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A colorimetric multivariable feedback control system for test environment ambient light control

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Increased information flow, new use cases and developed display technologies have created a need for mobile phone display functionality and thus also for testing those all in different ambient light conditions. In extensive subjective tests aiming to test comparability, reproducibility and easiness are the key figures. This is why a test room for illumination reproduction equipped with different light sources had been previously developed.

The goal of this thesis was to develop and implement a robust colorimetric feedback control system for this test environment that would be functional and capable of compensating error sources. The starting point was a human observer and color difference minimization the goal. Also previous studies were applied, CIEDE2000 color difference calculation and colorimetry being most important. Emphasis was on the development and implementation of a new controlling algorithm.

Light controlling is based on metamerism and the target was to achieve the ability to produce wanted chromaticity coordinate and illuminance and control them in real-time. The feedback from the system state was received using a miniature spectroradiometer. The controlling combined both classis PID controller and gravity based controlling where every light source was modeled into a chromaticity diagram according to its color coordinate. The idea behind the algorithm was that each lamp would work as a pushing or a pulling chromatic gravity point.

The goal of the study was fulfilled and a working controller was both developed and implemented. The difficulties were lamps' cross effects, a unique environment, human vision complexity and adaptation. Initial guesses importance, target's location in a color gamut and chosen lamp configuration were emphasized. Development proposals focused on test environment development, intelligent controller parameter tuning and initial state guess specifying.

Keywords: ambient light controlling, colorimetric control system, chromaticity controlling, illuminance controlling, CIEDE2000, gravity point based controlling method

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Kasvanut informaatiovirran määrä, uudet käyttötarkoitukset sekä kehittyneet näyttöteknologiat ovat luoneet tarpeen matkapuhelimien näyttöjen toimivuudelle ja näin ollen myös testaukselle eri ympäristönvalaistusolosuhteissa. Laajamittaisessa vertailukelpoisuuteen tähtäävässä subjektiivisessa testauksessa avainsanoja ovat toistettavuus ja helppous, jonka takia jo aiemmin oli kehitetty erilaisten valaistusominaisuuksien toistamiseksi lampuilla varustettu testitila. Tästä laitteistosta kuitenkin puuttui toimiva säätöjärjestelmä.

Tutkimuksen tavoitteena oli suunnitella ja toteuttaa tähän testitilaan toimiva robusti takaisinkytketty kolorimetrinen ohjausjärjestelmä joka pystyisi kompensoimaan virhelähteitä. Lähtökohtana pidettiin havainnoitsijana toimivaa ihmistä, tavoitteena havaitun värivaikutelmaeron minimointi. Työssä sovellettiin tähän liittyvää aiempaa tutkimusta, tärkeimpinä CIEDE2000 värierolaskenta ja kolorimetria. Pääpaino oli uuden säätöalgoritmin kehittämisellä ja implementoinnilla.

Valaistuksen säätö pohjautuu metameriaan ja sen tarkoitus oli kyetä tuottamaan haluttu värikoordinaatti ja valaistusvoimakkuus sekä mahdollistaa näiden reaaliaikainen korjaaminen. Takaisinkytkentä systeemin tilasta saatiin miniatyyrispektroradiometrin avulla. Säätöalgoritmissa yhdistettiin sekä klassinen PID-säädin että massapisteisiin perustuva säätö jossa jokainen valonlähde mallinnettiin väridiagrammiin sen värikoordinaatin perusteella. Algoritmin taustalla oli idea siitä, että jokainen lamppu toimisi näin eräänlaisena työntävänä tai vetävänä kromaattisena painovoimapisteenä.

Tutkimuksen tavoite saatiin täytettyä ja toimiva säädin sekä kehitettyä että implementoitua. Vaikeuksia olivat lamppujen ristikkäisvaikutukset, ympäristön ainutlaatuisuus, ihmisen näköjärjestelmän monimutkaisuus ja adaptoituminen. Työssä korostui erityisesti alkuarvauksen tärkeys, kohteen sijainti väriavaruudessa ja valitun lamppukokoonpanon oikeellisuus. Ilmenneet kehitysehdotukset keskittyivät laitteiston kehittämiseen, älykkääseen säätöparametrien virittämiseen ja alkuarvauksen tarkentamiseen.

