interface to a microcontroller, giving the highest level of noise immunity. The processor measures the period or counts the pulses from the sensor over a period.

The colour sensors can be integrated into a variety of solutions including colour calibration of computer monitors, automotive sensors, densitometers, laser printers, lighting control, LED test equipment, automation equipment, and cosmetics manufacturers (21). In terms of biomedical application, the uses of colour sensors are exampled by clinical diagnosis of skin erythema, dental matching, colour matching in plastic surgery and skin transplantation, and the clinical analysis of blood and urine strip tests (22).

3.2.1. State of the Art

There are a few companies that produce colour sensors.

Avago Technologies commercializes a digital colour sensor: ADJD-S313-QR999 is an array of complementary metal-oxide-semiconductor (CMOS) photodiodes covered with red, green and blue colour filters. It has a two-wire digital interface to set parameters and retrieve light data from the chip. Avago offers another solution: an integrated colour sensor and RGB LED controller, ADJD-J823 (23).

The Integrated Colour LTV Sensors produced by Texas Advanced Optoelectronic Solutions (TAOS) combine a photodiode, colour filter, and trans-impedance amplifier on a single die. TCS230 is constituted by a photodiode grid of 16 groups of 4 elements each. Each group has a red, a green and a blue sensors, and a clear sensor with no filter. The intensity of the colours sample is directly proportional to the frequency of a square wave, which is the output for each colour of the colour sensor (24).

Agilent offers a colour sensor, HDJD-S722-QR999, which combines a photodiode array and three trans-impedance amplifiers in one chip. The photodiode array is covered with a red, a green and a blue colour filters, and the sensor converts light to R, G and B analog voltage outputs (25).

EMTX Industries produces Colour_Max_1000 which is the only colour sensor in the market available in an M30 package. It recognizes up to 15 colours and RGB intensity. This colour sensor is accomplished by an application software (26).

Hamamatsu offers a great lack of colour sensors, differing on the active area, on the output and on the mounting (27).

Far off the MTCS series which are True Colour Sensors, used in this project, Mazet offers the MCS series which are RGB Colour Sensors with a high level of dynamism and a low level of technical complexity, having only 3 elements for detection, and take colour comparative readings (28). Mazet also offers other modules than MTCS-C2: MTCS-ME1 modEva-Board and MTCS-TIAM.

3.3. SPECTROMETERS

Spectrometry is the measurement of the reflectance or transmittance of a sample at discrete wavelengths (18). Data obtained from a spectrometer is the most complete description of a colour that can be achieved. The colour will appear to be the same when the spectral curves of two objects overlap completely; when spectral curves have the same shape but differ in amplitude, it indicates that is the same pigment at different densities.

For most applications a sampling interval of 20nm provides sufficient accuracy, reducing the time of measurements and instrument costs.

Spectral data is independent from the illuminant and device. Since spectral data is not dependent on a viewer, it can describe spectra beyond the visible (380-720nm), including ultraviolet (UV) and infrared (IR) radiation. Spectral data can be translated into colorimetric data with a few calculations.

Spectrophotometers measure visible light, near-ultraviolet, and near-infrared.

In the spectrometers, light enters and is collimated by a spherical mirror, being diffracted by a plane grating. The light is focused by another mirror being then projected onto a detector. In some spectrometers the detector can be a photomultiplier or a charge coupled device (CCD), dependent on the wavelength of light to be detected.

3.3.1. Colour Sensors vs. Spectrometers

Dependent on the application, one or the other instrument will be more appropriate, being necessary to understand their features.

Both types of instruments measure over the same range of wavelengths (about 400 to 700nm), treating the data obtained differently. Colour sensors provide data as tristimulus values (XYZ, L*a*b*, L*u*v*, etc), while spectrophotometers provide spectral data (light intensity as a function of wavelength), being possible by means of calculations to convert spectral data into tristimulus values, as mentioned before, but not the otherwise.

While colour sensors' operation principle is the use of photodiodes or filters that isolate a broad band of wavelengths, the spectrophotometers use a prism, grating or interference filter in order to isolate a narrow band of wavelengths.

Both instruments allow different combinations of illuminant and observer to calculate tristimulus values.

The spectrophotometers are preferable in research and development, while the colour sensors are more used in industry for regular comparisons of similar colours or for quality examination. The most important factor which contributes for the growing of colour sensors is their low-price, ~30€, while the spectrophotometers price is up to 3000€.

3.4. RGB DIGITAL CAMERAS

Another device used in colour measurement is RGB digital cameras. Their greatest advantage over the colour sensors is that the surface to be measured can be heterogeneous and larger. Most of the available colour sensors only measure an area of ~2cm^2, making the measurements obtained quite unrepresentative.

Digital colour cameras generally use a Bayer mask. Each square of four pixels has one red filter, one blue filter, and two green filters, producing an image in terms of RGB. Since the RGB colour space depends on external factors, such as the sensitivity of the sensors of the camera and illumination, the conversion from RGB to L*a*b* cannot be done directly using the CIE formulas (29). A combination of a digital camera and image processing software is required to overcome this difficulty.

4. COMPONENTS OF THE SYSTEM

4.1. MEASUREMENT SYSTEM ARCHITECTURE

The main components of this colour measurement system are the light source, the optical fibre, and the colour sensor (MTCS-C2 Board Colorimeter). An excellent interaction between these components is indispensable for the acquirement of good colour signals. The colour of an object depends on its reflecting characteristics and on the nature of the light source.

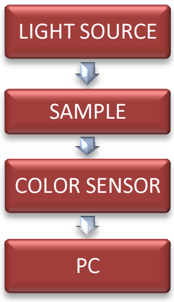

Figure 8 – Operation principle of the system.

The light source is used to give the same constant lighting conditions. It was used different LEDs rather a standard light source for illumination. The measurements were carried out in a dark environment to avoid reflections and interference.

The optical fibre is used to transmit the light of the light source into the sample, so it can present identical lighting conditions in every sampling, and it is also used to transmit the signal correspondent of the object's colour to the colour sensor. The optical fibre used has a low attenuation at the visible range of the lighting spectrum. Its core diameter is 1960µm, it has a numerical aperture of 0,5, and its refractive index is 1,49 (30).

When the signal reaches the colour sensor it will be converted into a current proportional to the incident light and then to tristimulus values, which will be processed by the computer. The colour sensor is integrated in a module that will be explained in more detail in Chapter 5.

Afterward, the colour data is displayed by the application software of the colour sensor, being then processed by Matlab®.

4.2. IMPLEMENTATION

This project involved the elaboration of four different experimental setups. The main difference between these experimental setups is that there was an evolution in terms of freedom and flexibility in operation, being the first experimental setup a bench model – Experimental setup A. As this experimental setup was not practical for measuring an object with greater dimensions, it was planned another type of configuration. So, the other experimental setups had an optical fibre measuring head for optimal flexibility. In order to configure this flexibility, we first thought to use an optical coupler – Experimental setup B. As we did not find an optical coupler with the desired characteristics, we chose a beam splitter – Experimental setup C. With this configuration there was a contamination of the signal, consequently it was planned another one – Experimental setup D.

4.2.1. Experimental setup A

This first experimental setup was very useful for taking the first conclusions about the function of the colour sensor. This experimental setup in terms of instrumentation is very simple being constituted of a light source and a sensing experimental setup.

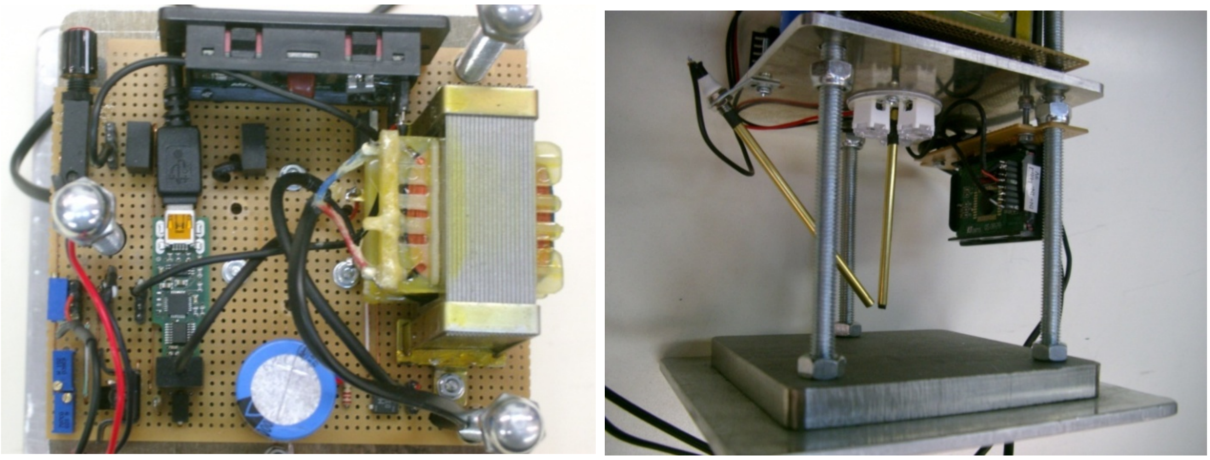

Figure 9– Different views of the experimental setup A: on the left, a top view, and on the right, a lateral view showing the different light sources.

The figure 9 on the left shows the current regulator circuit that controls the current which is present at the terminals of the light source. On the right is shown the two light sources used at different stages of the project.

In this first experimental setup, the light source used was initially a LED module constituted by three white LED's. It can be seen in the figure on the right lying in the top. The configuration of 0°/0° given by this light source and by the optical fibre was not the most appropriate. The first number is the angle of the light source, and the second number is the angle of the colour sensor. These two angles are related to the perpendicular of the surface of the sample being measured. This experimental setup has produced a bad signal-to-noise ratio (SNR) which had led to a disparity of results. Also, the distance between the three LED's and the sample was very large.

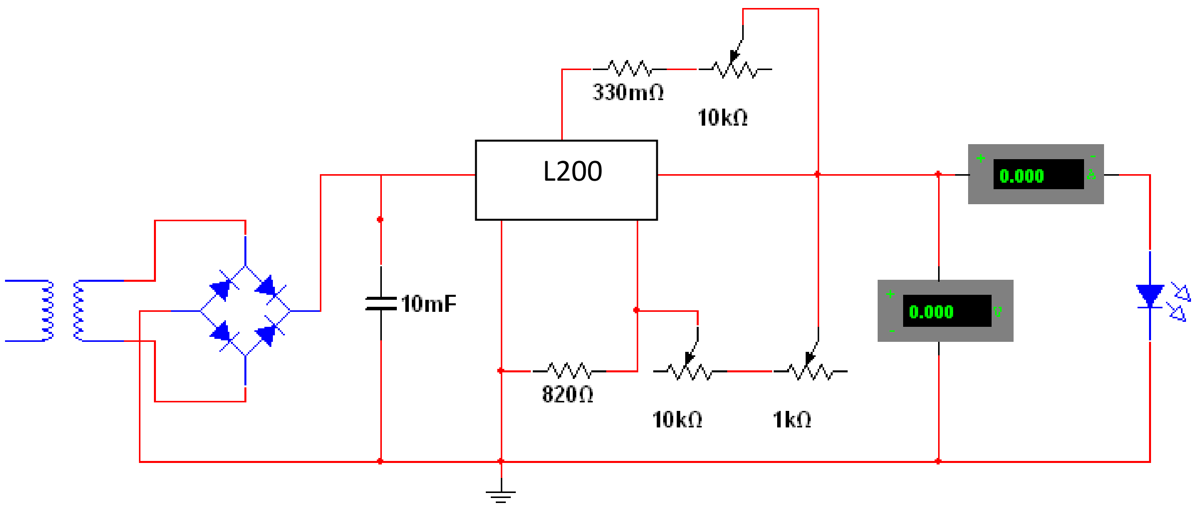

Figure 10 – Schematic diagram of the current regulator of Experimental setup A.

Consequently, it was placed a second LED. This was a simple white LED and it was positioned in the top, as it can be seen in figure 9 on the right. To the light source was attached an optical fibre so it could lead the light directly to the sample, giving a geometry of 45°/0°. This arrangement provided an increase of the results consistency.

The displays present in this experimental setup shows the current and the voltage present at the terminals of the light source. In order to alter the current, and consequently the voltage, it was set a variable resistor, or trimmer. This was intended to perform some experiences with the LED and to stabilize its intensity.

The transformer function in this circuit is to alter the voltage of the alimentation net to the values that the circuit is operational. The voltage available in the circuit is 9V.

In figure 9 on the left it is present the colour sensor. Its voltage supply is given by the USB port. As the colour sensor is not directly in contact with the sample, the interface is made by the optical fibre. Therefore, the optical fibre function is to transmit the signal from the sample, i.e. its colour, to the colour sensor.

4.2.2. Experimental setup B

As this first experimental setup, with its two different arrangements, was not ergonomic, a second one was designed.

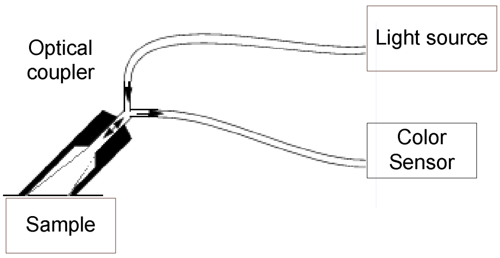

Figure 11- Schematic diagram of experimental setup B (31).

The greatest advance made with this experimental setup is the placement of an optical fibre measuring head. It is intended to perform an evolution in freedom and flexibility in operation.

The main components of this experimental setup are the optical coupler, the colour sensor and the light source.

An optical coupler splits light into two. The light from the illuminant is split to the optical fibre connected to the sample and to the optical fibre connected to the colour sensor, by a proper ratio transmission. Then the colour signal is transmitted to the colour sensor and back to the illuminant.

It was not possible to set up this configuration since no white light fibre couplers were available. Alternatively, an equivalent configuration, based on a beam splitter, was built.

4.2.3. Experimental setup C

So for this experimental setup, instead of an optical coupler, it was used a plate beam splitter. A beam splitter splits a beam of light in two: one is transmitted and the other is reflected. The pathway of the beams is similar to the one described for the optical coupler. The percentage of light transmitted and reflected is defined by the transmission/reflection ratio. For this project, the transmission/reflection ratio chosen was 50/50, reaching to the colour sensor a maximum of 25% of the incident light, excluding losses in the all optical system.

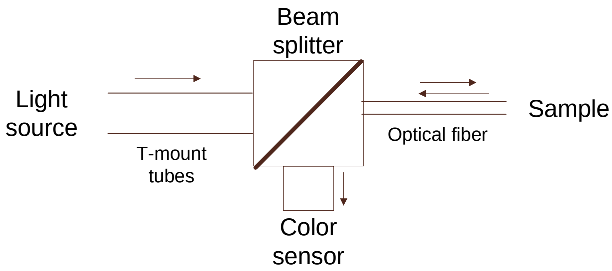

Figure 12 – Schematic diagram of experimental setup C.

Between the light source and the beam splitter was positioned a plan-convex lens (PCX) in order to focus the light in the optical fibre. The same procedure was taken into account for the colour sensor in order to have the colour signal focused.

The light path which is transmitted suffers a deviation from the axis due to the depth of the plate beam splitter. This means that some part of the light is not transmitted to the optical fibre, being reflected by the walls of the mount, which consequently 50% is reflected to the colour sensor. In addition, the terminals of the optical fibre had been polished with a micrometric sandpaper, behaving like a mirror, which means that a percentage of the light did not enter in the optical fibre being reflected back to the beam splitter and then to the colour sensor.

Unfortunately, this white light is not the only one which reaches the colour sensor. The component of the light which is reflected by the beam splitter is not absorbed by the walls of the mount, being equally reflected and then 50% transmitted to the colour sensor.

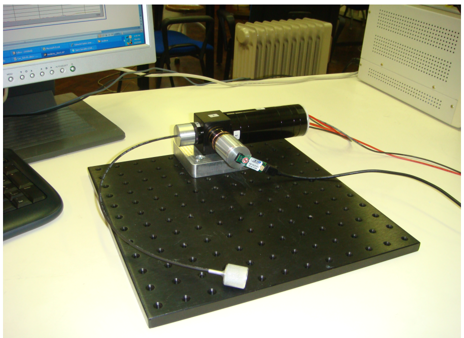

Figure 13 – General view of experimental setup C.

These two undesired components contaminate the colour signal, not being detected by the colour sensor. This happens because the colour signal is not 25% of the incident light, as mentioned before, being almost unnoticeable.

The idea of using only one optical fibre in touch with the sample turned out to be not very efficient. Therefore, another type of configuration was considered.

4.2.4. Experimental setup D

This configuration combines some features of the other experimental setups. It has no optical system complicated, having two optical fibres like Experimental setup A: one to guide the light into the sample, and the other to transmit the colour signal to the colour sensor. But, as with Experimental setups B and C, it has a measuring head in order to confer flexibility.

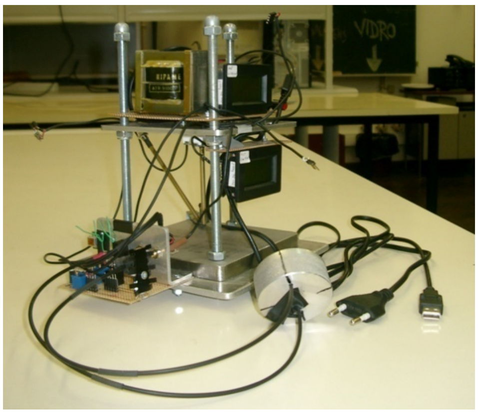

Figure 14 – General view of experimental setup D.

With this experimental setup it was tested three different measuring heads, differing only in the illuminant and colour sensor optical fibres angles.

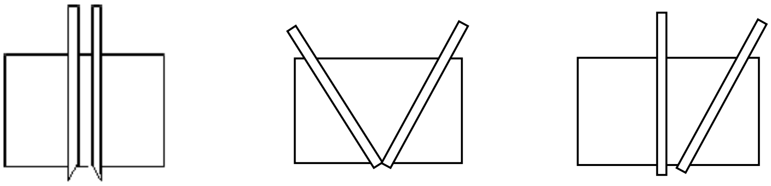

Figure 15 – The different measuring heads used in Experimental setup D. On the left, a measuring head with a configuration of 0°/0°; in the middle, a configuration of 45°/45°; on the right, a configuration of 45°/0°.

The measuring head on the left had a configuration of 0°/0°. The edges of the two optical fibres were polished with a sandpaper to form an angle in order to acquire the colour signal. It was needed a great light power in order to obtain more conclusive data.

The second measuring head tested was 45°/45°. As with Experimental setup A, it was only required a white LED in order to acquire consistent data. Also, with this geometry, there was no longer a strong dependence on the cut angle of the fibre.

The last measuring head used had a configuration of 45°/0°. It was used to obtain the final data, being the one which better results had produced.

In this experimental setup were tested different light sources. The influence of these light sources will be explained in more detail in the next chapter. Here, it will only be focused the changes made in the circuit in order to experiment them.

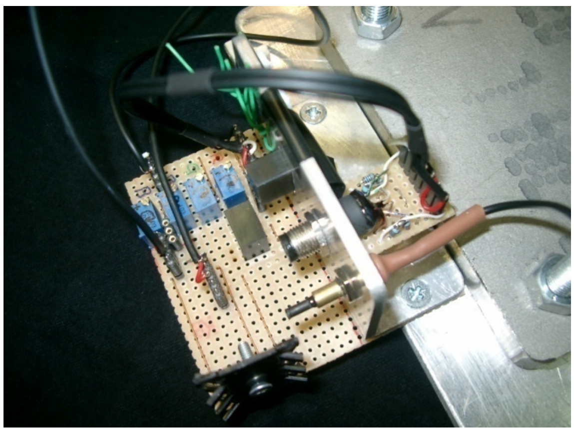

Figure 16 – The different light sources used in experimental setup D.

The first light source tested was the cool white LED. The circuit was the same used in Experimental setup A, but as mentioned before instead of the rigid configuration, this had a measuring head.

For the RGB LED it was made some changes in the last circuit to have the LED and, once again, to have the chance of regulating the current in the LEDs, and consequently their luminous intensity.

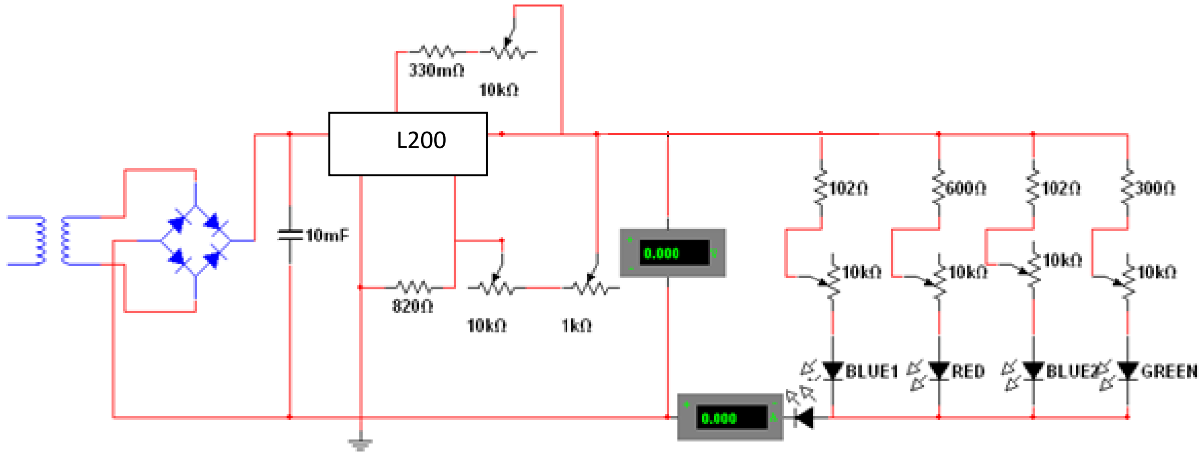

Figure 17 - Schematic diagram of the circuit used for the RGB LED in Experimental setup D.

Afterward, it was put the cool white LED and the RGB LED working at the same time in order to modulate the spectrum of the first LED.

For last, a high intensity LED was mounted. Its chromaticity coordinates was x=y=1/3 (note that are coordinates of CIE xyY and not of CIE XYZ), being the coordinates of the ideal white. Its circuit was the same for Experimental setup A and for the cool white LED in this same experimental setup.

5. COLOUR SENSOR

5.1. INTRODUCTION

For this project it was chosen MTCS-C2 Board Colorimeter, from Mazet. This board integrates all signal processing resources, including interfacing and measuring control (32).

Accomplishing the colour sensor, there is an application software, Jencolour. The colour sensor's software is primarily to visualize the different graphics of the data, dependent on the colour space used.

Besides Jencolour, it was also used Matlab® in order to obtain important values such as the light source coordinates, or to do signal processing.

5.2. MTCS-C2 BOARD COLORIMETER

MTCS-C2 Board Colorimeter is a module that contains MTCSiCS True Colour Sensor, MTI04CQ trans-impedance amplifier, C8051F321 micro controller with 10 bit A/D converter and USB interface, and a free memory space for compensation and correction data (Electrically Erasable Programmable Read-Only Memory - EEPROM) (32).

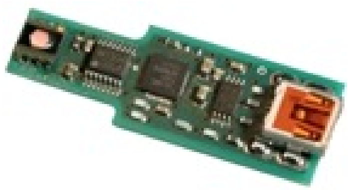

Figure 18 – MTCS-C2 Colorimeter Board (33).

The MTCSiCS series of True Colour Sensors consists of 19 groups with 3 photodiodes each, having an active area with 2,0mm of diameter. Sensors of this kind are based on the standard distribution functions, as defined under DIN 5033 Part 2 – Colour Measurement; CIE 1931 Standard Colorimetric Systems. The type and quality of the filter function determine the good results of colour measurement (34).

Each of the photodiodes is covered with dielectric spectral filters in order to correspond to its colour range, if possible for the primary standard CIE colour space. These dielectric filters guarantee a high transmission, high temperature stability, high signal frequency, reduced cross talk and a small size (34).

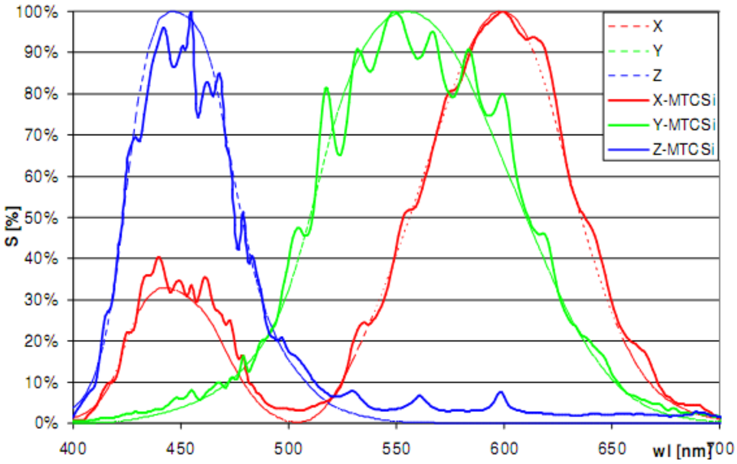

Figure 19 - Typical (relative) sensitivity (XYZ) of the colour sensor (MTCSiCS), and Standard Observer function (34).

Sensors with current output need a trans-impedance amplifier in order to transform and to amplify the smallest currents in those sensors. MTI04CQ provides a programmable bandwidth and high amplification (34).

The interface via USB to computer is conferred by the C8051F321 micro controller. Also, it controls and analyses the colour sensor signals, and activates the EEPROM for external memory space (32).

5.3. JENCOLOUR

This software accomplishes the colour sensor and displays the measured results graphically as XYZ-standard tristimulus values, in a standard chromaticity chart of CIE 1976 $L^*a^*b^*$ and as $L^*u^*v^*$ colour space.

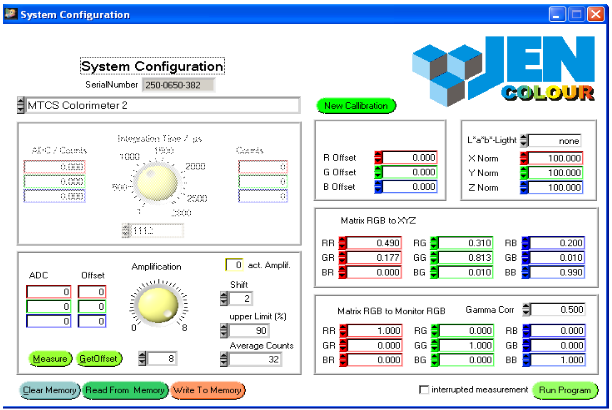

Figure 20– Jencolour system configuration.

This software availables all the values of the measurements in an Excel file and shows the data in three different colour spaces. Parameters such as integration time and mean values can be adjusted.

The light source and its coordinates (X_0, Y_0 and Z_0) can be introduced, having the chance of not using any of the standard illuminants that are already contemplated. It is also possible to define the gamma correction.

It is doable to proceed to a calibration of the sensor, where is calculated the RGB to XYZ matrix conversion and the RGB offsets.

5.3.1. Illuminant

In order to obtain the CIE LAB values it is necessary to have the chromaticity coordinates of the illuminant defined which is being used to carry out the colour measurements.

Jencolour, the application software of the colour sensor, has predefined the coordinates for some standard illuminants (A, C, D55, and D65), allowing the introduction of other chromaticity coordinates.

In this project, a standard light source for illumination was not used, but all measurements were taken under the same constant lighting conditions. Rather it was used, in different stages of the project, or LEDs or light power sources.

In order to obtain the illuminant chromaticity coordinates, it was necessary to get its spectrum. For the different light sources used it was always essential to compute their coordinates to proceed to a proper calibration.

Those spectrums were taken at the Departamento de Química of Faculdade de Ciências e Tecnologias da Universidade de Coimbra. To carry out the spectral measurements it was used USB4000 Miniature Fibre Optic Spectrometer from Ocean Optics. This device has a linear CCD array for detector, and its range of sensitivity covers the visible light. Its optical resolution is ~1,5nm full width at half maximum (FWHM) and has a 300:1 of signal-to-noise ratio (SNR) (35).

Figure 21 – USB4000 Miniature Fibre Optic Spectrometer (35).

The illuminant chromaticity coordinates were calculated from the spectrum of the light source by the equations 2.1. $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are referred to the observer, and $R_e(\lambda)$ is the intensity of the spectrum of the light source.

The observer considered for the computations was the 2° Standard Observer defined in 1931 by the CIE. Despite the 10° Standard Observer is considered to fit better the human eye response and to have better repeatability, in order to compare the results given by the colour sensor with the values tabled of the Colour Checker it was crucial to use in computations the 2° Standard Observer. The values of the 2° Observer are standard and are discriminated with an interval of 5nm.

Far off from what was first thought, to have the system calibrated it was necessary to take many spectrums. All the spectrums taken were discriminated with an interval of ~0,2nm.

Consequently, as the discrimination intervals of the observer and the spectrum files were different, there was the need to use Matlab® in order to process these values and to get the chromaticity coordinates of the illuminant.

All the chromaticity coordinates computed for each light source experimented in the project are shown in Appendix A.

The first light source used in the project, the 3LED module with a geometry of 0°/0°, was chosen because we intended that was needed a great power of light in order to proportionate an environment without contaminations. Due to the configuration, the results had a large standard deviation (SD), and for large currents there was a saturation of the colour sensor. Consequently, the spectrum of this light source was not taken.

For the rest of the light sources it was taken spectrums at different intensities of current, since this factor alters the spectrum's shape, and consequently the illuminant chromaticity coordinates.

With the white LED (Experimental setup A with geometry of 45°/0°) and with the configuration given it was reached good results, being achieved a good repeatability. This concept of illumination was implemented in Experimental setup D because it turned out to be the best option.

For Experimental setup C was chosen a light power source because it only would reach to the sample ~50% of the incident light and to the colour sensor a maximum of 25%, and as explained before it was not even near to this number the real percentage that reached the colour sensor.

For the last experimental setup, when accuracy was searched, we used different light sources in order to reach better results than with the other experimental setups. In different periods of the project, it was tested a cool white LED, a RGB LED and a high intensity LED.

The first light source tested was the cool white LED. Its spectrum revealed that it had predominance in the blue region.

In order to produce a flat spectrum, it was introduced a RGB LED. That “flat” spectrum was never really achieved successfully. As the RGB LED was not very powerful, it was experimented to have both of the LEDs turned on, and it was intended to modulate the spectrum of the cool white LED with the RGB LED.

The last LED tested was a high intensity that emits white light with a high colour-rendering index. Its emission spectrum is tuned for ideal white, without the impression of being blue shaded or cold. This is proportioned by the presence of a compound of terbium aluminum garnet (TAG) phosphor that converts the blue emission of the indium gallium nitride (InGaN) chip partially to amber, which mixed with the remaining blue produce white (36).

In the LED’s data sheet is presented the spectrum and the chromaticity coordinates (x,y) for a current of 20mA. The LED typical coordinates are x=0,33 and y=0,33, and the typical temperature is 5500k. The spectrum given by the data sheet and by the spectrometer is shown in figure 22. The curve found by the spectrometer was obtained with a current of 16mA.

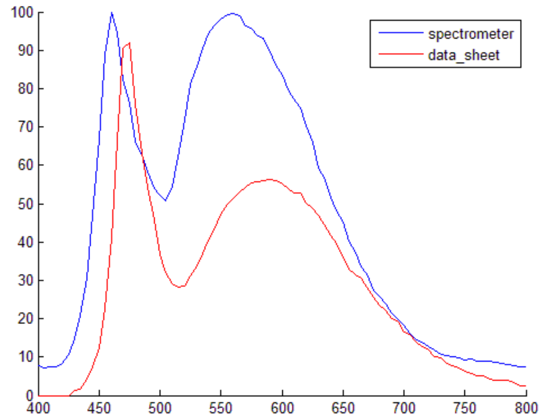

Figure 22- The high intensity LED spectrums: one given by its data sheet, and the other given by the spectrometer.

By inspection of the last figure, it can be concluded that not even the peaks of both curves match, which means that the peak is not registered at the same wavelengths (with the spectrometer the first peak occurs at a wavelength of 460nm, and with the data sheet the same peak occurs at 475nm), but also the relation between the first peak and the second is not the same in the two curves. The peak shift can be due to a bad calibration of the spectrometer, and the relation between them is probably due to an attenuation of the blue region of the optical fibre or to a bad optical coupling.

In order to try to achieve some conclusion, by signal processing, it was shifted first the curve given by the spectrometer to match the wavelength where the first peak of the data sheet spectrum occurs, and then the opposite, it was shifted the spectrum given by the data sheet to match the wavelength where the first peak of the spectrometer's curve occurs.

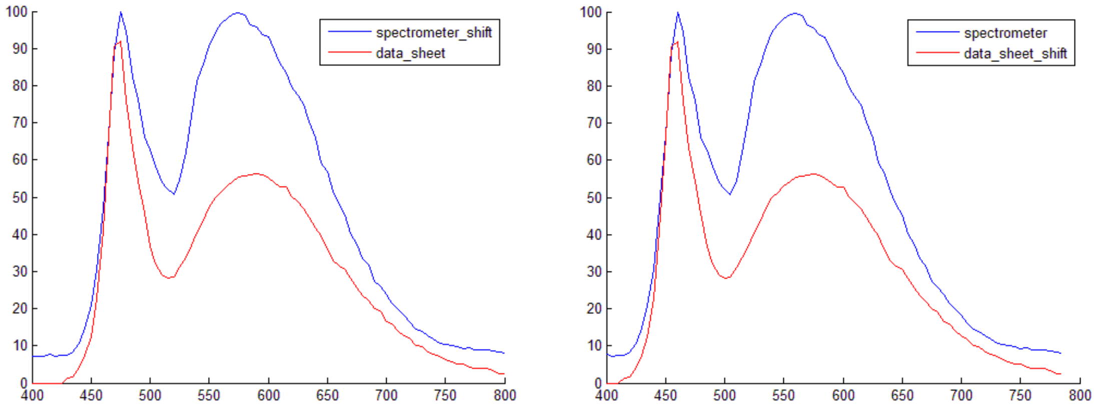

Figure 23 – The spectrums shifts in order to match the wavelengths where the first peak occurs.

For the spectrometer and data sheet shift graph the values range from 400nm to 785nm, because the values available on the data sheet ranged from 400nm to 800nm. The last 15nm could be rejected because the 2° Standard Observer for these wavelengths $\bar{x}(\lambda)$ and $\bar{y}(\lambda)$ are ≤ 0.000029353260, and $\bar{z}(\lambda)$ is zero, turning these values insignificant.

It was computed the chromaticity coordinates for the four cases: for the spectrum given by the spectrometer and for its spectrum wavelength shifted, and the same for the spectrum from the data sheet. All these chromaticity coordinates were introduced in the application software in order to try to evaluate the best results.

	Spectrometer	Spectrometer shift	Data sheet	Data sheet shift
X_0	90,628	93,932	98,436	98,957
Y_0	100	100	100	100
Z_0	66,753	47,468	64,967	93,153

Table 1 – The chromaticity coordinates given by the spectrometer and data sheet, and their shifts.

5.3.2. Calibration

Jencolour also allows the procedure of the colour sensor's calibration, which is crucial when accuracy and repeatability is wanted. Consequently, it is necessary to minimize all possible errors during the colour comparison.

The calibration is carried out on a known target set which consists of 24 target XYZ and RGB values for the monitor display. In the case of using other targets it is possible to create a file with the XYZ values correspondents.

Once the comparison between the existent file and the values attributed by the colour sensor is finished, the offset values and the conversion matrix are calculated. The matrix converts the values of RGB given by the sensor to the coordinates XYZ. These last values are then converted to the colour space desired.

The comparison can be done with a calibrated monitor, where the sensor is positioned in the middle of the coloured square, or with a reflecting target set.

In this project, the calibration was done with a Colour Checker chart, from Gretag Macbeth, which is a test pattern scientifically designed to help determine the true colour balance of any colour system.

Figure 24– Colour Checker chart (37).

A Colour Checker provides the needed standard with which to compare, measure and analyze differences in colour reproduction in various processes. The 24 squares are not only the same colour as their counterparts, but also reflect light the same way in all parts of the visible spectrum. Therefore, the squares will match the colours of natural objects under any illumination and with any colour reproduction process (38).

Since it was obtained different chromaticity coordinates, many calibration procedures were done.

As for the illuminant chromaticity coordinates, for every light source it will be referred in Appendix A its conversion matrix and RGB offsets.

For the first arrangement of Experimental setup A, since it was not obtained its chromaticity coordinates, it was not done any calibration procedure.

For the geometry 45°/0° of Experimental setup A, the calibrations revealed that despite a great repeatability of the results, the accuracy was not reached. This happened because of the difficulty to proceed to the calibration due to the rigid configuration.

With Experimental setup C, as the colour signal did not actually reach the sensor it was not done any calibration procedure. As mentioned in Chapter 4, the colour signal never achieved the colour sensor, being contaminated by a percentage of the illuminant. In order to try to discount this percentage it was first tried in Experimental setup A with the white LED plus a second white LED, simulating the illuminant and the light reflected in the walls of the optical system, respectively. By knowing the chromaticity coordinates of the white LED it could be inferred the influence of the second LED in the signal acquisition. This method was not conclusive, being not possible to calibrate the sensor with this configuration.

In the last experimental setup, with the cool white LED was achieved a great repeatability and a medium accuracy, due probably to the blue predominance in the spectrum. Consequently, it was tried in Matlab® to obtain “virtual” illuminant chromaticity coordinates with a certain compensation doing signal processing.

First, it was removed the peak in the blue region to help clarifying the influence of that predominance in the results.

Then, in order to diagnose the problem and to understand in what components the spectrum was deficient, the spectrum of the “real” illuminant was multiplied by two known symmetrical functions.

Afterward, by inspection of the 2° Standard Observer the spectrum of our illuminant was multiplied by three proper Gaussians, coinciding each Gaussian peak with $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ peaks. With this procedure, when with one square of the colour checker was finally obtained its true coordinates, for the others do not. This is probably due to the system being highly non-linear, each of the variables (L*, a*, and b*) depend on one or two values (X, Y, and Z) _ equations 2.4, 2.5, and 2.6, and these last also depend on other three variables (R, G, and B) _ matrix 2.2.

As mentioned before, the idea of using a RGB LED was to get a “flat” spectrum for all the wavelengths. With such spectrum, the different calibrations did not produce the expected results. The repeatability was achieved but the accuracy got worse. Depending on the spectrum, all the squares of the colour checker presented shades of blue, or shades of pink, etc.

Consequently, and because the RGB LED did not have the power needed, the next experiments were carried out with the two LEDs turned on. The results were the same as for the RGB LED alone.

Finally, with the high intensity LED the results were improved. It was found a good repeatability of the results, and accuracy got better. When chromaticity coordinates were introduced in the colour sensor’s software, it was achieved the following RGB offsets and conversion matrices.

	Spectrometer	**Spectrometer shift**	**Data sheet**	**Data sheet shift**
$\mathbf{R_{offset}}$	-16,954	-8,706	-9,348	-1,598
$\mathbf{G_{offset}}$	-16,420	-8,242	-9,849	-2,098
$\mathbf{B_{offset}}$	-2,997	-2,712	-2,890	-3,529

Table 2 – The RGB offsets obtained for each calibration.

Matrix 5.1 was found for a calibration of the chromaticity coordinates given by the spectrometer; matrix 5.2 corresponds to the spectrometer shift chromaticity coordinates; chromaticity coordinates given by the data sheet match matrix 5.3; and matrix 5.4 was achieved with the chromaticity coordinates given by the data sheet shift.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}728 & -0{,}426 & 0{,}312 \\ 0{,}149 & 0{,}280 & 0{,}039 \\ -0{,}003 & -0{,}026 & 1{,}99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad 5.1 \qquad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}798 & -0{,}440 & 0{,}370 \\ 0{,}108 & 0{,}404 & 0{,}045 \\ -0{,}072 & 0{,}052 & 2{,}207 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad 5.2$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}783 & -0{,}432 & 0{,}290 \\ 0{,}083 & 0{,}423 & -0{,}050 \\ -0{,}084 & 0{,}075 & 2{,}030 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad 5.3 \qquad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}740 & -0{,}422 & 0{,}316 \\ 0{,}161 & 0{,}290 & 0{,}072 \\ -0{,}194 & 0{,}200 & 1{,}605 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad 5.4$$

6. RESULTS

The colour signals were acquired with the same environmental conditions and under the same illumination with the same light source current (16mA). For the results presented in this chapter was chosen 6 of the 24 squares of the Colour Checker: numbers 6 (bluish green), 11 (yellow green), 15 (red), 16 (yellow), 19 (white), and 24 (black). Number 6 is intended to evaluate the performance of the blue and green filters, numbers 11 and 16 the red and green filters together, number 16 is intended to estimate the red filter performance alone, and numbers 19 and 24 are planned to evaluate the performance of all the colour sensor filters.

Each of the 6 patches was acquired 4 times, and for each time it was obtained about 30 signals, 1 per second. Assuming that the dispersion existent in the results is due to the noise which follows a Poisson distribution, and for large numbers this distribution approaches a Normal distribution, it was considered for calculations the mean result of all the 30 signals for each sample.

The values of reference used to compute the results are those presented in the Colour Checker chart, which contemplate the 2° Standard Observer and the D50 illuminant.

The results discussed were taken with the high intensity LED for the chromaticity coordinates given by the spectrometer, spectrometer wavelength shift, data sheet, and data sheet wavelength shift spectrums used in Experimental setup D. As mentioned before, for the last signals acquired it was used the 45°/0° measuring head and it was considered the 2° Standard Observer.

In this chapter will be discussed parameters such as repeatability, goodness-of-fit coefficient (GFC), root mean square error (RMSE), and the colour differences ΔE^*_{ab} and ΔE^*_{00}. The first is intended to evaluate the disparity of the results obtained, whether they are or not consistent; and the rest are intended to estimate the accuracy of the system. The Excel files will be available in Appendix C.

6.1. REPEATABILITY

Repeatability is the approximation in successive results, obtained under the same measurement conditions. The conditions for repeatability are the same measurement procedure, an only observer, the same measuring instrument, used under the same conditions, the same location, and repetition over a short period of time (39).

In the next table is shown the repeatability achieved with the different chromaticity coordinates.

REPEATABILITY				
Coordinates	**Spectrometer**	**Spectrometer shift**	**Data sheet**	**Data sheet shift**
L*	0,803	0,238	0,194	0,436
a*	1,094	3,074	0,663	4,415
b*	2,364	4,950	3,155	1,883

Table 3 – The repeatability of results for different chromaticity coordinates of the light source.

The coefficients presented in the table represent the value below which for two repeated measurements is expected, with a probability of 95%, to lay the absolute differences.

Considering the results, it can be concluded that the chromaticity coordinates obtained with the data sheet spectrum give more repeatable measurements than the others; in opposite, the measurements less repeatable are given by the chromaticity coordinates obtained with the spectrometer wavelength shift spectrum.

For every chromaticity coordinate, the L* coordinate is the most repeatable. This can be explained by the fact that this coordinate only depends on one variable, Y, and the other two, a* and b* depend on two variables, X and Y or Y and Z, respectively. The b* coordinate is the least repeatable probably due to a lower sensitivity of the colour sensor to the blue range (remember that b* coordinate is the yellow/blue axis).