Avainsanat: ympäristön valaistuksen säätö, kolorimetrinen säätöjärjestelmä, kromaattisuuden säätö, valaistusvoimakkuuden säätö, CIEDE2000, vetovoimapisteisiin perustuva säätö

PREFACE

This master's thesis is conducted to order of Nokia Oyj and as a partial fulfillment of the degree of Master of Science in Helsinki University of Technology Automation Technology Laboratory. First and foremost I would like to express my gratitude to my instructor M.Sc. Jussi Ropo and supervisor Professor Aarne Halme for guidance and advices during these months. Also I would like to thank Olli Suhonen who familiarized me with visual testing, colorimetry and world of displays in general, Mauri Vilpponen who handled practicalities and provided the opportunity to do this thesis, as well as all of my colleagues.

Last but not least my epic compliments to Johanna, my family and all of my friends.

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Tapio Finnilä

ACRONYMS

AC	Alternating Current
Autolights	Implemented light controlling software and module
A/D	Analog-to-Digital
BIPM	Bureau International des Poids et Mesures
CCT	Correlating Color Temperature
CIE	International Commission on Illumination
CIE 1924	CIE system of photometry established in 1924
CIE 1931	CIE 1931 chromaticity diagram (x and y) **or** CIE standard colorimetric observer (2°)
CIE 1964	Supplementary standard colorimetric observer (10°)
CIE 1976	Uniform Chromaticity Scale diagram (u' and v')
CIEDE2000	CIE 2000 color-difference formula
CIELAB	CIE 1976 (L* a* b*) color space
CIELUV	CIE 1976 (L* u* v*) color space
D65	A standard illuminant defined by CIE
D/A	Digital-to-Analog
F11	A standard illuminant defined by CIE
F12	A standard illuminant defined by CIE
GA	Genetic Algorithm
HUT	Helsinki University of Technology
ISE	Integral of the Square Error
JND	Just-Noticeable Difference
LCD	Liquid Crystal Display
PID	Proportional-integral-derivative
RGB	Red, Green and Blue
RS-232	An interface standard used in computer serial ports
SimOne	Used test environment
USB	Universal Serial Bus
USC	Uniform Chromaticity Scale

SYMBOLS

lm	Lumen
I	Radiant intensity
x, y	Coordinates of CIE 1931 chromaticity diagram
$\bar{x}(\lambda),\ \bar{y}(\lambda),\ \bar{z}(\lambda)$	Color matching functions
$\Phi(\lambda)$	Spectral power distribution of a stimulus
X, Y, Z	Tristimulus values
X_n, Y_n, Z_n	Reference white
$S(\lambda)$	Relative spectral power distribution of light source or illuminant
λ	Wavelength
u', v'	CIE 1976 chromaticity coordinates
$u'_n,\ v'_n$	CIE 1976 chromaticity coordinates of the reference white
*L**	Lightness of CIELAB
*a**	Redness-greenness of CIELAB
*b**	Yellowness-blueness of CIELAB
$C*_{ab}$	Chroma of CIELAB
h_{ab}	Hue of CIELAB
st	Steradian
cd	Candela
$V(\lambda)$	Luminous efficiency function
Φ	Radiant flux
Φ_v	Luminous flux in photometry
Q	Energy in radiometry
E	Irradiance in radiometry
E_v	Luminous flux density in photometry, illuminance
L	Radiance in radiometry
L_v	Luminance in photometry
lux	$[lm/m^2]$
nit	$[cd/mm^2]$
K_m, k	constant (683 lm/W)
W	Watt

Hz	Hertz
ΔE_{00}	CIEDE2000 color difference
K	Kelvin
$S(\lambda)$	Spectral response in device calibration
$U_T(\lambda)$	Non-calibrated spectral response
$CC(\lambda)$	Calibration coefficients
J	Joule
L, M, S, N	Membership sectors' increment values
α_L, α_M, α_S	Angles between membership sectors
F_{1-4}	Increment weighting factors of chromaticity controlling

1 INTRODUCTION

Today's information flow has created a need for high quality displays. As recently as a few years ago the dominant source of visual information in handheld devices was black-and-white display. The technology of color LCD displays was very immature and not suitable for mobile phones. The first color displays were not designed to present high quality visual information, resolution was poor and the color reproduction capability was low due to small color space. Constantly growing rate of visual information and ability to access it everywhere, as well as mobile phone cameras, have created a need for better displays. And vice versa; at the same time advanced display technologies have made increased information handling possible.