6.2. ACCURACY

The accuracy of the system will be evaluated first by means of the coordinates (L*, a* and b*), then in terms of the patches. For the first it will be considered the GFC which measures how well a set of results fits the values expected, and the RMSE which is a statistical measure of the differences between the signal obtained and the theoretical. The accuracy of the patches will be evaluated with the colour differences ΔE^*_{ab} and ΔE^*_{00}.

The GFC is calculated with the coefficient of determination which is the square of the coefficient of correlation, corresponding a GFC ≥ 99,5% to an acceptable recovery. This is given by:

$$r^2 = \frac{\left(\sum_{i=6,11,15,16,19,24} f(x_i) * y_i\right)^2}{\left(\sum_{i=6,11,15,16,19,24} f(x_i)^2\right) * \left(\sum_{i=6,11,15,16,19,24} y_i{}^2\right)} \quad 6.1$$

The RMSE was computed from the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=6,11,15,16,19,24}(f(x_i) - y_i)^2}{6}} \quad 6.2$$

In both equations $f(x_i)$ is referred to the patch signal obtained and y_i is referred to the theoretical value which is taken from the Colour Checker chart. The values found are presented in the next two tables.

GFC (%)				
Coordinates	**Spectrometer**	**Spectrometer shift**	**Data sheet**	**Data sheet shift**
L*	99,687	99,564	99,715	98,352
a*	85,509	92,468	72,375	84,843
b*	51,845	14,164	76,564	73,060

Table 4 – The goodness-of-fit coefficient of results for different chromaticity coordinates of the light source.

RMSE				
Coordinates	**Spectrometer**	**Spectrometer shift**	**Data sheet**	**Data sheet shift**
L*	5,638	8,205	5,560	9,239
a*	10,481	7,917	15,972	10,733
b*	32,910	47,321	21,758	21,689

Table 5 – The root mean square error of results for different chromaticity coordinates of the light source.

By inspection of the two tables, the most accurate results are found for the L* coordinate, as what happened for repeatability. For all the chromaticity coordinates studied, it was obtained a GFC ≥ 99,564% which means that the results are acceptable.

The a* coordinate had found its best result for the chromaticity coordinates given by the spectrometer wavelength shift, being an almost acceptable result. Comparing the matrix conversion coefficients for the X computation, which among the Y coordinate are the coordinates needed to calculate a* (remember equations 2.4, 2.5, and 2.6), of all the 4 matrices it is noticeable that there is not a great difference, being the results only explained by the illuminant chromaticity coordinates which in case for the a* calculation seems that the spectrometer wavelength shift spectrum conduct to a better computed X_0 (=93,932).

The worst accuracy found was for the b* coordinate, due probably, as mentioned before, to a lower sensitivity of the colour sensor to the blue range. The best results were given by the chromaticity coordinates of the data sheet and data sheet wavelength shift spectrums, being impossible to consider those results accurate. Although, the difference between them can be explained by the matrix conversion coefficients:

$$Y_{data\ sheet} = 0{,}083 * R + 0{,}423 * G - 0{,}050 * B \quad 6.3$$

$$Y_{data\ sheet\ shift} = 0{,}161 * R + 0{,}290 * G + 0{,}072 * B \quad 6.4$$

Note that for the Y computation the B dependence is symmetrical, which will influence the b* calculation, giving better results to the signals acquired with the chromaticity coordinates of the data sheet wavelength shift introduced. The worst accuracy was found for the chromaticity coordinates given by the spectrometer shift and is due to a smaller Z_0 = 47,468, since the matrix conversion coefficients of the data sheet shift and the spectrometer shift are very similar.

In order to obtain more exact results it could be used the data sheet wavelength shift spectrum to obtain the illuminant chromaticity coordinates, although the results can be considered accurate only for the L* coordinate. Despite the chromaticity coordinates given by the spectrometer wavelength shift spectrum produce good signals for L* and a* coordinates, the b* coordinate presents the worst result.

These last two tables are intended to evaluate the accuracy obtained for each patch. It was computed the colour differences ΔE^*_{ab} and ΔE^*_{00} for the signals acquired. The results discussed in this sub-chapter will be referent to ΔE^*_{00}, since it is the colour difference that nowadays is accepted to be the most accurate.

ΔE^*_{ab}				
Patch	**Spectrometer**	**Spectrometer shift**	**Data sheet**	**Data sheet shift**
6	35,252	62,420	34,385	17,735
11	15,892	43,674	19,462	25,227
15	43,033	41,571	20,674	34,458
16	24,562	35,316	19,296	13,612
19	47,355	75,034	41,872	10,890
24	33,993	7,231	25,451	39,976

Table 6 – The colour difference ΔE^*_{ab} for each patch.

ΔE*$_{00}$				
Patch	**Spectrometer**	**Spectrometer shift**	**Data sheet**	**Data sheet shift**
6	42,547	12,213	61,176	47,231
11	55,181	33,173	20,600	40,947
15	37,341	55,525	25,468	10,307
16	39,479	53,200	66,264	62,576
19	23,380	28,832	21,312	10,024
24	21,369	7,938	18,353	22,768

Table 7 - The colour difference ΔE*$_{00}$ for each patch.

The patch for what is found a less difference in the results is number 24, being impossible to consider it an accurate result since it causes a noticeable colorimetric difference between the recovered and original signals. In the opposite, patch number 16 was found to produce the largest difference in the results.

These results inform us that a signal with larger values, in terms of L*a*b* coordinates, will produce larger differences in the signal acquisition, being less accurate.

The chromaticity coordinates, given by the spectrometer wavelength shift spectrum, are those which produce the most accurate results, followed by the chromaticity coordinates given by the used LED data sheet wavelength shift spectrum. On the contrary, the signals acquired with the chromaticity coordinates given by the spectrometer curve are the most distant from the values tabled of the Colour Checker.

7. CONCLUSIONS AND FUTURE WORK

7.1. CONCLUSIONS

Four experimental setups were thought, being tested three of them that are able to measure colour repeatedly. Different light sources were used in order to obtain the best chromaticity coordinates, and many calibrations procedure were done to get better results.

With experimental setup A we proved that it is possible to use colour sensors to measure colour with good repeatable values. For this it is crucial to use a geometry of 45°.

The general concept of experimental setup B was the ideal since it would provide an optimal flexibility. As an optical coupler with such characteristics is unavailable, the beam splitter turned out to be the best option.

With Experimental setup C a fixed, undesired light component is present in all samplings, which would have to be numerically removed, not being successfully achieved.

Consequently, another experimental setup was planned, Experimental setup D, which used two optical fibres, like Experimental setup A. This concept proved to be the best for the colour signal acquisition. The results were taken with this experimental setup.

The most repeatable results were obtained for the chromaticity coordinates given by the data sheet spectrum, being the L* coordinate the one for it is found more repeatable results (=0,194).

Accuracy was not actually reached with the different systems proposed. Even though, the data sheet shift chromaticity coordinates revealed to produce closer signals to the original.

As what was pretended, this study revealed that colour sensors produce repeatable results, and accuracy was not achieved probably due to a bad optical coupling: first, between the LED and the optical fibre; and between the optical fibre and the sample (it is possible that in the measuring head there are reflections, contaminating the colour signal). Another possible explication is the non-linearity between the Standard Observer and the typical sensitivity of the colour sensor (remember figure 19 on Chapter 5).

7.2. FUTURE WORK

The original idea of this project was to apply colour sensors in biomedical devices or to replace other colour measurement technologies by this one. Since, it was not predicted that the colour sensor calibration would take so long, this concept was never applied in any device.

Consequently, for future work, colour sensors should be implemented in blood glucose colorimeters, in devices for quantification of the colour skin, or clinical analysis of urine, in order to evaluate if they can replace the existent techniques.

In the consequence of this work, it is also necessary to change the interface of the light-sample, to reduce possible interferences.

It is important to keep the investigation in order to achieve accuracy of the results, so that colour sensors could successfully replace spectrometers in different applications.

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APPENDICES

APPENDIX A

For the 3LED module it was not taken its spectrum, consequently it was not done any calibration procedure.

The white LED and cool white LED chromaticity coordinates are for a current of 15mA.

The light power source spectrum was taken in the place of the colour sensor, after the light optical pathway, for a current of 700mA. It was not done any calibration procedure.

The RGB LED chromaticity coordinates are for a current of 62mA, having the 3 peaks the same intensity counting.

The RGB LED plus cool white LED chromaticity coordinates are for a current of 40mA and 9mA, respectively.

CHROMATICITY COORDINATES

	3LED module	White LED	Light power source	Cool white LED	RGB LED	RGB LED + Cool white LED
X_0	-	92,013	98,7631	85,423	96,586	86,198
Y_0	-	100	100	100	100	100
Z_0	-	244,563	67,380	125,593	98,479	107,064

RGB OFFSETS

	3LED module	White LED	Light power source	Cool white LED	RGB LED	RGB LED + Cool white LED
R_{offset}	-	-282,515	-	13,852	20,077	-10,997
G_{offset}	-	-862,527	-	20,314	13,810	-14,818
B_{offset}	-	51081,827	-	-22,816	19,541	-10,561

MATRICES CONVERSION

$$3LED\ module:\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$White\ LED:\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}503 & -0{,}381 & -0{,}004 \\ 0{,}328 & -0{,}203 & -0{,}002 \\ 0{,}236 & -0{,}129 & -0{,}001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$Light\ power\ source:\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$Cool\ white\ LED:\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}031 & -0{,}017 & 0{,}000 \\ 0{,}020 & -0{,}007 & 0{,}000 \\ 0{,}006 & -0{,}006 & 0{,}015 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$RGB\ LED:\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1{,}648 & 1{,}349 & -1{,}775 \\ 0{,}675 & 2{,}548 & -1{,}913 \\ -7{,}778 & 8{,}857 & 2{,}823 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$RGB\ LED + Cool\ white\ LED:\quad \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2{,}322 & -1{,}628 & 0{,}397 \\ 0{,}643 & 0{,}484 & -0{,}415 \\ 0{,}259 & -0{,}251 & 2{,}543 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

APPENDIX B

In this appendix will be defined every variables of equation 2.19 presented in Chapter 2 (40).

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{K_L * S_L}\right)^2 + \left(\frac{\Delta C'}{K_C * S_C}\right)^2 + \left(\frac{\Delta H'}{K_H * S_H}\right)^2 + R_T * \left(\frac{\Delta C'}{K_C * S_C}\right) * \left(\frac{\Delta H'}{K_H * S_H}\right)}$$

$$\overline{L'} = \frac{L_1 + L_2}{2}$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\bar{C} = (C_1 + C_2)/2$$

$$G = \left(1 - \sqrt{\frac{\overline{C^7}}{\overline{\overline{C^7} + 25^7}}}\right)/2$$

$$a_1' = a_1 * (1 + G)$$

$$a_2' = a_2 * (1 + G)$$

$$C_1' = \sqrt{a'^2_1 + b_1^2}$$

$$C_2' = \sqrt{a'^2_2 + b_2^2}$$

$$\overline{C'} = (C'_1 + C'_2)/2$$

$$h'_1 = \begin{cases} tan^{-1}(b_1/a'_1), & tan^{-1}(b_1/a'_1) \geq 0 \\ tan^{-1}(b_1/a'_1) + 360°, & tan^{-1}(b_1/a'_1) < 0 \end{cases}$$

$$h'_2 = \begin{cases} tan^{-1}(b_2/a'_2), & tan^{-1}(b_2/a'_2) \geq 0 \\ tan^{-1}(b_2/a'_2) + 360°, & tan^{-1}(b_2/a'_2) < 0 \end{cases}$$

$$\bar{H}' = \begin{cases} \dfrac{(h'_1 + h'_2 + 360°)}{2}, & |h'_1 - h'_2| > 180° \\ \dfrac{(h'_1 + h'_2)}{2}, & |h'_1 - h'_2| \leq 180° \end{cases}$$

$$T = 1 - 0{,}17\cos(\bar{H}' - 30°) + 0{,}24\cos(2\bar{H}') + 0{,}32\cos(3\bar{H}' + 6°) - 0{,}20\cos(4\bar{H}' - 63°)$$

$$\Delta h' = \begin{cases} h'_2 - h'_1, & |h'_2 - h'_1| \leq 180° \\ h'_2 - h'_1 + 360°, |h'_2 - h'_1| > 180° & ; h'_2 \leq h'_1 \\ h'_2 - h'_1 - 360°, |h'_2 - h'_1| > 180°; h'_2 \leq h'_1 \end{cases}$$

$$\Delta h' = L_2 - L_1$$

$$\Delta C' = C'_2 - C'_1$$

$$\Delta H' = 2 * \sqrt{C'_1 * C'_2} * \sin\left(\frac{\Delta h'}{2}\right)$$

$$S_L = 1 + \frac{0{,}015 * (\bar{L}' - 50)^2}{\sqrt{20 + (\bar{L}' - 50)^2}}$$

$$S_C = 1 + 0{,}045 * \bar{C}'$$

$$S_H = 1 + 0{,}015 * \bar{C}' * T$$

$$\Delta\theta = 30 * exp\left\{-\left(\frac{\bar{H}' - 275°}{25}\right)^2\right\}$$

$$R_C = \sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}$$

$$R_T = -2 * R_C * \sin(2 * \Delta\theta)$$

$$K_L = 1$$

$$K_C = 1$$

$$K_H = 1$$

APPENDIX C

In this appendix will be presented the Excel tables that conducted to the results discussed in Chapter 6.

L*							
	Patch	**Measurements**				**Mean**	**SD**
		1	**2**	**3**	**4**		
Spectrometer	**6**	67,691	68,113	67,842	67,000	67,661	0,474
	11	75,952	75,857	75,758	75,826	75,848	0,081
	15	42,089	41,988	42,221	41,467	41,941	0,330
	16	88,815	88,772	88,693	88,359	88,660	0,207
	19	105,839	105,785	105,687	106,456	105,942	0,348
	24	26,294	26,291	26,280	26,294	26,290	0,007
Spectrometer shift	**6**	72,972	72,994	73,055	72,946	72,992	0,047
	11	74,356	74,204	74,053	74,076	74,172	0,139
	15	43,177	43,200	43,241	43,231	43,212	0,029
	16	88,557	88,465	88,466	88,334	88,455	0,091
	19	115,290	115,251	115,101	115,280	115,231	0,088
	24	20,932	21,001	21,112	21,057	21,026	0,077
Data sheet	**6**	70,899	71,023	70,939	71,076	70,984	0,080
	11	73,162	73,088	72,925	23,058	73,058	0,099
	15	39,277	39,277	39,320	39,276	39,284	0,025
	16	89,359	89,497	89,500	89,577	89,483	0,090
	19	107,104	106,968	106,972	107,003	107,012	0,063
	24	23,203	23,199	23,180	23,167	23,187	0,017
Data sheet shift	**6**	69,000	69,182	69,058	69,042	69,070	0,078
	11	72,243	72,191	72,165	72,059	72,164	0,077
	15	39,124	38,872	38,946	39,207	39,037	0,155
	16	88,446	88,722	88,729	88,953	88,713	0,207
	19	104,241	104,211	104,126	104,085	104,166	0,073
	24	0,325	0,632	0,644	0,946	0,637	0,254

a*							
	Patch	**Measurements**				**Mean**	**SD**
		1	**2**	**3**	**4**		
Spectrometer	**6**	-29,012	-29,938	-29,722	-28,051	-29,181	0,851
	11	-30,398	-30,086	-30,599	-30,328	-30,353	0,212
	15	41,762	41,730	41,239	41,232	41,490	0,295
	16	9,510	9,361	9,320	9,095	9,321	0,172
	19	13,781	13,817	13,602	14,024	13,806	0,173
	24	14,963	15,084	14,734	14,963	14,936	0,146
Spectrometer shift	**6**	-33,267	-33,323	-33,110	-32,994	-33,173	0,150
	11	-29,841	-29,751	-29,580	-29,557	-29,682	0,137
	15	37,229	37,125	38,031	37,807	37,548	0,440
	16	2,321	2,354	2,611	2,224	2,378	0,165
	19	5,549	5,629	5,636	5,721	5,634	0,071
	24	-10,418	-8,032	-4,216	-6,013	-7,170	2,668
Data sheet	**6**	-45,998	-45,811	-46,434	-46,650	-46,223	0,386
	11	-39,450	-39,242	-39,654	-39,791	-39,534	0,240
	15	33,097	33,097	33,774	33,435	33,351	0,324
	16	-6,202	-6,116	-6,080	-4,227	-6,156	0,070
	19	-4,235	-4,468	-4,359	-4,088	-4,287	0,164
	24	-23,766	-28,931	-25,512	-26,743	-24,478	2,097
Data sheet shift	**6**	-39,684	-39,460	-39,418	-39,754	-39,554	0,194
	11	-35,079	-34,879	-35,192	-34,413	-34,891	0,344
	15	34,393	34,011	34,133	34,295	34,208	0,169
	16	-5,794	-5,811	-5,813	-5,897	-5,829	0,046
	19	-8,087	-8,114	-8,053	-8,168	-8,105	0,048
	24	-2,764	2,006	2,088	6,739	2,017	3,880

b*							
	Patch	**Measurements**				**Mean**	**SD**
		1	**2**	**3**	**4**		
Spectrometer	**6**	-35,504	-34,183	-34,385	-36,183	-35,064	0,945
	11	70,674	69,756	71,627	73,167	71,306	1,457
	15	-13,083	-12,402	-13,576	-13,610	-13,168	0,565
	16	56,064	56,490	57,009	57,854	56,854	0,770
	19	-42,790	-42,727	-42,647	-43,797	-42,990	0,541
	24	-30,706	-31,490	-30,731	-30,908	-30,908	0,388
Spectrometer shift	**6**	-60,433	-60,487	-60,912	-60,472	-60,576	0,225
	11	13,885	14,451	14,175	13,581	14,023	0,374
	15	-9,728	-9,346	-11,254	-10,604	-10,233	0,861
	16	44,321	45,326	44,882	46,224	45,188	0,804
	19	-71,265	-71,288	-70,948	-71,418	-71,230	0,199
	24	1,209	1,500	-5,780	-6,013	-2,271	4,189
Data sheet	**6**	-31,969	-32,587	-31,830	-32,016	-32,101	0,334
	11	44,873	44,752	47,555	46,577	45,939	1,362
	15	25,399	25,399	21,776	23,036	23,903	1,803
	16	82,304	82,031	80,869	81,082	81,571	0,703
	19	-39,347	-39,026	-38,922	-39,389	-39,171	0,232
	24	5,919	3,653	6,367	6,863	5,700	1,418
Data sheet shift	**6**	-16,463	-16,957	-16,700	-16,876	-16,749	0,219
	11	34,459	34,871	34,882	34,368	34,645	0,270
	15	-0,720	0,189	-0,202	-0,384	-0,279	0,379
	16	74,092	73,369	73,670	33,102	73,558	0,425
	19	-0,047	-0,033	-0,039	0,068	-0,013	0,054
	24	-34,010	-34,297	-36,151	-37,202	-35,416	1,525

SPECTROMETER

L*	Standard Deviation	Variance	MEAN	Color Checker		PRODUCT	MEAN^2	CC^2	DIFFERENCE	DIFFERENCE^2
6	0,474	0,225	67,661	70,719		4784,952	4578,075	5001,177	-3,058	9,348
11	0,081	0,007	75,848	72,532		5501,404	5752,912	5260,891	3,316	10,996
15	0,330	0,109	41,941	42,101		1765,771	1759,073	1772,494	-0,160	0,026
16	0,207	0,043	88,660	81,733		7246,427	7860,551	6680,283	6,927	47,980
19	0,348	0,121	105,942	96,539		10227,506	11223,644	9319,779	9,403	88,411
24	0,007	0,000	26,290	20,461		537,918	691,160	418,653	5,829	33,976
Mean of variance		0,084			SUM	30063,977	31865,415	28453,277	SUM	190,736
SW		0,290			SQUARE OF THE SUM	903842731,678				
					PRODUCT		906675452,645		RMSE	5,638
REPEATABILITY		0,803								
					DETERMINATION COEFFICIENT			0,997		

a*	Standard Deviation	Variance	MEAN	Color Checker		PRODUCT	MEAN^2	CC^2	DIFFERENCE	DIFFERENCE^2
6	0,851	0,724	-29,181	-33,397		974,544	851,506	1115,360	4,216	17,778
11	0,212	0,045	-30,353	-23,709		719,635	921,294	562,117	-6,644	44,140
15	0,295	0,087	41,490	53,378		2214,676	1721,455	2849,211	-11,888	141,314
16	0,172	0,030	9,321	4,039		37,649	86,889	16,314	5,282	27,904
19	0,173	0,030	13,806	-0,425		-5,868	190,605	0,181	14,231	202,521
24	0,146	0,021	14,936	-0,079		-1,180	223,080	0,006	15,015	225,446
Mean of variance		0,156			SUM	3939,457	3994,830	4543,188	SUM	659,104
SW		0,395			SQUARE OF THE SUM	15519317,987				
					PRODUCT		18149262,179		RMSE	10,481
REPEATABILITY		1,094								
					DETERMINATION COEFFICIENT			0,855		

b*	Standard deviation	Variance	MEAN	Color Checker		PRODUCT	MEAN^2	CC^2	DIFFERENCE	DIFFERENCE^2
6	0,945	0,894	-35,064	-0,199		6,978	1229,461	0,040	-34,865	1215,546
11	1,457	2,122	71,306	57,255		4082,628	5084,553	3278,135	14,051	197,432
15	0,565	0,319	-13,168	28,190		-371,200	173,391	794,676	-41,358	1710,468
16	0,770	0,593	56,854	79,819		4538,021	3232,366	6371,073	-22,965	527,396
19	0,541	0,293	-42,990	1,186		-50,986	1848,155	1,407	-44,176	1951,534
24	0,388	0,150	-30,908	-0,973		30,074	955,315	0,947	-29,935	896,115
Mean of variance		0,729			SUM	8235,514	12523,241	10446,277	SUM	6498,490
SW		0,854			SQUARE OF THE SUM	67823691,386				
					PRODUCT		130821246,264		RMSE	32,910
REPEATABILITY		2,364								
					DETERMINATION COEFFICIENT			0,518		

PATCH		L'bar	C1		C2	Cbar	G	a'1	a'2	C'1	C'2	C'bar	h'1
6		69,190		33,398	45,618	39,508	0,010	-33,726	-29,468	33,727	45,802	39,764	46,137
11		74,190		61,970	77,497	69,734	0,000	-23,714	-30,359	61,971	77,500	69,736	288,359
15		42,021		60,365	43,530	51,947	0,001	53,457	41,552	60,435	43,589	52,012	346,155
16		85,196		79,921	57,613	68,767	0,000	4,040	9,323	79,921	57,613	68,767	85,979
19		101,240		1,260	45,153	23,206	0,195	-0,508	16,495	1,290	46,046	23,668	89,369
24		23,375		0,976	34,328	17,652	0,358	-0,107	20,286	0,979	36,971	18,975	89,847

h'2		H'bar	T			Δh'	ΔL'	ΔC'	ΔH'	SL	SC	SH	Δθ
49,981	3,844	48,059		1,252	3,844	3,844	-3,058	12,075	73,812	1,280	2,789	1,747	4,895E-35
293,028	4,669	290,693		0,740	4,669	4,669	3,316	15,528	100,099	1,357	4,138	1,774	20,230
342,408	3,747	344,281		0,343	3,747	-3,747	-0,160	-16,846	-97,977	1,104	3,341	1,267	0,014
80,728	5,251	83,354		0,747	5,251	-5,251	6,927	-22,308	-66,959	1,524	4,095	1,770	9,029E-25
290,957	201,588	370,163		1,033	201,588	-158,412	9,403	44,756	9,524	1,766	2,065	1,367	1,529E-05
303,249	213,402	376,548		1,115	213,402	-146,598	5,829	35,992	10,390	1,394	1,854	1,317	2,050E-06

RC	RT	KL	KC		KH		ΔE*00		PATCH	ΔE*ab	ΔE*ab Mean	STANDARD DEVIATION
0,981	-1,92E-34	1		1	1		42,547		6	35,252		
1,000	-0,744	1		1	1		55,181		11	15,892		
0,997	-0,055	1		1	1		77,341		15	43,033	33,348	11,627
1,000	-3,610E-24	1		1	1		38,479		16	24,562		
0,637	-3,894E-05	1		1	1		23,380		19	47,355		
0,356	-2,918E-06	1		1	1		21,369		24	33,993		

SPECTROMETER SHIFT

L*	Standard Deviation	Variance
6	0,047	0,002
11	0,139	0,019
15	0,029	0,001
16	0,091	0,008
19	0,088	0,008
24	0,077	0,006
Mean of variance		0,007
SW		0,086
REPEATABILITY		0,238

	MEAN	Color Checker	PRODUCT	MEAN^2	CC^2
	72,992	70,719	5161,905	5327,799	5001,177
	74,172	72,532	5379,862	5501,523	5260,891
	43,212	42,101	1819,275	1867,290	1772,494
	88,455	81,733	7229,725	7824,358	6680,283
	115,231	96,539	11124,242	13278,080	9319,779
	21,026	20,461	430,208	442,083	418,653
SUM			31145,217	34241,132	28453,277
SQUARE OF THE SUM			9,700E+08		
PRODUCT				974272409,916	
DETERMINATION COEFFICIENT					0,996

	DIFFERENCE	DIFFERENCE^2
	2,273	5,166
	1,640	2,690
	1,111	1,235
	6,722	45,191
	18,692	349,374
	0,565	0,319
SUM		403,974
RMSE		8,205

a*	Standard Deviation	Variance
6	0,150	0,023
11	0,137	0,019
15	0,440	0,194
16	0,165	0,027
19	0,071	0,005
24	2,668	7,119
Mean of variance		1,231
SW		1,110
REPEATABILITY		3,073

	MEAN	Color Checker	PRODUCT	MEAN^2	CC^2
	-33,173	-33,397	1107,894	1100,478	1115,360
	-29,682	-23,709	703,741	881,048	562,117
	37,548	53,378	2004,221	1409,830	2849,211
	2,378	4,039	9,603	5,653	16,314
	5,634	-0,425	-2,394	31,739	0,181
	-7,170	-0,079	0,566	51,406	0,006
SUM			3823,631	3480,153	4543,188
SQUARE OF THE SUM			14620152,980		
PRODUCT				15810987,232	
DETERMINATION COEFFICIENT					0,925

	DIFFERENCE	DIFFERENCE^2
	0,224	0,050
	-5,973	35,682
	-15,830	250,598
	-1,662	2,761
	6,059	36,708
	-7,091	50,280
SUM		376,079
RMSE		7,917

b*	Standard deviation	Variance
6	0,225	0,051
11	0,374	0,140
15	0,861	0,741
16	0,804	0,646
19	0,199	0,040
24	4,189	17,546
Mean of variance		3,194
SW		1,787
REPEATABILITY		4,950

	MEAN	Color Checker	PRODUCT	MEAN^2	CC^2
	-60,576	-0,199	12,055	3669,485	0,040
	14,023	57,255	802,885	196,644	3278,135
	-10,233	28,190	-288,470	104,716	794,676
	45,188	79,819	3606,893	2041,991	6371,073
	-71,230	1,186	-84,478	5073,642	1,407
	-2,271	-0,973	2,210	5,158	0,947
SUM			4051,094	11091,636	10446,277
SQUARE OF THE SUM			16411364,782		
PRODUCT				115866300,286	
DETERMINATION COEFFICIENT					0,142

	DIFFERENCE	DIFFERENCE^2
	-60,377	3645,415
	-43,232	1869,008
	-38,423	1476,333
	-34,631	1199,278
	-72,416	5244,005
	-1,298	1,685
SUM		13435,724
RMSE		47,321

PATCH	L'bar	C1	C2	Cbar	G	a'1	a'2	C'1	C'2	C'bar	h'1
6	71,855	33,398	69,065	51,231	0,002	-33,452	-33,228	33,452	69,091	51,272	61,122
11	73,352	61,970	32,828	47,399	0,003	-23,776	-29,766	61,995	32,904	47,450	329,452
15	42,657	60,365	38,917	49,641	0,002	53,487	37,624	60,461	38,991	49,726	349,164
16	85,094	79,921	45,251	62,586	0,000	4,041	2,378	79,921	45,251	62,586	84,933
19	105,885	1,260	71,452	36,356	0,017	-0,432	5,731	1,262	71,460	36,361	89,698
24	20,743	0,976	7,521	4,249	0,499	-0,118	-10,747	0,980	10,985	5,983	87,059

h'2		H'bar	T		Δh'	ΔL'	ΔC'	ΔH'	SL	SC	SH	Δθ
61,285	0,163	61,204	0,552	0,163	0,163	2,273	35,639	7,810	1,321	3,307	1,424	5,192E-31
334,762	5,309	332,107	0,642	5,309	5,309	1,640	-29,092	42,263	1,344	3,135	1,457	0,163
344,777	4,387	346,970	0,575	4,387	-4,387	1,111	-21,470	-78,892	1,094	3,238	1,429	0,008
87,031	2,098	85,982	1,061	2,098	2,098	6,722	-34,670	104,263	1,522	3,816	1,996	4,47688E-24
274,557	184,859	362,127	1,264	184,859	-175,141	18,692	70,197	7,292	1,836	2,636	1,689	0,000
371,938	284,879	409,499	0,781	284,879	-75,121	0,565	10,005	0,906	1,434	1,269	1,070	8,071E-12

RC	RT	KL	KC	KH		ΔE*00
0,997	-2,070E-30	1	1	1		12,213
0,994	-0,635	1	1	1		33,173
0,996	-0,030	1	1	1		55,525
0,999	-1,7893E-23	1	1	1		53,200
0,966	-0,001	1	1	1		28,832
0,007	-2,164E-13	1	1	1		7,938

PATCH	ΔE*ab	ΔE*ab Mean	STANDARD DEVIATION
6	60,420	43,874	23,091
11	43,674		
15	41,571		
16	35,316		
19	75,034		
24	7,231		

DATA SHEET

L*	Standard Deviation	Variance
6	0,080	0,006
11	0,099	0,010
15	0,025	0,001
16	0,090	0,008
19	0,063	0,004
24	0,017	0,000
Mean of variance		0,005
SW		0,070
REPEATABILITY		0,194

MEAN	Color Checker		PRODUCT	MEAN^2	CC^2
70,984	70,719		5019,919	5038,732	5001,177
73,058	72,532		5299,050	5337,486	5260,891
39,284	42,101		1653,888	1543,219	1772,494
89,483	81,733		7313,685	8007,145	6680,283
107,012	96,539		10330,807	11451,515	9319,779
23,187	20,461		474,437	537,654	418,653
		SUM	30091,787	31915,750	28453,277
		SQUARE OF THE SUM	9,055E+08		
		PRODUCT		908107669,555	
		DETERMINATION COEFFICIENT			0,997

DIFFERENCE	DIFFERENCE^2
0,265	0,070
0,526	0,277
-2,817	7,936
7,750	60,057
10,473	109,678
2,726	7,433
SUM	185,452
RMSE	5,560

a*	Standard Deviation	Variance
6	0,386	0,149
11	0,240	0,058
15	0,324	0,105
16	0,070	0,005
19	0,164	0,027
24	2,097	4,398
Mean of variance		0,790
SW		0,889
REPEATABILITY		2,462

MEAN	Color Checker		PRODUCT	MEAN^2	CC^2
-46,223	-33,397		1543,718	2136,589	1115,360
-39,534	-23,709		937,316	1562,951	562,117
33,351	53,378		1780,199	1112,276	2849,211
-6,156	4,039		-24,866	37,902	16,314
-4,287	-0,425		1,822	18,380	0,181
-24,488	-0,079		1,935	599,652	0,006
		SUM	4240,123	5467,749	4543,188
		SQUARE OF THE SUM	17978646,550		
		PRODUCT		24841010,456	
		DETERMINATION COEFFICIENT			0,724

DIFFERENCE	DIFFERENCE^2
-12,826	164,513
-15,825	250,436
-20,027	401,089
-10,195	103,947
-3,862	14,916
-24,409	595,790
SUM	1530,690
RMSE	15,972

b*	Standard deviation	Variance
6	0,334	0,111
11	1,362	1,855
15	1,803	3,252
16	0,703	0,494
19	0,232	0,054
24	1,418	2,012
Mean of variance		1,296
SW		1,139
REPEATABILITY		3,154

MEAN	Color Checker		PRODUCT	MEAN^2	CC^2
-32,101	-0,199		6,388	1030,450	0,040
45,939	57,255		2630,260	2110,428	3278,135
23,903	28,190		673,811	571,330	794,676
81,571	79,819		6510,938	6653,873	6371,073
-39,171	1,186		-46,457	1534,352	1,407
5,700	-0,973		-5,547	32,495	0,947
		SUM	9769,394	11932,927	10446,277
		SQUARE OF THE SUM	95441066,225		
		PRODUCT		124654663,079	
		DETERMINATION COEFFICIENT			0,766

DIFFERENCE	DIFFERENCE^2
-31,902	1017,714
-11,316	128,043
-4,288	18,383
1,752	3,070
-40,357	1628,671
6,673	44,535
SUM	2840,416
RMSE	21,758

PATCH		L'bar	C1		C2	Cbar	G	a'1		a'2	C'1	C'2		C'bar	h'1	
6		70,852		33,398	56,276	44,837	0,004		-33,535	-46,414	33,536		56,434	44,985		43,770
11		72,795		61,970	60,608	61,289	0,000		-23,720	-39,553	61,974		60,621	61,297		297,277
15		40,692		60,365	41,032	50,698	0,002		53,472	33,410	60,448		41,080	50,764		384,097
16		85,608		79,921	81,803	80,862	0,000		4,039	-6,157	79,921		81,803	80,862		87,209
19		101,775		1,260	39,405	20,332	0,282		-0,545	-5,495	1,305		39,554	20,430		89,248
24		21,824		0,976	25,143	13,059	0,449		-0,114	-35,477	0,980		35,932	18,456		-88,895

h'2		H'bar	T			Δh'	ΔL'	ΔC'		ΔH'	SL	SC		SH	Δθ	
34,686	9,085	39,228		0,611	9,085	-9,085	0,265		22,898	85,750	1,306		3,024	1,413		7,084E-38
310,703	13,426	303,990		1,612	13,426	13,426	0,526		-1,354	51,059	1,336		3,758	2,482		7,819
395,599	11,502	389,848		1,381	11,502	11,502	-2,817		-19,368	-50,564	1,126		3,284	2,051		2,050E-08
-85,727	172,936	0,741		1,188	172,936	-172,936	7,750		1,882	161,266	1,530		4,639	2,441		1,623E-51
442,056	352,807	445,652		1,107	352,807	-7,193	10,473		38,249	6,311	1,774		1,919	1,339		1,742E-19
350,867	439,762	310,986		0,782	439,762	79,762	2,726		34,952	9,719	1,417		1,831	1,217		3,778

RC	RT	KL	KC		KH		ΔE*00			PATCH	ΔE*ab	ΔE*ab Mean		STANDARD DEVIATION		
0,992	-2,811E-37	1		1	1		61,176			6	34,385					
0,999	-0,140	1		1	1		20,600			11	19,462					
0,997	-8,170E-08	1		1	1		25,468			15	20,674	25,795		10,624		
1,000	-6,492E-51	1		1	1		66,264			16	12,926					
0,442	-3,082E-19	1		1	1		21,312			19	41,872					
0,327	-0,625	1		1	1		18,353			24	25,451					

DATA SHEET SHIFT

L*	Standard Deviation	Variance
6	0,078	0,006
11	0,077	0,006
15	0,155	0,024
16	0,207	0,043
19	0,073	0,005
24	0,254	0,064
Mean of variance		0,025
SW		0,157
REPEATABILITY		0,43611995

	MEAN	Color Checker	PRODUCT	MEAN^2	CC^2
	69,070	70,719	4884,586	4770,713	5001,177
	72,164	72,532	5234,210	5207,665	5260,891
	39,037	42,101	1643,511	1523,915	1772,494
	88,713	81,733	7250,747	7869,925	6680,283
	104,166	96,539	10056,062	10850,514	9319,779
	0,637	20,461	13,030	0,406	418,653
SUM			29082,146	30223,137	28453,277
SQUARE OF THE SUM			8,458E+08		
PRODUCT				859947282,490	
DETERMINATION COEFFICIENT					0,984

	DIFFERENCE	DIFFERENCE^2
	-1,649	2,718
	-0,368	0,135
	-3,064	9,386
	6,980	48,715
	7,627	58,168
	-19,824	392,999
SUM		512,121
RMSE		9,239

a*	Standard Deviation	Variance
6	0,194	0,038
11	0,344	0,118
15	0,169	0,029
16	0,046	0,002
19	0,048	0,002
24	3,880	15,055
Mean of variance		2,541
SW		1,594
REPEATABILITY		4,415

	MEAN	Color Checker	PRODUCT	MEAN^2	CC^2
	-39,554	-33,397	1320,982	1564,511	1115,360
	-34,891	-23,709	827,221	1217,354	562,117
	34,208	53,378	1825,953	1170,186	2849,211
	-5,829	4,039	-23,542	33,973	16,314
	-8,105	-0,425	3,445	65,699	0,181
	2,017	-0,079	-0,159	4,070	0,006
SUM			3953,900	4055,791	4543,188
SQUARE OF THE SUM			15633324,151		
PRODUCT				18426221,176	
DETERMINATION COEFFICIENT					0,848

	DIFFERENCE	DIFFERENCE^2
	-6,157	37,907
	-11,182	125,028
	-19,170	367,490
	-9,868	97,370
	-7,680	58,990
	2,096	4,395
SUM		691,179
RMSE		10,733

b*	Standard deviation	Variance
6	0,219	0,048
11	0,270	0,073
15	0,379	0,144
16	0,425	0,180
19	0,054	0,003
24	1,525	2,325
Mean of variance		0,462
SW		0,680
REPEATABILITY		1,883

	MEAN	Color Checker	PRODUCT	MEAN^2	CC^2
	-16,749	-0,199	3,333	280,526	0,040
	34,645	57,255	1983,589	1200,264	3278,135
	-0,279	28,190	-7,878	0,078	794,676
	73,558	79,819	5871,336	5410,798	6371,073
	-0,013	1,186	-0,015	0,000	1,407
	-35,416	-0,973	34,460	1254,293	0,947
SUM			7884,825	8145,959	10446,277
SQUARE OF THE SUM			62170472,902		
PRODUCT				85094938,575	
DETERMINATION COEFFICIENT					0,731

	DIFFERENCE	DIFFERENCE^2
	-16,550	273,899
	-22,610	511,220
	-28,469	810,510
	-6,261	39,199
	-1,199	1,437
	-34,443	1186,320
SUM		2822,584
RMSE		21,689

PATCH		L'bar	C1	C2	Cbar	G	a'1	a'2	C'1	C'2	C'bar	h'1
6		69,895	33,398	42,954	38,176	0,012	-33,812	-40,046	33,813	43,407	38,610	26,365
11		72,348	61,970	49,169	55,570	0,001	-23,731	-34,923	61,978	49,192	55,585	304,382
15		40,569	60,365	34,209	47,287	0,003	53,531	34,306	60,500	34,307	47,403	359,701
16		85,223	79,921	73,789	76,855	0,000	4,039	-5,829	79,921	73,789	76,855	86,901
19		100,352	1,260	8,105	4,683	0,499	-0,637	-12,147	1,346	12,147	6,746	1,142
24		10,549	0,976	35,473	18,225	0,343	-0,106	2,709	0,979	35,519	18,249	89,874

h'2		H'bar	T		Δh'	ΔL'	ΔC'	ΔH'	SL	SC	SH	Δθ
22,708	3,657	24,537	0,985	3,657	-3,657	-1,649	9,594	-74,096	1,291	2,737	1,571	7,701E-43
315,206	10,824	309,794	1,134	10,824	10,824	-0,368	-12,786	-84,483	1,329	3,501	1,946	4,324
359,533	0,168	359,617	0,586	0,168	-0,168	-3,064	-26,193	-7,631	1,128	3,133	1,417	0,000
-85,512	172,413	0,694	1,231	172,413	-172,413	6,980	-6,132	150,905	1,524	4,458	2,419	1,558E-51
360,060	358,918	360,601	1,590	358,918	-1,082	7,627	10,801	-4,167	1,752	1,304	1,161	0,000
274,331	184,457	362,102	1,261	184,457	-175,543	-19,824	34,541	2,263	1,588	1,821	1,345	0,000

RC	RT	KL	KC	KH		ΔE*00		PATCH	ΔE*ab	ΔE*ab Mean	STANDARD DEVIATION
0,977	-3,009E-42	1	1	1		47,321		6	17,735		
0,998	-1,400	1	1	1		40,947		11	25,227		
0,994	-0,001	1	1	1		10,307		15	34,458	23,620	11,650
1,000	-6,230E-51	1	1	1		62,576		16	13,612		
0,010	-9,918E-06	1	1	1		10,024		19	10,890		
0,315	0,000	1	1	1		22,768		24	39,796		

APPENDIX D

The data sheets of MTCS-C2 Colorimeter Board, its colour sensor (MTCSiCS), and the high intensity LED.

VERSION CHANGE		
NO.	ISSUE	APPROVED
1	V 1.67	2008-05-30

Technical Documentation

MTCS-C2

with

JENCOLOR color sensors

µC Version 0.12 PC SW Version. 1.67

Table of Contents

1. Introduction 2

2. Starting Up 3

2.1 Scope of Delivery 3

2.2 System Requirements 3

2.3 Components Hook-up 3

2.4 Software/Driver Installation 4

3. Hardware 5

3.1 MTCS-C2 Board 5

4. Software 6

4.1 Software Start 6

4.2 Color Detection and Measurement 9

4.3 Menu 10

4.3.1 Save Value 11

4.3.2 Color Patch 12

4.3.3 Config File 13

4.3.4 System Configuration 13

4.3.5 Exit 13

4.4 Changing the System Configuration 14

4.4.1 MTCS-C2 Configuration MTCS-C2 16

4.4.2 MTCS-C2 DI Configuration 17

4.5 Target-oriented Calibration 18

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1. Introduction

Industrial color detection, measurement and monitoring are becoming easier. Notably, where it is claimed that colors are to be detected, measured or compared "like human eyes" in a highly dynamic working environment and with little technical effort, MAZeT's JENCOLOR OEM color sensor design provides the optimal solution, both technically and economically.

Sensors of this type use the RGB Tri-Stimulus method, imitating the human eye's natural color perception (MCS series), or, alternatively, a method according to DIN 5033, Part 2 – Color Measurement; Standard Colorimetric Systems – CIE 1931 Tri-Stimulus Value Function (MTCS series)[1]. JENCOLOR ICs are available in different styles and package versions and can be fitted with a broad range of accessory items (e.g. demonstrator of system testing, testing and function boards, software libraries).

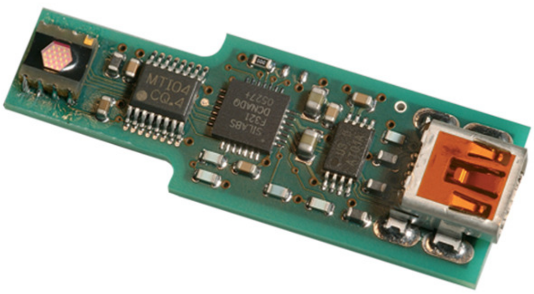


Figure 1: MTCS-C2 Board Colorimeter

In addition to its IC solutions, MAZeT offers a MTCS-C2 hardware solution based on the MTCS series, which will hereafter be referred to as "colorimeter 2" and will be described below. Alongside the color sensor IC, the board integrates all signal processing resources, including interfacing and measuring control and can be adapted within a Design In project.