Mobile phones are used more and more in different kinds of environments and certain phone models are profiled to certain kinds of use. For example, there are enterprise phones for business people, sport phones for active lifestyle, life style phones for trendy users, music phones for music lovers and many others. Each phone brings different needs for the display and different use scenarios have different ambient light conditions varying from pitch black to overhead sunshine. To really get trustworthy data and to develop practicable display solutions for real-life use test environment ambient light control was needed to enable testing reproducibility.

The work behind this Master's Thesis was conducted during summers 2006 and 2007 at the Display Laboratory of Nokia Technology Platform's Production Technology which had the unique environment that needed this kind of ambient lighting controlling. The controlling method that this thesis covers was developed by the terms of this specific environment.

By understanding the first chapter the reader should have a picture of the background and targets of this thesis and why it was conducted. The second chapter gathers the needed theory of measured and controlled phenomenon, mostly concentrating on colorimetry. Chapter three clings to the human aspect and gives some boundaries for the controlling procedure itself. At this point the ground for the measured and controlled phenomenon is mostly covered.

Chapter four engrosses into used hardware, environment and equipment. The fifth section is the most essential part, covering the developed light controlling method and exploiting the discoveries of all the earlier chapters. Chapter six has its focus on the implementation of the controlling method described in the previous chapter and chapter seven examines the results of the new light controlling technique.

Chapter eight is all about summarization and nine sets some new targets for further development that aroused during the months of development.

1.1 Background

For a mobile phone manufacturer it is important to be able to compare its own products, competitors' products and suppliers' samples in different lighting conditions. There have been some studies of measuring displays (at least one conducted by Nokia) and at least an equivalent number of technical conditions that determine whether the display will fulfill the performance expectations or not. It is easy to say what makes a perfect display on paper but unfortunately the case is not the same in real life. A potential customer is often not interested in the technical superiority of a display - the first impression, comparison between two samples and a leading position in a certain category and price range is much more crucial. [1]

For most of the end users technical specifications and terms like color gamut, contrast ratio, brightness, color depth and resolution are less relevant. For example the end user could describe wide color gamut and good color depth as *"deep natural colors"*, displays' brightness as *"like a bright star"* and visibility in dark or sunlight as *"very clear"*. The conditions where a display outperforms another are most likely the extreme, not normal office lighting. The users have noted the performance of spearhead phones' displays; *"very easy to read in direct sunlight when the front mounted sensor has turned off the backlight completely"* and *"displays are among the best ones"*. [2] [3] [4]

One important aspect in developing a product that gets this kind of feedback is the possibility to conduct real-environment user studies. To perform this task normal office lighting is not enough, different ambient lighting conditions are needed and it is not feasible to travel around trying to find those conditions. And of course there is limited lab space at Nokia premises, so the most potential solution would be to use one room to reproduce all the needed ambient lighting conditions. We must bear in mind the most fundamental aspect of an experiment as well - repeatability, which in this case means repeatability of same scenarios in different locations during different occasions. All this brings us closer to the goal of this master thesis, described more exactly in chapter 1.2.

1.2 Target

The starting point was an existing test environment called SimOne, which had been used for testing purposes previously. It has also worked as an environment for some public studies and for normal subjective tests like pair comparison, double staircase etc. One of its flaws had been a lack of robust light controlling method with a proper feedback. [5] [6]

One of the profound requirements was that the controlling should be fast, stable, accurate and robust. Also, because the testing environment exists in a few different locations with little different configurations, the controlling should also be somewhat hardware independent and drastic hardware modifications should be avoided. This also gave requirements for repeatability and uniformity in order to make lighting scenarios comparable between different sites.

So the foremost goal of this project was to create a stable and a reliable light controlling method for the testing environment of mobile displays. It should be able to simulate and reproduce various lighting scenarios, for instance vary lighting from a dim indoor lighting to a bright day. Reproducing would be based on metamerism and thus desirable output variables are chromaticity coordinates and illuminance Controlling should be made real-time with feedback from the light measurement device in order to adjust variations in the lighting conditions, compensate possible external light sources and correct the lighting intensity instability caused by the thermal effects of the light sources itself. Because the users would be people ranging from novices to experts, a humane approach should be kept in mind. Repeatability, stability, speed, robustness, accuracy and uniformity of the lighting could be called the key figures.