The MTCS-C2 kit includes PC software "colorimeter2.exe" under Windows XP™ to handle functions like sensor calibration and anything in connection with measured value representation and output, e.g. in the CIE Lab color space. Furthermore an API Application Programming Interface (MTCSApi.DLL) with test software can also be supplied (optional).

If required, dedicated drivers and software libraries (tools for calculating the color range and calibration) can be produced and supplied for necessary adjustments to the software.

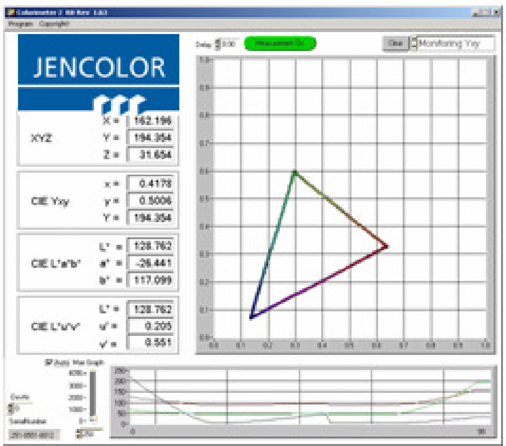


Figure 2: Operator interface mtcs-Software

Please do not hesitate to contact us for latest information about available components and scopes of delivery.

[1] For data and application sheets, you should contact one of our sales offices.

2. Starting Up

2.1 Scope of Delivery

MTCS-C2 delivery includes[2]:

- MTCS-C2 (μC Version 0.1x)
- Documentation
- optional[3] USB cable
- Optional "colorimeter2.exe" PC software (with USB driver of SYS and MTCSApi.dll type)[fn]
- Optional macro functions library
- Optional 10° optics consisting of shutter

2.2 System Requirements

For start-up procedures, the following system resources are required:

- PC Pentium 150 MHz or higher
- 8 MB RAM
- 5 MB free hard drive memory
- One free USB (2.0) port
- MS Windows™ XP / 2000

2.3 Components Hook-up

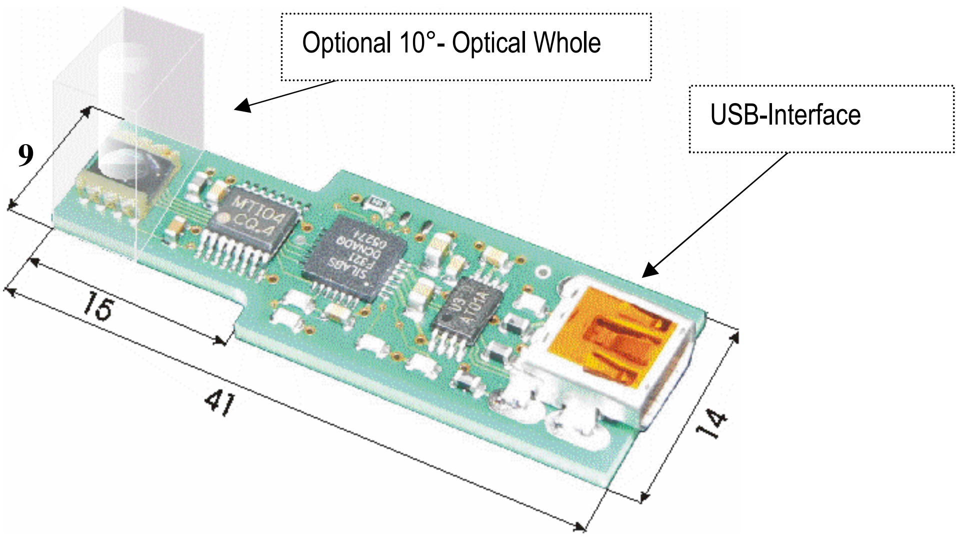


Figure 3; MTCS-C2 Board

[2] Please note, all components must be ordered as single positions.

[3] Please specifically indicate when enquiring / ordering

2.4 Software/Driver Installation

The "colorimeter2.exe" PC software (with USB driver of SYS and MTCSApi.dll type) is installed on your PC by using the setup.exe program.

After a successful installation, the setup procedure should copied the files “usbcolor2.inf“ and “usbio.sys“ files to the directories “windows\inf“ and the “windows\system32\drivers“. Use the USB cable (supplied) to connect the MTCS-C2 to one of your PC's free USB (2.0) ports. The device manager will output a message “found new device“on the screen.

Select “Automatic software installation“, then press “Continue“.

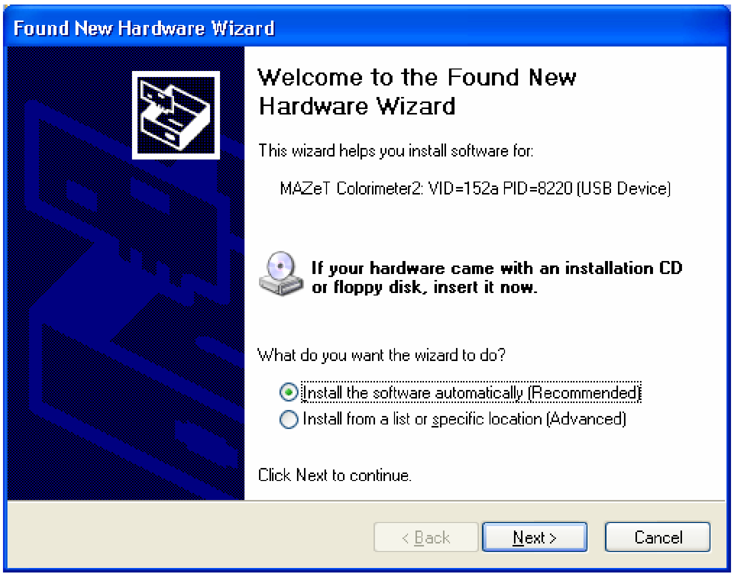


Figure 4 assistant for USB driver installation, 1. Page

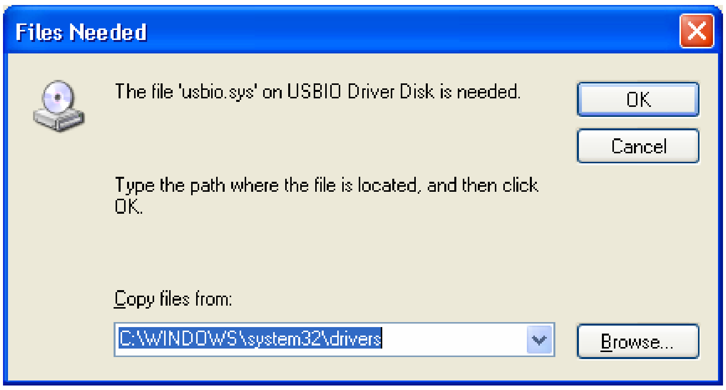


Figure 5; Microsoft assistant for USB driver installation

In case the software does not install automatically, you should check the directory to which the setup procedure had copied the .ini and .sys files. Take this directory for the further driver installation.

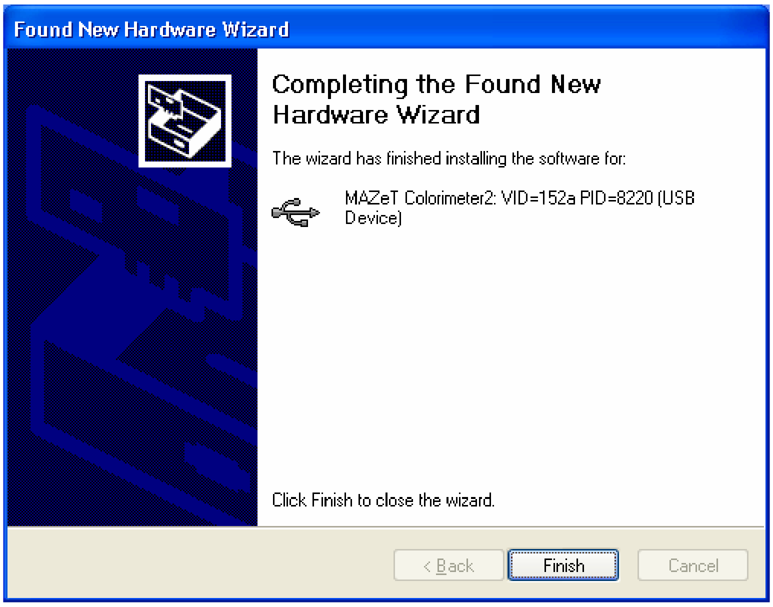


Figure 6 Assistant for USB driver installation, final page

After pressing "Finish“ the USB driver installation is completed.

After a successfully driver and software installation please connect the colorimeter board via USB to the PC and start the MTCS software.

3. Hardware

3.1 MTCS-C2 Board

The following components are integrated on this board[4]:

- MTCSiCS True – Color – Sensor
- MTI04CQ transimpedance amplifier
- C8051F321 micro controller with 10 bit AD converter and USB interface
- EEPROM - Free memory space for compensation and correction data

The board is supplied with voltage via the USB interface.

The micro controller has the following functions:

- Controlling and analyzing of the color sensor signals
- Activating the EEPROM for external memory space
- Communication via USB

[4] The data sheets for the individual devices can be obtained from the MAZeT sales office.

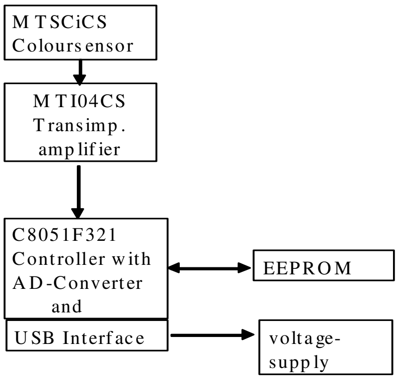


Figure 7; MTCS-C2 principle block diagram

The µC C8051F321 firmware is designed to support communication via the USB interface, to handle all customized measuring algorithms, simple ADC access operations and averaging of multiple ADC access operation and to manage customised settings and data for calibrating the sensors.

4. Software

4.1 Software Start

Based on an Ini-file some functions and parameters are to be defined in the C2 software. Please do not change the details in the Ini-file without support by MAZeT or your distribution partner[5]. The Ini-file includes the following sections and parameters:

Ini-File: conf.ini

```
[section1]
// Boardtyp wechseln 0=modeva 1=col2
// change Boardtyp 0=modeva 1=col2
BoardTyp=0
DeviceAnzahl=1
Serial=0
Trennzeichen="."
// amplification adjustable in the main-panel
// Verstaerkungsfaktor im main-panel einstellbar
ShowVerstaerkung=0
// multiplikation with mti- amplification
Amplification=1
// at the starttime excel will be running
// beim Start wird excel geoeffnet
Excel=0
Column=12
//Wait =1 wait for confirmation and singlemeasurment
//Wait =1 auf Bestaetigen warten und Einzelmessung
```

[5] Also do not change the values in the ini-File under [COLORIMETER2] und [modEVA].

Wait=0

[COLORIMETER2]
productid = 8220
vendorid = 152a
AnzeigeText=Colorimeter 2

[modEVA]
productid = c35d
vendorid = 400
AnzeigeText=MTCS Mod Eva

DeviceAnzahl bigger as 1: some devices with the same ID's can be connected.
Trennzeichen: "." or "," are possible. It is the description of the decimal point by saving.
Serial=1 a connection to the serial port is possible.
Excel=1 at the start time excel will be running. All measurements will be writing to the excel-form.
A user software session can be started by selecting "mtcs.exe" (START/PROGRAM/modEVA_Rev___/modeva___). The window for USB System-Setup will open (Figure 8or Figure 9). It contains standard entries for "Vendor_ID" and "Product_ID" representing specific Colorimeter conventions. These should not be changed. Please check whether the window "BoardTyp" includes the right hardware type connected to the PC (colorimeter2) and/or correct it.

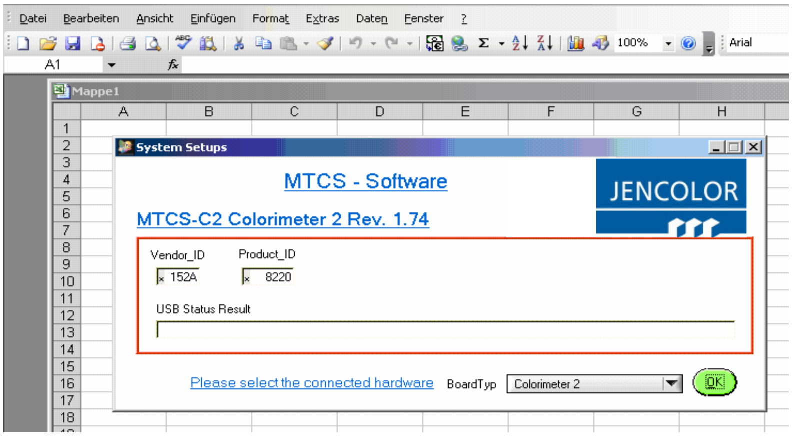


Figure 8; System Setups – Startup window with mit excel=1

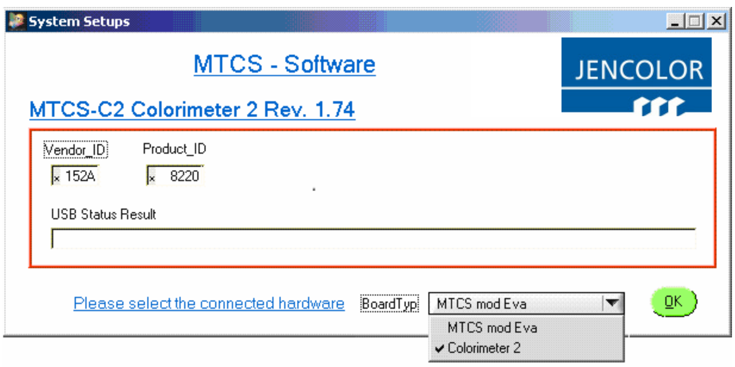


Figure 9; System Setups – Startup window

To check interface communication, click the OK button or the F8 function button.

When the Colorimeter2 is correctly installed as a USB device, the firmware revision number 0.1x is read and displayed (**Figure 10; System setups –** established
).

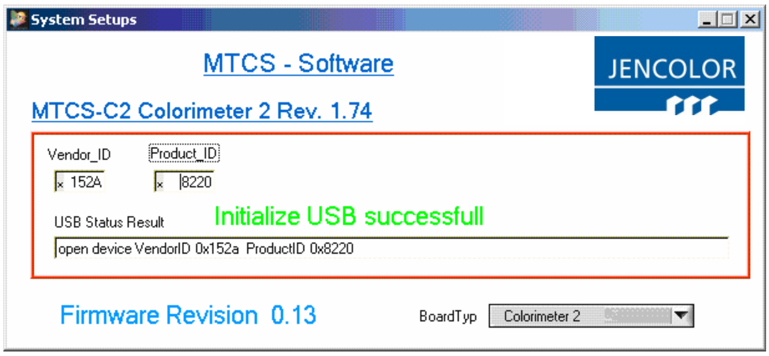


Figure 10; System setups – USB communication successfully established

After **Figure 10; System setups –** established
 the window is automatically closed and the main window for carrying out measurements (see Section: : **4.2**) or the window for configuring the measuring environment on the erased memory space (see Section: 4.3) is opened.

If "....resetUSB" appears in the "USB Status Result" line, it is recommended to terminate the program, to split and rejoin the USB connection on the hardware side (Reset hardware) and to restart the PC software.

4.2 Color Detection and Measurement

Figure 11; Main window for color measurement
shows the main window for color measurement visualisation.

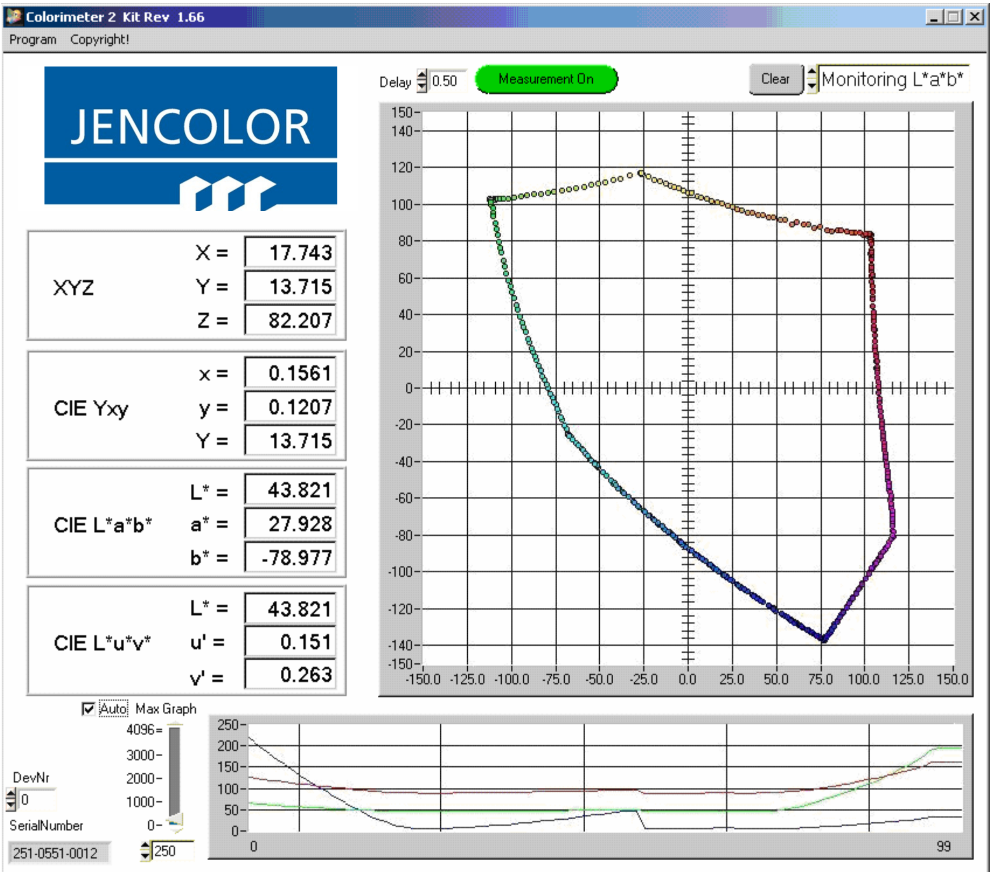


Figure 11; Main window for color measurement

The measured results are represented graphically as XYZ standard Tri-Stimulus values, in a standard chromaticity chart of CIE 1976 L*a*b*and as L*u*v color space. Please ensure that the color values can only be interpreted more or less in the sense of the color measurement when the board is calibrated to a measurement standard.[fn]

A measurement can be triggered and cancelled by clicking the green “Measurement On / Off“ or “ENTER” button (if the focus is non the "Measurement On / Off“ button). By variation of the “delay” time (next to "Measurement On / Off" - input in seconds), a desired waiting time between two measurements can be changed. The "delay“ time also changes the measurement time provided that the other values set in the program (e.g. averaging) and the computing power of the data processor allow this.

For graphical display, you may choose between Yxy, L*a*b* or L*u*v* from the list in the top right. A given graphic can be deleted with the “Clear Graph“ button or the “DELETE” key. At the bottom of the window there is an additional area in which the progression of recent values is displayed
(Figure 12; Graph of the values
). On the left, the display scale can be adjusted by setting a maximum value for the y-axis. If no progression gauge is displayed for continuous measurement it may be necessary for the area to be adapted. Selecting "Auto" automatically adjusts the area.
On the left side you can read the serial number of the actually device.
DevNr is for the selection of the device. It is only visible, if

- in the ini_File conf.ini the DeviceAnzahl is bigger then 1
- more as 1 device with the same VendorID and ProduktID are connected

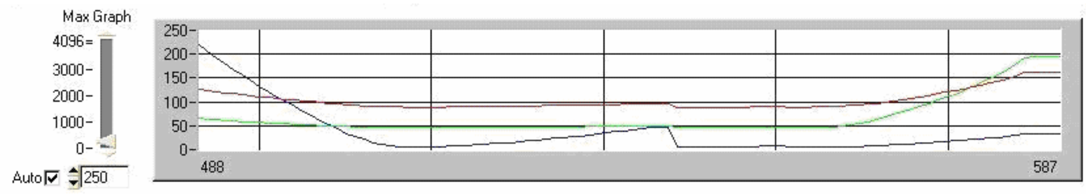


Figure 12; Graph of the variation over time of measured values

4.3 Menu

A variety of actions ("Program“, **Figure 14**) can be selected by using the menu next to the program information ("Copyright“, **Figure 13; Copyright**). This is described below.

Figure 13; Copyright

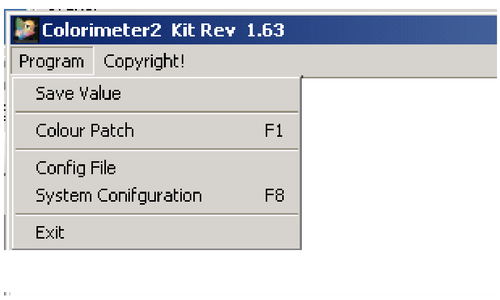


Figure 14; Menue

4.3.1 Save Value

Selecting “Save Value“ from the “Program“ menu enables you to save the measurement data as individual values or as a continuous list of all of the measurements as a measurement report in an external file.

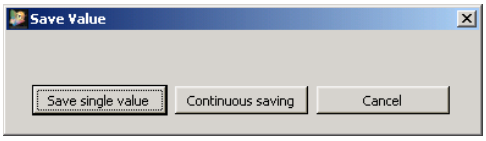


Figure 15; Save option: individual data or continuous saving

“Save single value“ saves the last measurement in a file. This function can also be carried out directly by pressing the F10 button.

If “Continuous saving“ is selected, data is saved according to all measurement specifications. By adjusting the time intervals, measurements can be carried out in succession by entering the delay time in seconds in the “delay” field.

A file name must be entered before the data can be saved (Figure 30).

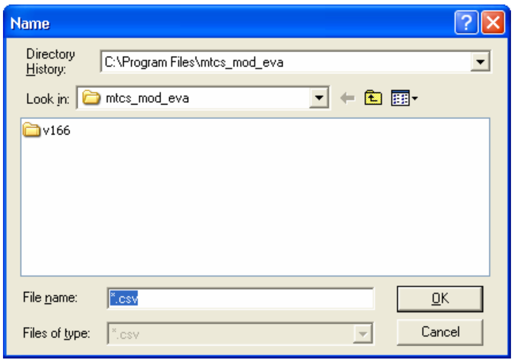


Figure 16; Enter a file name in order to save the data

Enter a name and press OK – the data will be saved in this *.csv file.

The entry “Stop Save value“ is in the “Save Value“ menu.

When activating the saving of data via the menu, there is the possibility to add new measurement data to the most recently used file or to put it in a new file. The request is carried out in accordance with figure 31.

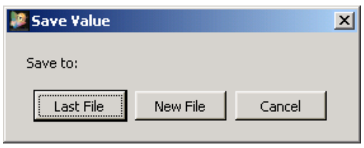
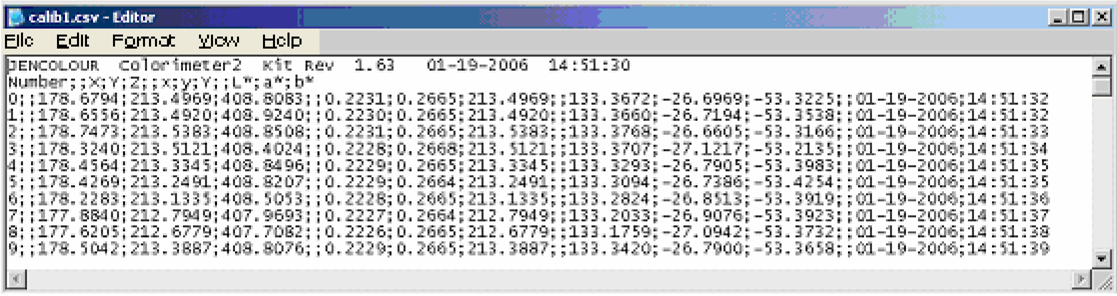


Figure 17; Save option: save in the most recent or a new file

The .csv file has the following format.

- Line 1: JENCOLOR Colorimeter2 Kit Revision 1.67
  date and time of creation
- Line 2: data file No.;; X;Y;Z;; x;y;Y;; Lab;; Date ;
  Time, separated with semicolons
- The data appears from line 3 onwards
  The choice of separator (decimal point or comma in real numbers) is recorded in the ini file (see below).



calib1.csv - Editor

File Edit Format View Help

```
JENCOLOUR  Colorimeter2  Kit Rev  1.63   01-19-2006  14:51:30
Number;;X;Y;Z;;x;y;Y;;L*;a*;b*
0;;178.6794;213.4969;408.8083;;0.2231;0.2665;213.4969;;133.3672;-26.6969;-53.3225;;01-19-2006;14:51:32
1;;178.6556;213.4920;408.9240;;0.2230;0.2665;213.4920;;133.3660;-26.7194;-53.3538;;01-19-2006;14:51:32
2;;178.7473;213.5383;408.8508;;0.2231;0.2665;213.5383;;133.3768;-26.6605;-53.3166;;01-19-2006;14:51:33
3;;178.3240;213.5121;408.4024;;0.2228;0.2668;213.5121;;133.3707;-27.1217;-53.2135;;01-19-2006;14:51:34
4;;178.4564;213.3345;408.8496;;0.2229;0.2665;213.3345;;133.3293;-26.7905;-53.3983;;01-19-2006;14:51:35
5;;178.4269;213.2491;408.8207;;0.2229;0.2664;213.2491;;133.3094;-26.7386;-53.4254;;01-19-2006;14:51:35
6;;178.2283;213.1335;408.5053;;0.2228;0.2665;213.1335;;133.2824;-26.8513;-53.3919;;01-19-2006;14:51:36
7;;177.8840;212.7949;407.9693;;0.2227;0.2664;212.7949;;133.2033;-26.9076;-53.3923;;01-19-2006;14:51:37
8;;177.6205;212.6779;407.7082;;0.2226;0.2665;212.6779;;133.1759;-27.0942;-53.3732;;01-19-2006;14:51:38
9;;178.5042;213.3887;408.8076;;0.2229;0.2665;213.3887;;133.3420;-26.7900;-53.3658;;01-19-2006;14:51:39
```

Figure 18; Organization of saved data

Continuous data saving can be terminated when measurement ceases or by selecting "Stop Save value" from the "Program" menu.

4.3.2 Color Patch

Selecting "Color Patch" from the menu enables the measured colors to be visualised as a corresponding colored window on the user interface. In addition, RGB values are indicated (Figure 19).

An evident matrix for the calculation of the RGB monitor values from the ADC raw data is a prerequisite for enabling the correct colors to be displayed (see section 4.5).

.

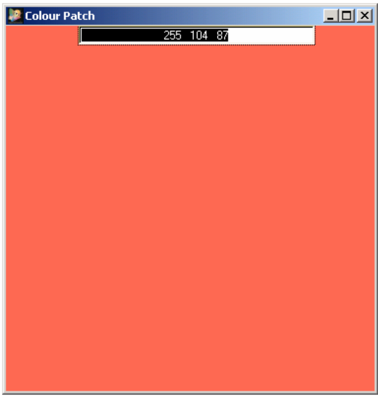


Figure 19; Color Patch display

> ***Attention!***
> Clear differences may occur in the color reproduction of the measured targets due to different display types or different settings in the color management of the PC and graphics card.

4.3.3 Config File

Selecting “Config File“ from the “Program“ menu enables application-specific system configurations and calibration data to be loaded and stored (see section 4.5; Configuration of the application (measuring mode)).

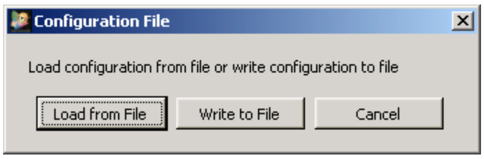
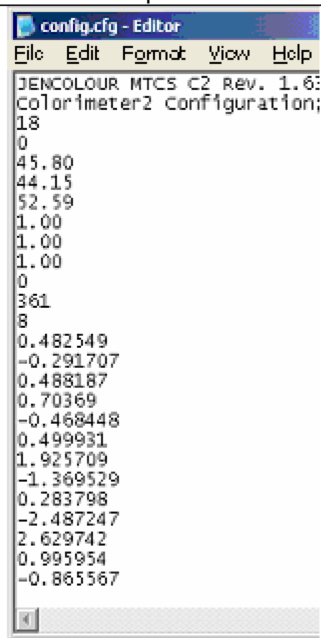


Figure 20; Accessing the system configuration file

The data is stored in a *.cfg file, organized in the following way:

Line	Contents	Example
1-2	SW Revision / Date / Time	
3	Type of configuration	
4	0	
5-7	Offset measurement value	
8-10	X, Y, Z for type of illumination	
11	0	
12	Max. Number of integration intervals	
13	Intensification	
14-22	Matrix raw data => XYZ	
23-31	Matrix raw data => RGB monitor	

4.3.4 System Configuration

The sensor system is set to corresponding types of measurement with specific parameters by using System Configuration. There is a detailed description in section 4.4.

4.3.5 Exit

Selecting “Exit“ from the “Program“ menu terminates the PC software.

4.4 Changing the System Configuration

It is only necessary to change the system configurations during initial operation or when changing the measurement type.

The window for changing the system configuration is opened by going to the ”Program/ System Configuration“ menu or by pressing the F8 button. When the program is run, this user interface is automatically loaded if no configuration data is stored (initial operation).

Figure 21; Reference to empty EEPROM

The following tasks are carried out via the „Application Setups“ dialogue box:

- Application requirement (measurement type)
- Adjustment of measurement conditions (integration time, mean values, etc.)
- Definition of colorimetric ambient conditions (offset, type of standard light, gamma correction)
- Determination of the gain matrix for color range transformation due to target-specific comparison
- Memory allocation on the board

If no configuration is saved (“no saved configuration“), the notification in Figure 21 appears directly after the USB initialization and then the user interface appears, shown in Figure 22.

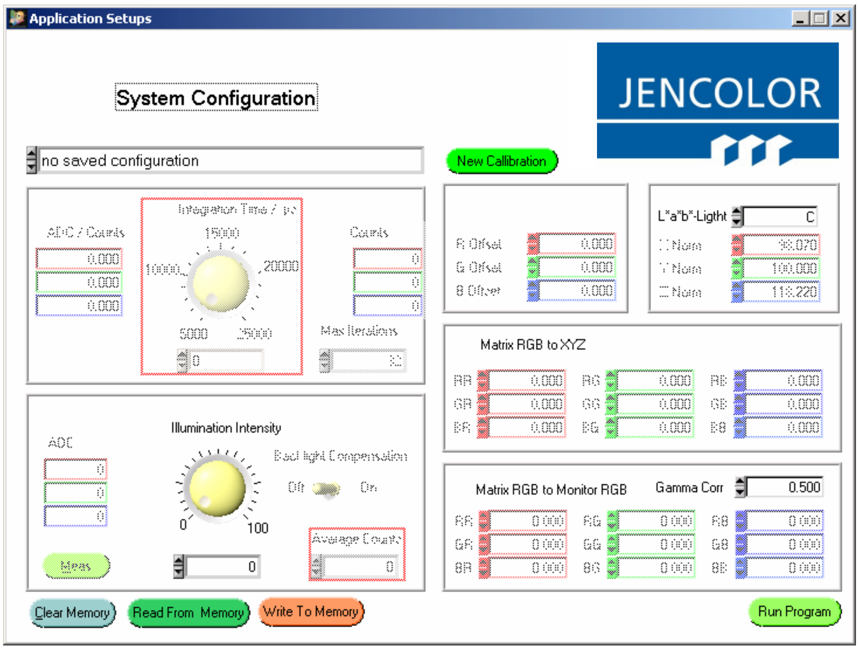


Figure 22; Example of configuration

The choice of application complies with the measurement type used and is selected from the list at the top left.

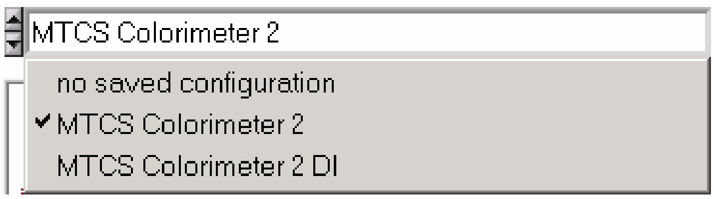


Figure 23; Application configuration (measurement type)

Depending on the application selected, the fields permitted for change are activated.

The configuration data is handled using the ”Clear Memory“, ”Read From Memory“ and ”Write To Memory“ buttons in the memory on the main board.

After the configuration is changes, the “Run Program“ remains inactive until the data is saved, using ”Write To Memory“ or reset, using ”Read From Memory“.

Once the system in successfully configured, you can return to measuring mode by pressing the “Run Program“ or F8 button (Main window for color measurement, Figure 22.

4.4.1 MTCS-C2 Configuration MTCS-C2

In the MTCS-C2 configuration, “Average Counts“ determines the number of measurement values by averaging. For example, the MTCS-C2 board can be set to measure light sources, e.g. LEDs or TFT monitors.

An adjustment of the 10 bit ADC value can be entered in the “Shift“ field and transmitted via the firmware.

The “Amplification“ rotary knob adjusts the intensification on the MTI. There are 8 intensification levels.

If the intensification=0, the intensification is automatically determined. In order to do this, the tolerance value is required.

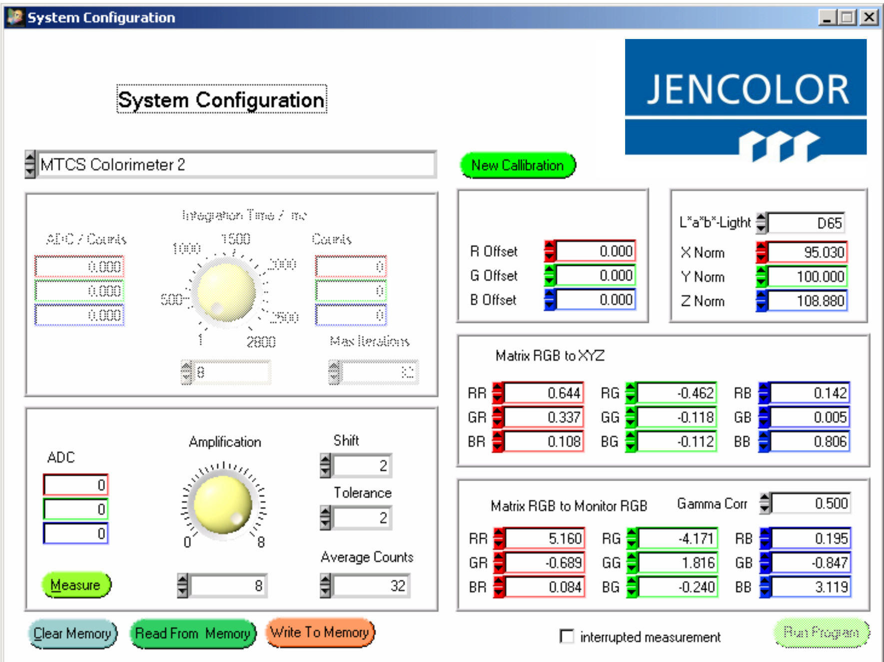


Figure 24; Example of configuration for MTCS-C2

In order for the system to be configured, the sensor must be directed at a white surface. With TFT monitors, it can be carried out on the screen with an appropriate light background.

Pressing the “Measure” button triggers a measurement and the corresponding measurement values (ADC values with fixed adjustment “Shift”) of the three measuring channels are displayed.

After the measuring conditions are adjusted, the system can be calibrated by generating a target-oriented gain matrix. This is explained in more detail in section 4.5.

4.4.2 MTCS-C2 DI Configuration

DI stands for Digital Integration, which means that the ADC values (with fixed adjustment "Shift") are added up over a fixed period of time.

The configuration is carried out by means of the active fields, as in Figure 25.
The integration time is entered into the "Integration Time / ms" field. It can vary between 0ms and 2800ms.

A measurement is carried out in the given integration time. The measurement value ("ADC/Counts") represents the integral deviation of the signal lever divided by the number of integration intervals ("Counts").

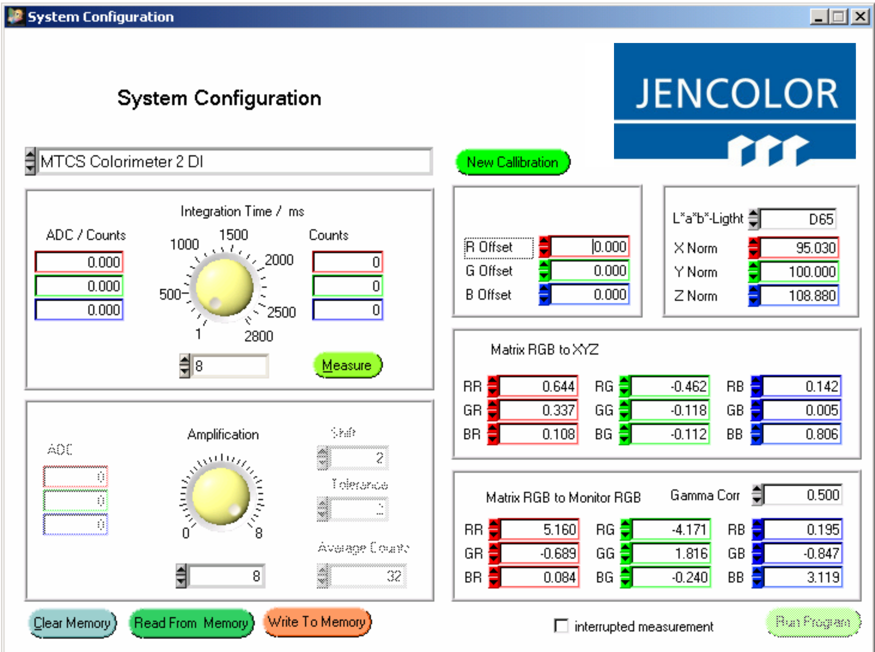


Figure 25; Example configuration for MTCS-C2 DI

The integration time is adjusted using the top rotary knob. The intensification is adjusted using the bottom rotary knob.

The intensification is adjusted on the MTI in the "Amplification" field.

A measurement is triggered when the "Measure" button is pressed and the corresponding measurement values (ADC/Counts-Values) are displayed on the three measuring channels.

4.5 Target-oriented Calibration

The system comparison (Figure 26) is carried out on a known target set when the “New Calibration“ button is pressed. In the process, the actual system values are calculated to the targets with known XYZ values and, as a result, the offset values and the gain matrix are calculated. The comparison starts with the following window:

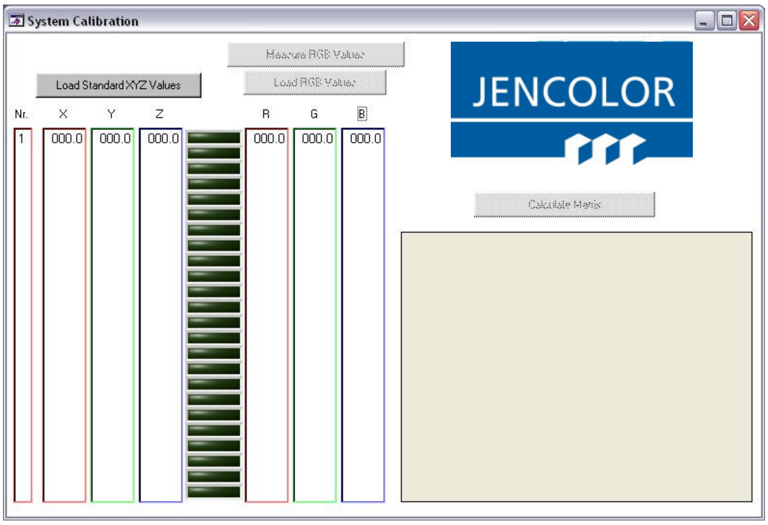
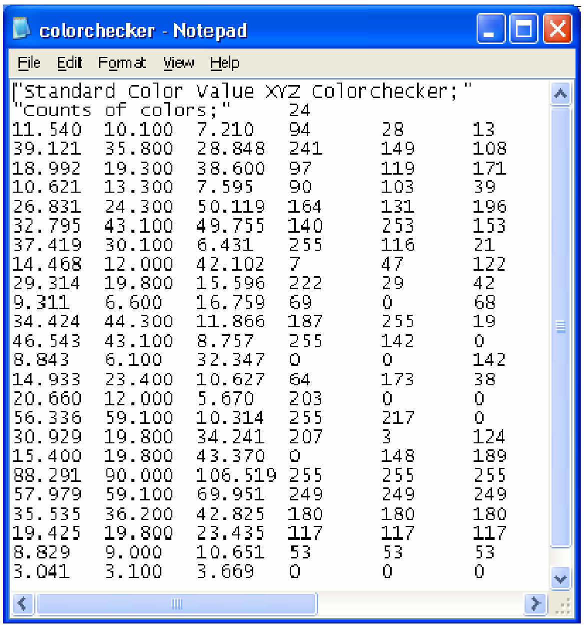


Figure 26; Start of System Calibration

The data for a known and measured target set is loaded by pressing the ”Load Standard XYZ-Value“ button. This dataset consists of a minimum of 3 (24 recommended) target XYZ and RGB values for the monitor display.




```
"Standard Color Value XYZ Colorchecker;"
"Counts of colors;"     24
11.540  10.100  7.210   94      28      13
39.121  35.800  28.848  241     149     108
18.992  19.300  38.600  97      119     171
10.621  13.300  7.595   90      103     39
26.831  24.300  50.119  164     131     196
32.795  43.100  49.755  140     253     153
37.419  30.100  6.431   255     116     21
14.468  12.000  42.102  7       47      122
29.314  19.800  15.596  222     29      42
9.311   6.600   16.759  69      0       68
34.424  44.300  11.866  187     255     19
46.543  43.100  8.757   255     142     0
8.843   6.100   32.347  0       0       142
14.933  23.400  10.627  64      173     38
20.660  12.000  5.670   203     0       0
56.336  59.100  10.314  255     217     0
30.929  19.800  34.241  207     3       124
15.400  19.800  43.370  0       148     189
88.291  90.000  106.519 255     255     255
57.979  59.100  69.951  249     249     249
35.535  36.200  42.825  180     180     180
19.425  19.800  23.435  117     117     117
8.829   9.000   10.651  53      53      53
3.041   3.100   3.669   0       0       0
```

Figure 27; Target Dataset

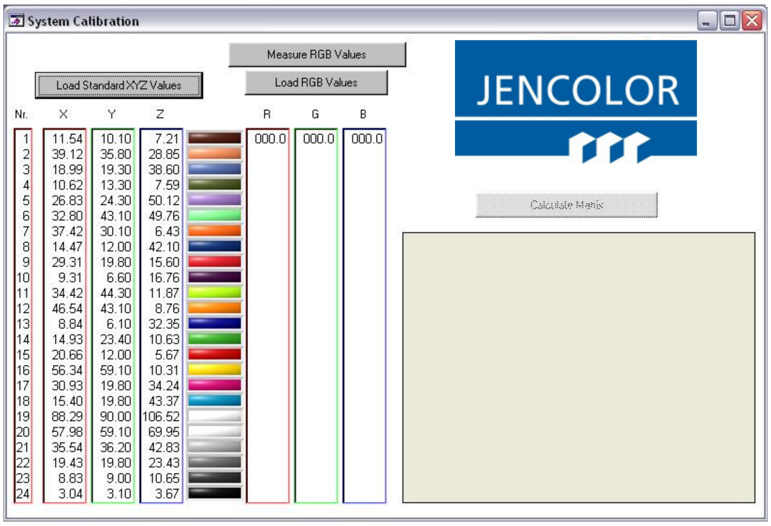
The dataset can be calculated using the radiance measurement, for example from the color range data provided from a colorchecker from the company, GretagMacbeth (Figure 28).