The environment itself had a prior controlling solution based on a non-real-time pre-calibrated method which bound the measurement device into one specific spot and did not take into account external lighting, variations in the environment itself and the thermal effect of the lamps. Because of these flaws the old implementation was not fully working nor used when designing of the new solution started. There were no proposals for the new controlling method, only a baseline how well it should perform, which was more or less robustness, reliability and accuracy.

In the early state the target of this thesis formed to cover the development of a new controlling method for both chromaticity and luminance controlling using user selectable lamps. When controlling only illuminance it was clear that a classic PID-controller with a proper feedback would be enough, but for chromaticity controlling there were no prior solutions. The new evolved controlling method, which is fully described in chapter 5, is based on an idea of measuring each lamps color coordinate one at a time and placing them into a two dimensional chromaticity diagram where they would be perceived as '*gravity points*'. The feedback would come from a light measurement device and the prevailing illumination be controlled according to selected measurement point, which generally would be the table level but could be whatever spot in the environment - eye level, for example.

All in all this thesis covers the evolution of this new ambient light controlling method, and the backgrounds, implementation, performance testing and future development of said method.

2 MEASURED PHENOMENON

As light has been studied over decades and its visible part is an everyday phenomenon we should give a short introduction to light itself. Being a part of electromagnetic radiation we mostly comprehend light as a sensation that is formed by eye, thus meaning the visible part of it, which is a very narrow band of the electromagnetic spectrum as can be seen in Figure 2-1. Considering this thesis' controlling point of view I willfully bypass different light theories and entrust those to reader's hobbyism.

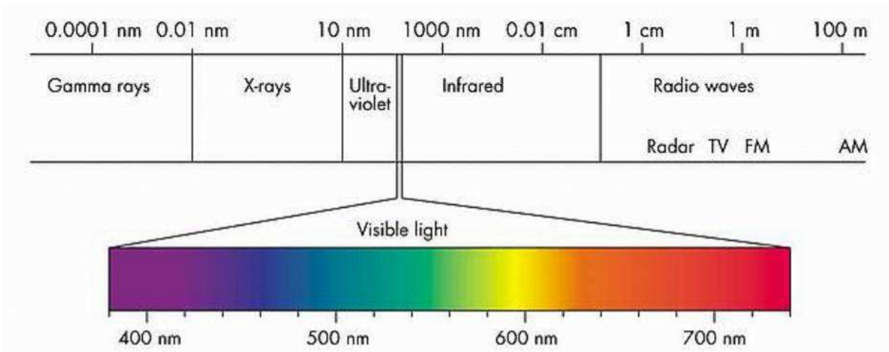

Figure 2-1. Electromagnetic spectrum [7]

At the end the prime measured phenomenon in this work is the color and the intensity of illumination. To measure those and to utilize the measurements the basic theory behind color appearance should be familiar. Fortunately this part of the theory is exceedingly studied compared to light controlling. The emphasis is on *colorimetry* but *radiometry* and *photometry* will pave the way.

2.1 RADIOMETRY

Radiometry studies the whole optical radiation spectrum, the electromagnetic radiation between the frequencies $3*10^{11}$ and $3*10^{16}$ Hz which means wavelengths range from 0.01µm to 1000µm. Every system has a response which is calculated by multiplying the spectral energy distribution with the system's optical response curve. When the system is the human eye and the optical response curve is the spectral response of the eye the step from radiometry to photometry is taken. [8] [9]

Even though this thesis stays strictly in the visible area of light some radiometric units should be made familiar.

Energy which is measured in joules [J] is an SI-deriver unit. The symbol for it is *Q*. When energy is derived with respect to time we get *power*, also known as *radiant flux*, which is also an SI-derived unit. The symbol of power is Φ and unit is watt [W] (J = Ws). It simply defines how much energy arrives to a surface in a certain time without specifying the size of the surface. Normally Φ is used for continuous and *Q* for pulse-like radiation sources. [8] [9] [10]

Irradiance E is power (radiant flux) per unit surface area when radiation uniformly distributed over the surface, unit of irradiance is Wm^{-2}. [8] [9] [10]

$$E = \frac{d\Phi}{dA} \qquad (1)$$

Radiant intensity's symbol is I and it is defined as radiant flux per unit solid angle, unit of radiant intensity is Wsr^{-1}. [8] [9]

$$I = \frac{d\Phi}{d\omega} \qquad (2)$$

Radiance's symbol is L and its unit is $Wsr^{-1}m^{-2}$. In common sense it expresses the quantity of power arriving (or leaving) into a surface at a certain point per a solid angle ($d\omega$) per unit projected area ($dA\cos\theta$), θ is an angle between a certain direction and surface's normal. [8] [9] [10]

$$L = \frac{d^2\Phi}{d\omega dA\cos\theta} \qquad (3)$$

2.2 PHOTOMETRY

As stated earlier the line between radiometry and photometry is thin, while radiometry has a broader concept photometry can be seen as a "sub module". The obvious reason behind why photometry has developed into a field of its own is the fact that it covers the area where the human eye is involved. [8] [9]

Photometry's wavelength range is limited to the visible part of light, approximately between 360 and 830 nm. The spectrum of the light is also weighted with the standard observer's spectral response curve also known as the spectral luminous efficiency function. Two different efficiency functions exists, one for photopic and one for scotopic vision, these vision types are discussed more closely in Chapter 3. In this case the photopic luminous efficiency function $V(\lambda)$ in Figure 2-2 is sufficient. These two discrepancies and little different symbols and units are the only characterizing features between radiometry and photometry. [8] [9] [11]

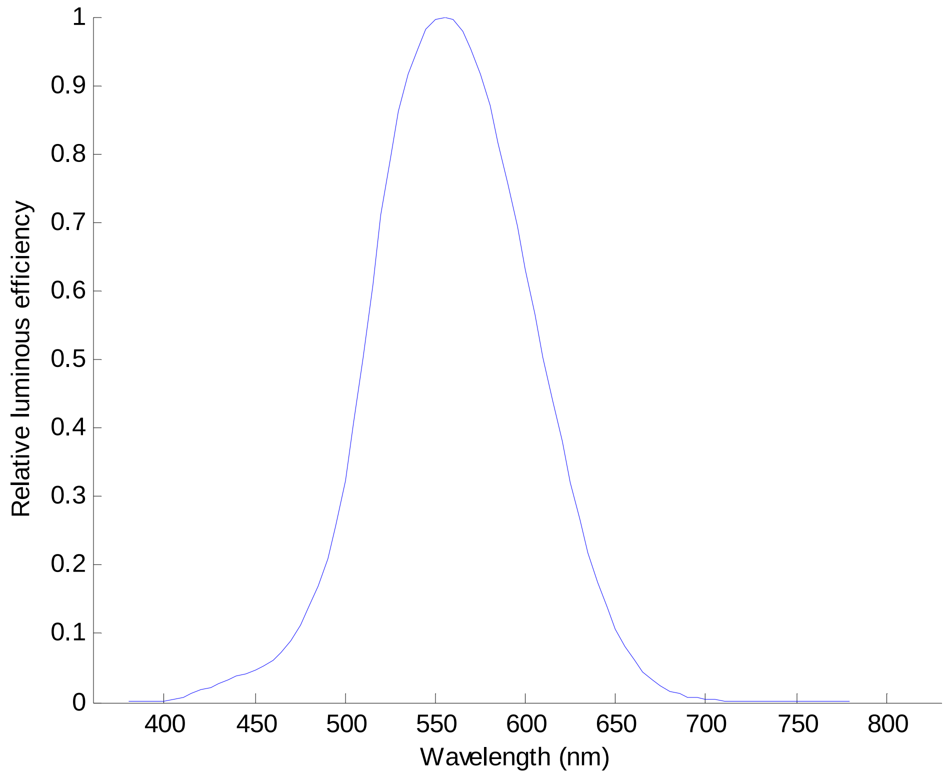

Figure 2-2. Photopic luminous efficiency function [12]

The first photopic luminous efficiency function was established by CIE system of photometry in 1924, in year 1990 it was updated because the weight of higher blue response was not enough. [12]

Because the difference between photometry and radiometry is limited to the weighting function the radiometric equations are alike relevant in photometry. Only the symbols and units differ, the photometric symbols have lower index *v* to denote visual light. The SI unit for light is candela and its name reveals its origin, a candle. It has had different definitions but according to Optical society of America the present is defined by BIPM as follows: *"The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency* $540 * 10^{12}$ *Hz and that has a radiant intensity in that direction of 1/683 W/sr"*. [9]

Luminous flux is photometric equivalent to radiant flux weighted with luminous efficiency function, its symbol is Φ_v and unit lumen [lm]. Lumen is derived from candela and is defined as a luminous flux emitted into solid angle of 1 sr having a luminous intensity of 1 cd. Equation 4 is used for luminous flux calculation. [9]

$$\Phi_v = K_m \int_o^\infty \frac{d\Phi(\lambda)}{d\lambda} V(\lambda) d\lambda, \tag{4}$$

where K_m is a constant 683 lm/W.