Figure 28; GretagMacbeth Colorchecker

The use of other targets presumes knowledge of the XYZ values. By monitoring with a spectrometer, an appropriate file can be created for luminescent objects.

The loaded target file is displayed with the XYZ numerical values and the combination color of the monitor in tabular form (Figure 29).

The actual values are entered automatically during a comparison on a calibrated monitor. For this, the senor is positioned in the middle of the colored surface or in the separate color patch field and the comparison is started by clicking on “Measure RGB Values”. The RGB monitor values deposited in the file are successively adjusted and the corresponding actual values are recorded.



Nr.	X	Y	Z	R	G	B
1	11.54	10.10	7.21	000.0	000.0	000.0
2	39.12	35.80	28.85			
3	18.99	19.30	38.60			
4	10.62	13.30	7.59			
5	26.83	24.30	50.12			
6	32.80	43.10	49.76			
7	37.42	30.10	6.43			
8	14.47	12.00	42.10			
9	29.31	19.80	15.60			
10	9.31	6.60	16.76			
11	34.42	44.30	11.87			
12	46.54	43.10	8.76			
13	8.84	6.10	32.35			
14	14.93	23.40	10.63			
15	20.66	12.00	5.67			
16	56.34	59.10	10.31			
17	30.93	19.80	34.24			
18	15.40	19.80	43.37			
19	88.29	90.00	106.52			
20	57.98	59.10	69.95			
21	35.54	36.20	42.83			
22	19.43	19.80	23.43			
23	8.83	9.00	10.65			
24	3.04	3.10	3.67			

Figure 29; System Calibration: Required Values

When the comparison is carried out on a reflecting target set, the sensors are successively adjusted to measured target colors and the respective actual value is entered when "Measure" is activated (Figure 30).

In the case of incorrect measurements, the last measurement can be deleted and repeated by pressing the "Repeat" button.

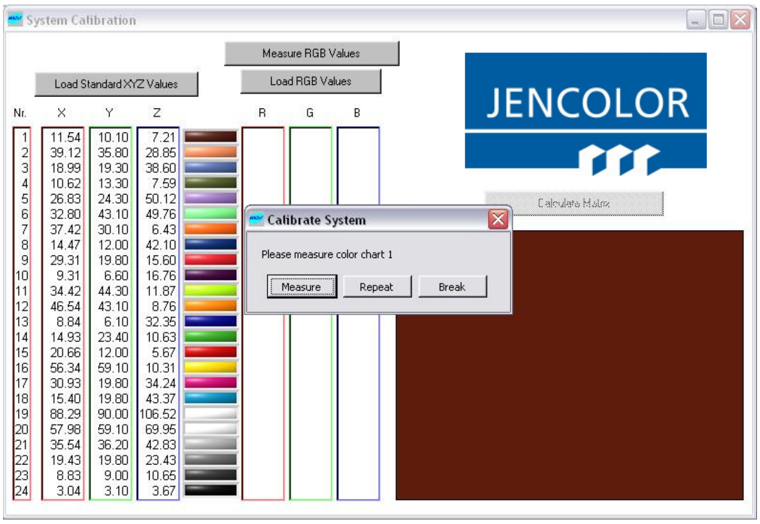


Figure 30; System Calibration: Entering the actual values

Use the "Break" button to cancel the calibration and return to the "Application Setups" dialogue box.

Once all 24 actual values have been entered, the file is saved and the offset values are calculated. A pre-prepared actual value file can be loaded by pressing "Load RGB Values".

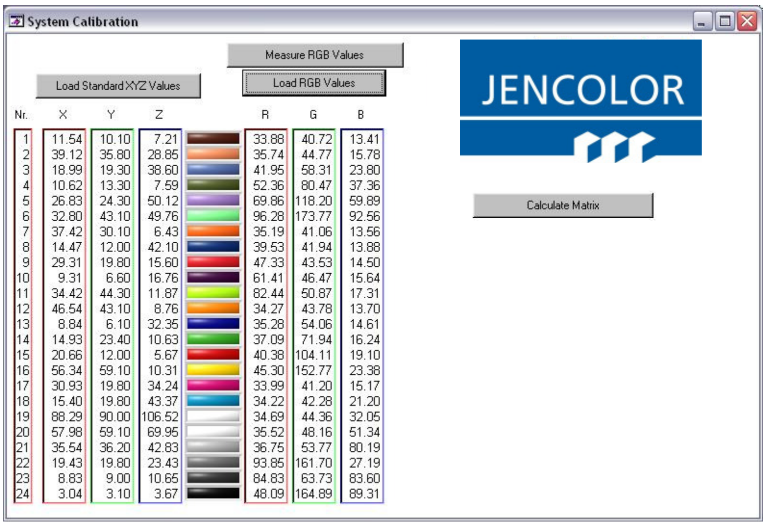


Figure 31; System Calibration: Matrix Calculation

If the offset-corrected actual values are available, the "Calculate Matrix" button is activated (Figure 31). You can click to calculate the gain matrices, complete the comparison and revert the software back to the "Application Setups" dialogue box, in which the determined offset values and matrices are displayed.

For the lab values calculated in the measurement, it is still necessary to enter the type of illumination, for which the calibration was carried out ("L*a*b*Light" in Figure 25).

The determined calibration data is deposited into the onboard memory when the "Write to Memory" button is pressed. It becomes available automatically after the system is rebooted, without the need to carry out a new comparison.

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REVISIONS		
REV.	DESCRIPTION	APPROVED
1	V 2.7	2008-08-22

Data Sheet

MTCSiCS

Integral True Color Sensor – LCC8

Table of Contents

1. FUNCTION 2
2. APPLICATION 2
3. FEATURES 2
4. MAXIMUM RATINGS / CHARACTERISTICS 3
5. CHARACTERISTIC CURVE 4
6. PACKAGE OVERVIEW 5
7. PIN-CONFIGURATION 7
8. SOLDERING PROFILE 7
9. APPLICATION CIRCUIT 8
10. ORDERING INFORMATION 8

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1. FUNCTION

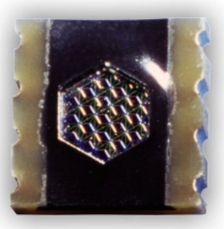
The True Color Sensors are made of 19 x 3 photo diodes (special PIN silicon technology with extended sensibility) integrated on chip. The diodes are carried out as segments of a multiple-element hexagonal matrix structure with the diameter of 2,0 mm.

The design as Si-PIN photo diodes allows signal frequencies up to MHz-range. In order to achieve a small cross talk between the photodiodes the individual sectors were separated from each other by additional structures.

Each of these photodiodes is sensitized with new dielectric spectral filter (named True Color Filter[1]) for its color range, preferably for the primary color standard CIE (Commission Internationale de l'Eclairage or International Commission on Illumination) color space.

2. APPLICATION

- Quality control
- Monitoring the production
- Control of manufacturing
- Detection of color marks
- Color measurement



3. FEATURES

Dielectric filters guaranties the good optical properties of the color sensors, such as:

- high transmission
- no ageing of the filter
- high temperature stability
- high signal frequency
- reduced cross talk
- small size (diameter of the optical sensitive surface ca. 2 mm)
- alike tri-stimulus interference filter for color measurement to DIN 5033 (CIE 1931)
- LCC package
- RoHS-conform

[1] The new generation of JENCOLOR sensors is committed to implementing (see relative sensitivity) the standard distribution functions as defined under DIN 5033 Part 2 – Color Measurement; CIE 1931 Standard Colorimetric Systems. This implementation method allows colors to be determined according to the three-range procedure that is defined in part 6 of DIN 5033.

4. MAXIMUM RATINGS / CHARACTERISTICS

(T_A = 25°C; per single diode)

Description	Symbol	Condition	min.	typ.	max.	Unit
Diameter of light sensitivity area	D			2,0		mm
Light sensitivity area per single color array (19 diodes)	A			0,76		mm²
Typical photo sensitivity of color ranges	S_{max}	λ_Z = 445 nm	0,21	0,23	0,25	A/W
		λ_Y = 555 nm	0,30	0,33	0,36	
		λ_{Xk} = 445 nm	0,11	0,12	0,13	
		λ_{Xl} = 600 nm	0,31	0,35	0,38	
Spectral tolerance of filter curve	$\Delta\lambda(\lambda)$				<1%*λ	nm
Reverse voltage	V_R		0	2,5	5	V
Dark current	I_R	V_R = 2,5V			10	pA
Terminal capacitance	C	V_R = 2V			70	pF
Rise and fall time of photo-current	t_r, t_f				2	µs
Noise equivalent power	NEP	f_R = 100 Hz			$<10^{-13}$	W/√Hz
Cross-talk					<1	%
Angle of incidence	φ	$\Delta\lambda_{(Filter)}$ < 1%*λ			10	Grad
Standard Operating temperatures[2]	T_{op}		-20		+100	°C
Storage temperature range	T_{st}	RH < 70%	-40		+100	°C
Baking treatment before soldering	T_B	24 h	120	125	130	°C
Moisture sensitivity Level	MSL	J-STD-020B		3		
Soldering temperature (see chapter 8 soldering profile)	T_S	20 sec			240	°C

[2] special on request

5. CHARACTERISTIC CURVE

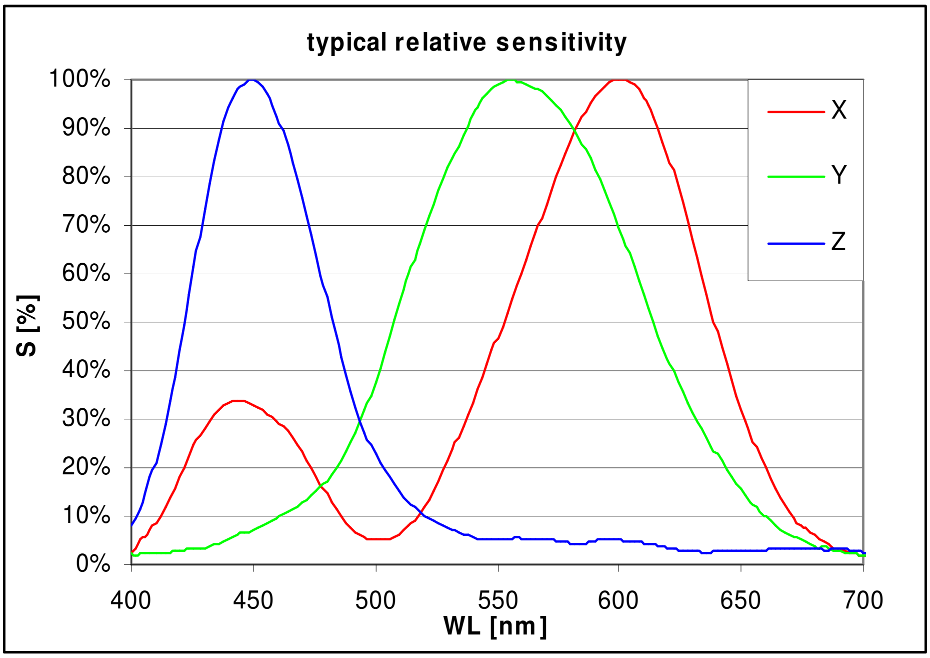


Figure: Typical (relative) sensitivity (XYZ) of the color sensor (MTCSiCS) scanned by width broadband light[3],

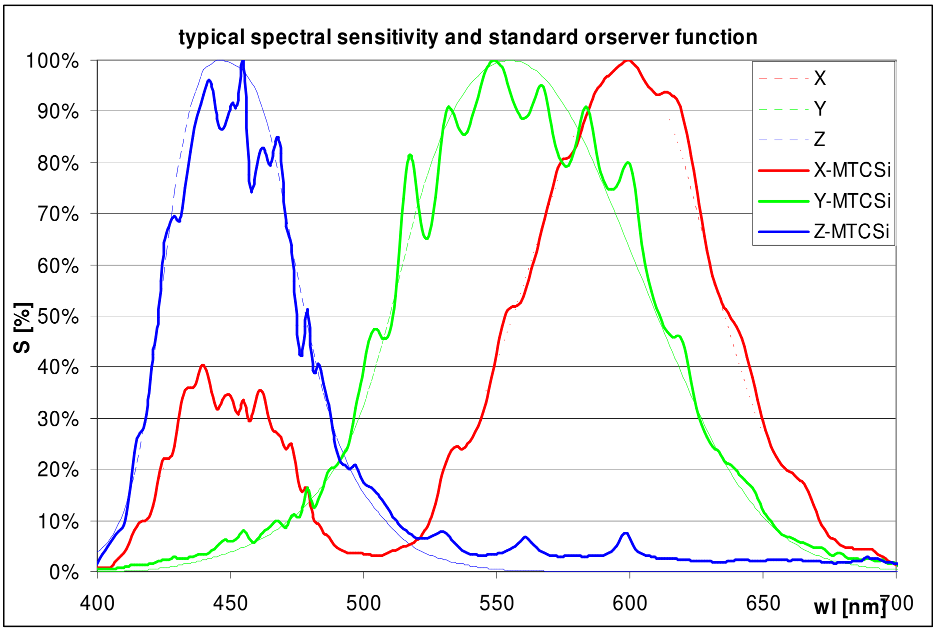
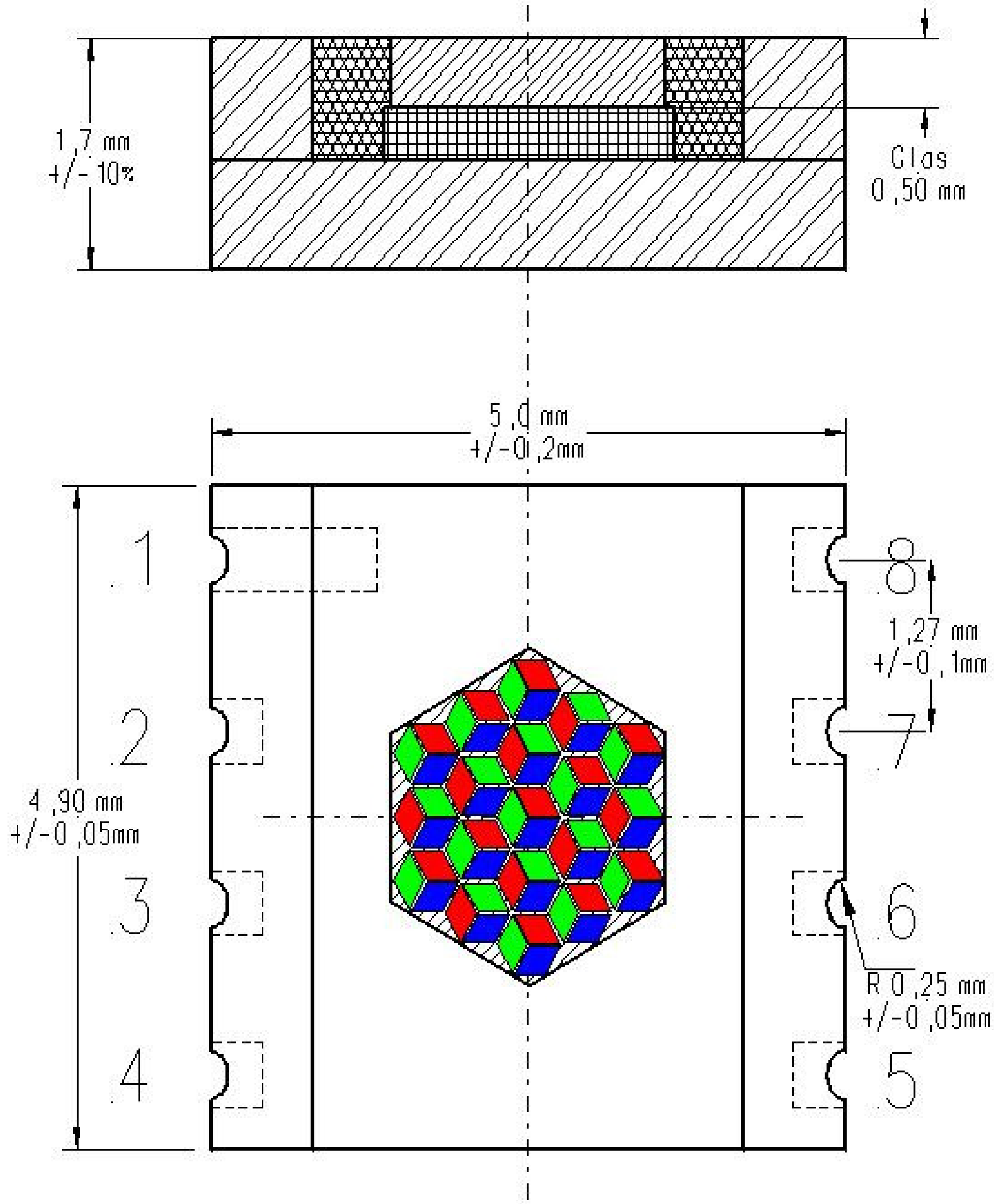


Figure: Typical (relative) sensitivity (XYZ) of the color sensor (MTCSiCS), scanned by narrow-band light[4]

[3] Typical characteristic sensitivity; scanned by monochromatic light with FWHM 27nm

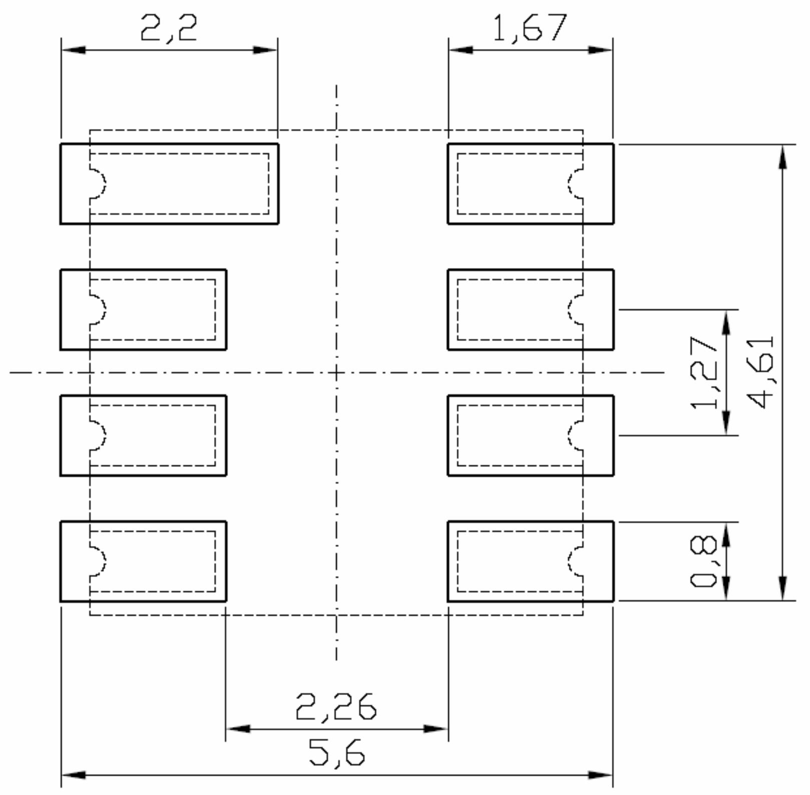
[4] Typical characteristic sensitivity; scanned by monochromatic light with FWHM 2nm

6. PACKAGE OVERVIEW[5]

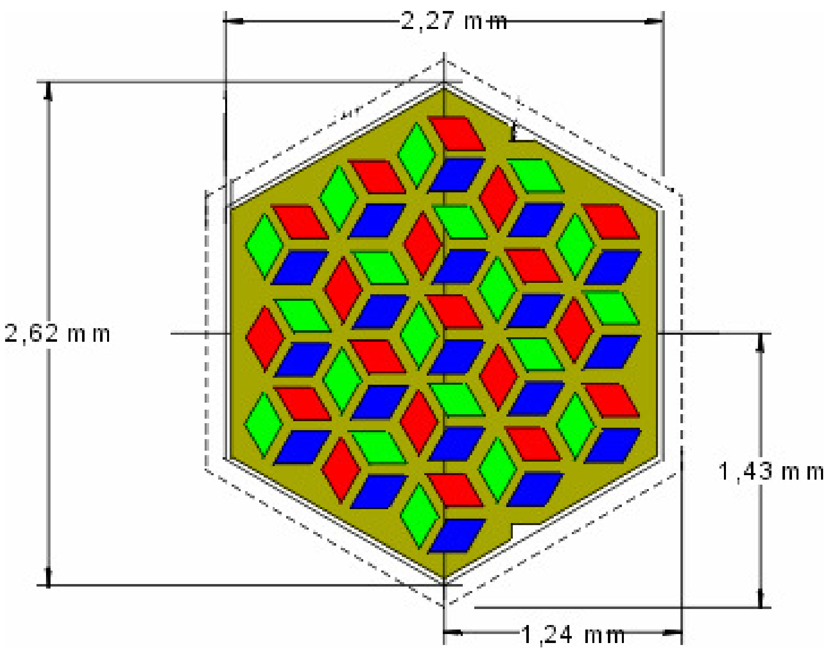


MTCSiCS in 8 Pin LCC package (side view and front side)

[5] Please, protect the sensible surface (glass) of the sensor against scratch and similar mechanical injuries. It will have negative effects for the perfect function of the sensor.



MTCSiCS in 8 Pin LCC package (back side) [6]



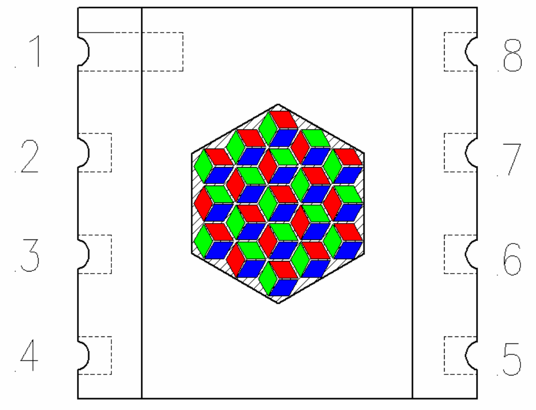
Filter dimensions of MTCSiCS

[6] Please note that on the back side of the package in midsize a blank metallic label with the name of the sensor could be. Please check it and note such a label before you use the components.

7. PIN-CONFIGURATION

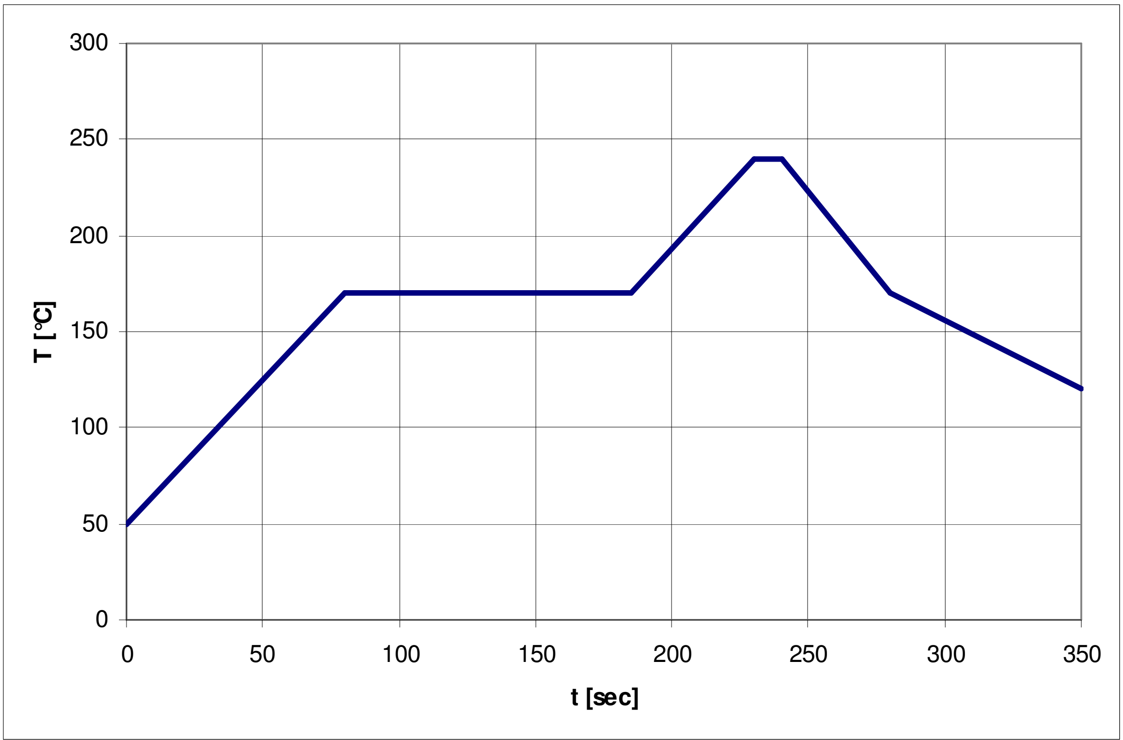
(Top view)

PIN	description
1	Y (green)
2	nc
3	nc
4	Z (blue)
5	X (red)
6	nc
7	TrD[7]
8	K common cathode



LCC 8 package

8. SOLDERING PROFILE

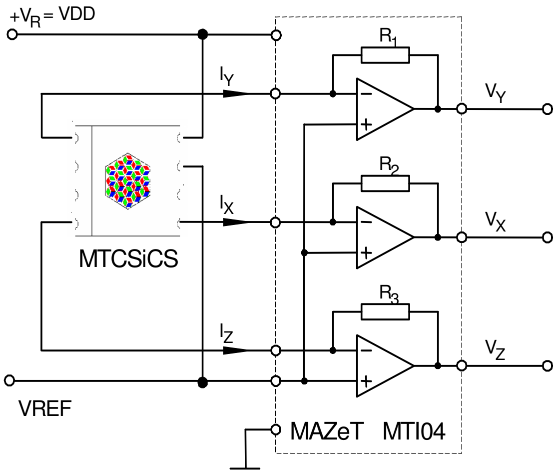


TYPICAL SOLDERING PROFILE

[7] TrD is a separation (protective) diode to split the potential of the 3 functional diodes. It's important for shielding the single color diodes to avoid a cross-talk among the 3 color areas/diodes. The TrD has to be connected with the Vref (use the 4th channel of the amplifier e.g. MTI04).

9. APPLICATION CIRCUIT

Opposite figure shows a circuit for the conversion of photo current to an equivalent voltage. These voltage can be processed e.g. with an ADC. By the selection of suitable resistors the output voltage range can be adjusted to the photo current value. (for example the pin-programmable transimpedance amplifier MTI04).



10. ORDERING INFORMATION

True Color sensor with LCC8-package	**MTCSiCS**
Modular application board modEVA	**MTCS-ME1**
Functional application board Colorimeter II	**MTCS-C2**

For further information please contact:

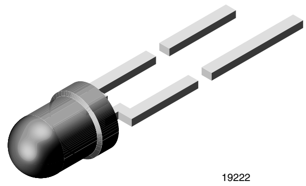
MAZeT GmbH
Sales office:
Göschwitzer Straße 32
07745 JENA
GERMANY
Phone: +49 3641 2809-0
Fax: +49 3641 2809-12
E-Mail: sales@MAZeT.de
Url: http://www.MAZeT.de

WARNINGS

Personal Injury – Do not use these products as safety or emergency stop devices, or in any other applications where failure of the product could result in personal injury. **Failure to comply with these instructions could result in death or serious injury.**

Misuse of Documentation – The information presented in this data sheet is for reference only. Because these products are under development do not use this document as product installation guide. Before you start any development ask your supplier for the latest version of this sheet. **Failure to comply with these instructions could result in death or serious injury.**

White LED in 3mm T 1 Waterclear Package



19222

FEATURES

- High efficient InGaN technology
- Chromaticity coordinate categorized according to CIE1931 per packing unit
- Typical chromaticity coordinates x = 0.33; y = 0.33
- Typical color temperature 5500 K
- ESD-withstand voltage up to 1 kV acc. to JESD22-A114-B
- Small viewing angle, high luminous intensity
- Chip embedded in elastic resin, improved robustness against temperature cycle stress
- Lead (Pb)-free device
- RoHS compliant

DESCRIPTION

High Intensity LED with typical color coordinates x = 0.33, y = 0.33 (typical color temperature 5500 k). This LED emits white light with a high color rendering index.

The emission spectrum is tuned for ideal white, without the impression of being blue shaded or "cold". The package is a standard 3 mm.

The internal reflector is filled with a compound of TAG phosphor and an elastic resin.

Therefore the chip is better protected against temperature cycle stress.

The phosphor converts the blue emission of the InGaN chip partially to amber, which mixes with the remaining blue to produce white.

APPLICATIONS

- Indicator and backlighting
- Indoor and outdoor message panels
- Alternative to incandescent lamps
- Marker lights

PARTS TABLE

PART	COLOR, LUMINOUS INTENSITY	ANGLE OF HALF INTENSITY (± J)	TECHNOLOGY
VLHW4900	White, I_V > 240 mcd	16°	InGaN / TAG on SiC
VLHW4902	White, I_V = (430 to 2000) mcd	16°	InGaN / TAG on SiC

ABSOLUTE MAXIMUM RATINGS[1] VLHW490.				
PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Reverse voltage[2]		V_R	5	V
DC Forward current	$T_{amb} \leq 50$ °C	I_F	30	mA
Surge forward current	$t_p \leq 10$ µs	I_{FSM}	0.1	A
Power dissipation		P_V	126	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 100	°C
Storage temperature range		T_{stg}	- 40 to + 100	°C
Soldering temperature	t ≤ 5 s	T_{sd}	260	°C
Thermal resistance junction/ ambient		R_{thJA}	400	K/W

[1] T_{amb} = 25 °C, unless otherwise specified
[2] Driving the LED in reverse direction is suitable for short term application

OPTICAL AND ELECTRICAL CHARACTERISTICS[1] WHITE VLHW490.							
PARAMETER	TEST CONDITION	PART	SYMBOL	MIN	TYP.	MAX	UNIT
Luminous intensity[2]	I_F = 20 mA	VLHW4900	I_V	240	500		mcd
		VLHW4902	I_V	430		2000	mcd
Luminous flux	I_F = 20 mA		ϕ_V		250		mlm
Chromaticity coordinate x acc. to CIE 1931	I_F = 20 mA		x		0.33		
Chromaticity coordinate y acc. to CIE 1931	I_F = 20 mA		y		0.33		
Angle of half intensity	I_F = 20 mA		φ		± 16		deg
Forward voltage	I_F = 20 mA		V_F		3.5	4.2	V
Reverse voltage	I_R = 10 µA		V_R	5			V
Temperature coefficient of V_F	I_F = 20 mA		TC_V		- 4		mV/K
Temperature coefficient of I_V	I_F = 20 mA		TC_I		- 0.5		% / K

[1] T_{amb} = 25 °C, unless otherwise specified
[2] in one Packing Unit $I_{Vmin}/I_{Vmax} \leq 0.5$

CHROMATICITY COORDINATE CLASSIFICATION				
GROUP	X		Y	
	MIN	MAX	MIN	MAX
3	0.280	0.325	0.210	0.340
4	0.305	0.350	0.260	0.390
5	0.330	0.375	0.310	0.440

LUMINOUS INTENSITY CLASSIFICATION		
GROUP	LIGHT INTENSITY [MCD]	
STANDARD	MIN	MAX
Z	240	480
AA	320	640
BB	430	860
CC	575	1150
DD	750	1500
EE	1000	2000

TYPICAL CHARACTERISTICS (TAMB = 25 °C UNLESS OTHERWISE SPECIFIED)

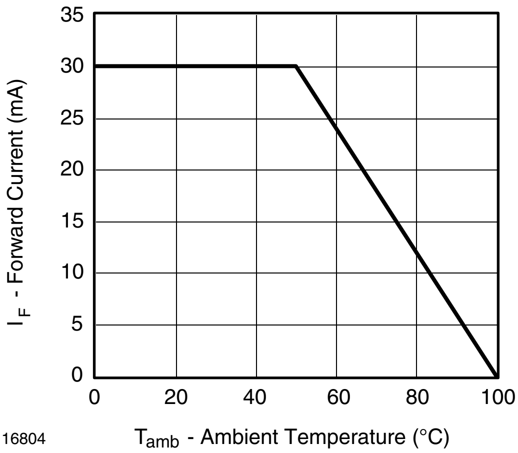


Figure 1. Forward Current vs. Ambient Temperature

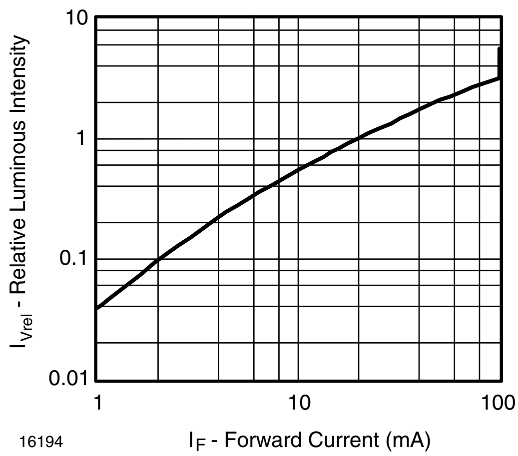


Figure 2. Relative Luminous Intensity vs. Forward Current

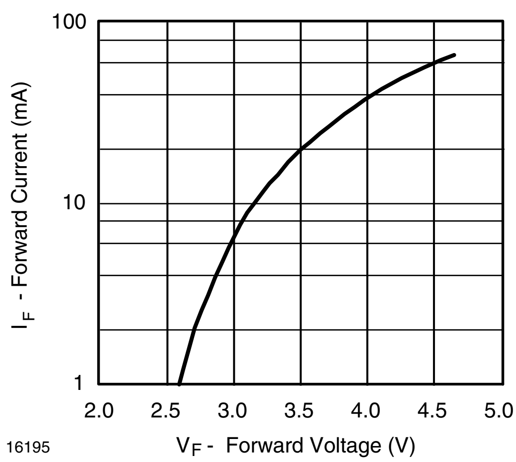


Figure 3. Forward Current vs. Forward Voltage

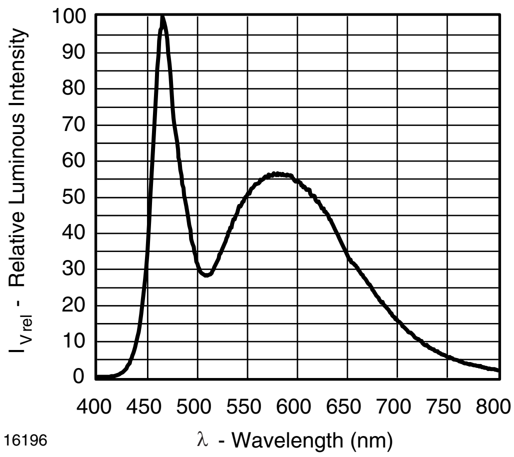


Figure 4. Relative Intensity vs. Wavelength

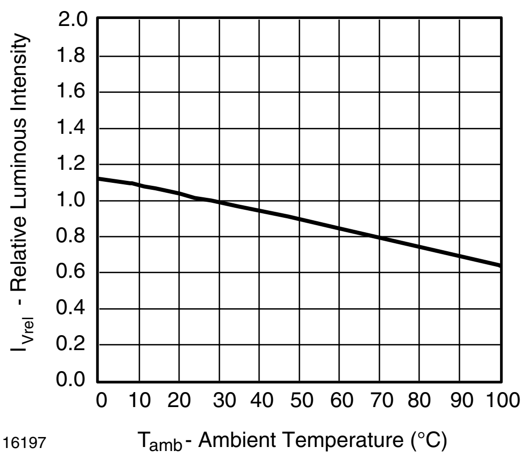


Figure 5. Rel. Luminous Intensity vs. Ambient Temperature

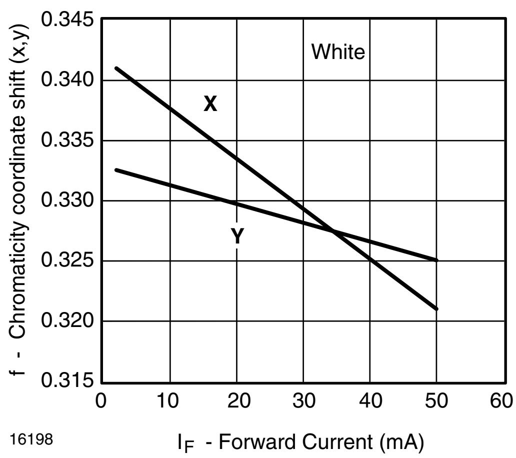


Figure 6. Chromaticity Coordinate Shift vs. Forward Current

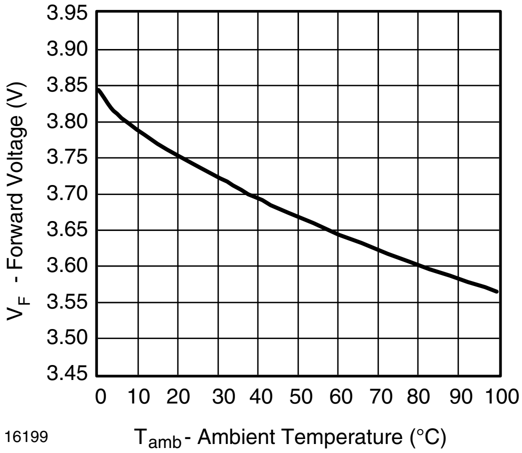


Figure 7. Forward Voltage vs. Ambient Temperature

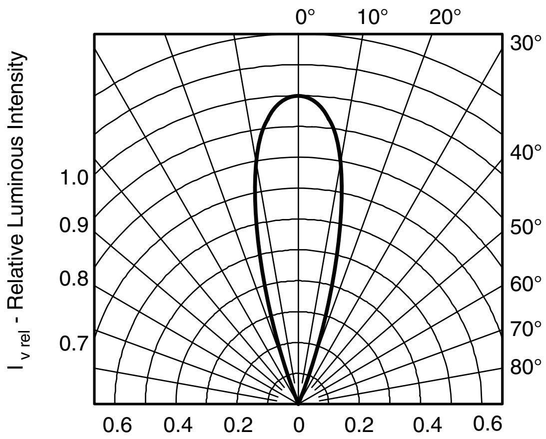


Figure 8. Rel. Luminous Intensity vs. Angular Displacement

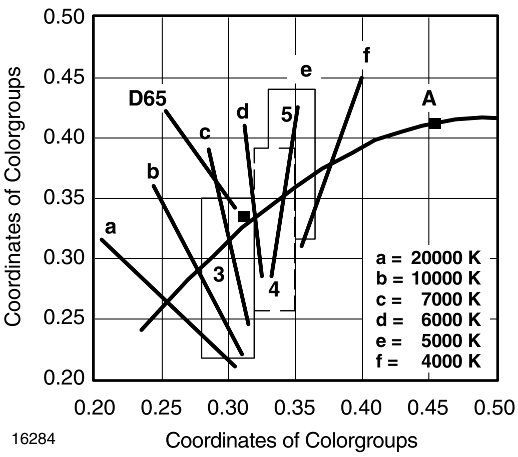
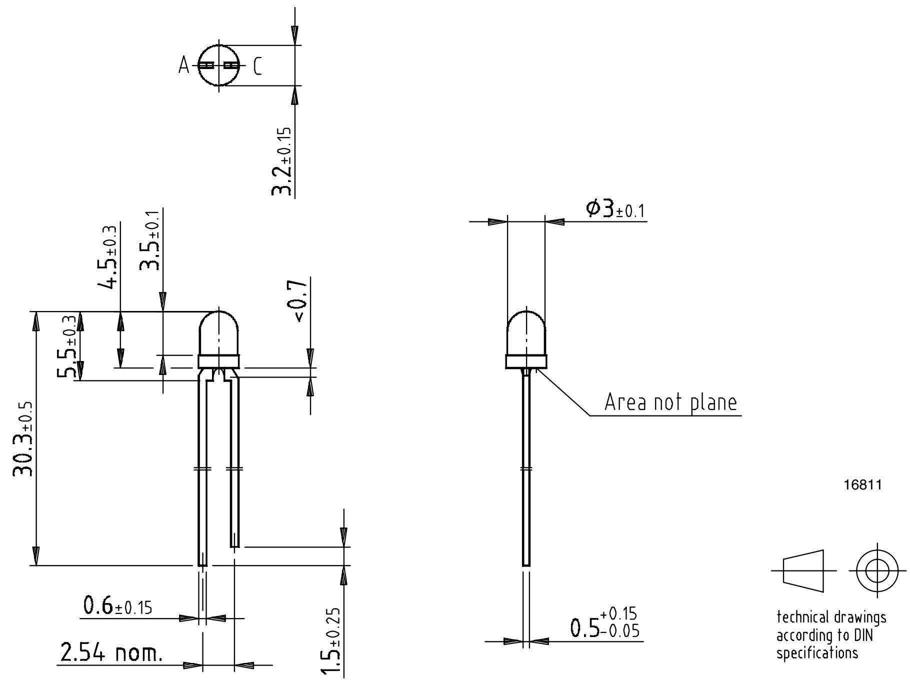
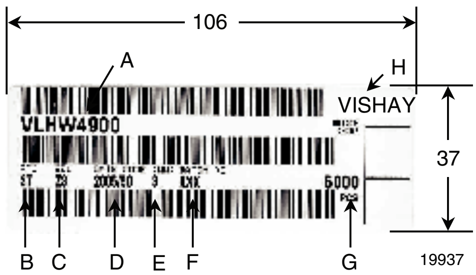


Figure 9. Coordinates of Colorgroups

PACKAGE DIMENSIONS IN MM



BARCODE-PRODUCT-LABEL



A) Type of component
B) Manufacturing plant
C) SEL - Selection Code (Bin):
e.g.: Z = Code for Luminous Intensity Group
3 = Code for Chromaticity Coordinate
D) Date Code year/week
E) Day Code (e.g. 1: Monday)
F) Batch No.
G) Total quantity
H) Company Code

Ozone Depleting Substances Policy Statement

It is the policy of Vishay Semiconductor GmbH to

1. Meet all present and future national and international statutory requirements.
2. Regularly and continuously improve the performance of our products, processes, distribution and operating systems with respect to their impact on the health and safety of our employees and the public, as well as their impact on the environment.

It is particular concern to control or eliminate releases of those substances into the atmosphere which are known as ozone depleting substances (ODSs).

The Montreal Protocol (1987) and its London Amendments (1990) intend to severely restrict the use of ODSs and forbid their use within the next ten years. Various national and international initiatives are pressing for an earlier ban on these substances.

Vishay Semiconductor GmbH has been able to use its policy of continuous improvements to eliminate the use of ODSs listed in the following documents.

1. Annex A, B and list of transitional substances of the Montreal Protocol and the London Amendments respectively
2. Class I and II ozone depleting substances in the Clean Air Act Amendments of 1990 by the Environmental Protection Agency (EPA) in the USA
3. Council Decision 88/540/EEC and 91/690/EEC Annex A, B and C (transitional substances) respectively.

Vishay Semiconductor GmbH can certify that our semiconductors are not manufactured with ozone depleting substances and do not contain such substances.

Vishay Semiconductor GmbH, P.O.B. 3535, D-74025 Heilbronn, Germany

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