From this study's point of view the SI-derived unit *luminous flux density*, which is irradiance weighted with luminous efficiency function, is maybe the most interesting. More commonly the luminous flux is known as illuminance marked with symbol E_v and unit lm/m^2. It also has a special name *lux* (as a unit and as a symbol). Because light measurement devices measure lux it is very important in light engineering and later on we will use this abbreviation a lot. Also *lux* will be one of the three controlled variables. [9]

The final one of these photometric units is *luminance* of which symbol is L_v and unit cd/m^2 or $lm/m^2/sr$. It should be observed that luminance has a nickname *nit*, although its usage is discouraged here and elsewhere the reader may encounter it while working on a field of photometry. Luminance is most commonly used in the context of flat emitting surfaces, like displays, to characterize the brightness. [1] [9]

2.3 COLORIMETRY

Both color as a term and color as a visual perception are very mundane concepts. One of the most common questions asked by children is *"what is your favorite color?"* Everyone has his or her opinion on different colors in different occasions, how to define what is red or what is yellow. Sometimes it is not just an opinion but the sensitivity curves can also vary. Color is not a physical magnitude, if it was, photometric theory would be enough and colorimetry would be useless.

The fundamental goal of this thesis and requirements behind it is an ability to reproduce desired illumination of certain intensity and color, thus forming a sensation for a human observer. In order to achieve this we must know what color to aim at and how to measure the current state colorimetry refers to this measuring of color. According to Wyszecki basic colorimetry defines whether two lights with different spectral power distributions produce the same color effect. This phenomenon is called metamerism which is dealt more closely in chapter 2.3.7. [11] [13]

2.3.1 Illuminants and black body radiators

When a spectral power distribution of a light source is under examination we speak of spectroradiometry. A spectral power distribution is a simple representation which consists of radiometric quantity as a function of wavelength. Radiometric quantities of different light sources vary significantly, and because absolute level does not influence to the chromaticity calculation the spectral power distribution is often normalized. Traditional approach of normalization is to scale the value of wavelength 560 nm to 1.0 or 100, however there is no specific defined normalization method. One custom which is also used in some parts of this thesis is to normalize the maximum value to match 1.0. Despite the method, after normalization we can speak of relative spectral power distribution which is dimensionless. [11][14]

There is also a special type of theoretical light sources known as *black-body radiator* or *Planckian radiator* which are situated along *Planckian locus*. These radiators are perfect emitters of energy emitting it only due to thermal excitation and the value is thus reported in absolute temperature (Kelvin, K). When the temperature of the black body increases the emitted energy shifts toward shorter wavelengths. A color temperature itself defines the spectral power distribution (and the color via it) by Planckian equations as a function of a single variable. Because perfect black-body radiators seldom exists, correlated color temperature (CCT) is introduced. CCT of a lights source is simply a temperature of a black body radiator whose perceived color most closely resembles the light source. Although CCT can be calculated for any light source only colors near the Planckian locus make some sense. Color temperature itself is widely used in photography and other practical real-life applications, because real world emitters normally have a correlating color temperature. Because of this, and the fact that Planckian locus encompasses quite a broad color range from red to blue, different color temperatures are implemented as lighting scenarios later on. [11] [14]

2.3.2 Visual response

Because the spectrum itself does not tell everything about the perceived colors it must be calculated using the spectral tristimulus values of the CIE 1931 standard colorimetric observer, functions can be seen in Figure 2-3 and the equations later. Even though CIE provides tristimulus values with seven significant digits at 1 nm intervals and between 360-830 nm, for practical applications (like in this case) it is feasible to cut the range from both ends, resulting to 380-800 nm. Extreme values are insignificant from color sensation point of view, add unnecessary calculation and can reach outside the wavelength range of measurement devices. These functions are experimental, based on the assumption of trichromatic nature of the human eye, but still CIE has defined only agreed metrics for color measurement. The function of a human eye is described more closely in chapter 3.1. It must be noted that CIE has also established other color matching function, CIE 1964 supplementary standard colorimetric observer, also known as *10° observer* which was constructed using 10° visual field. Hence forth everything in this thesis related to color matching functions deals with CIE 1931 2° observer and 10° is totally left out. [1] [11] [15] [16]

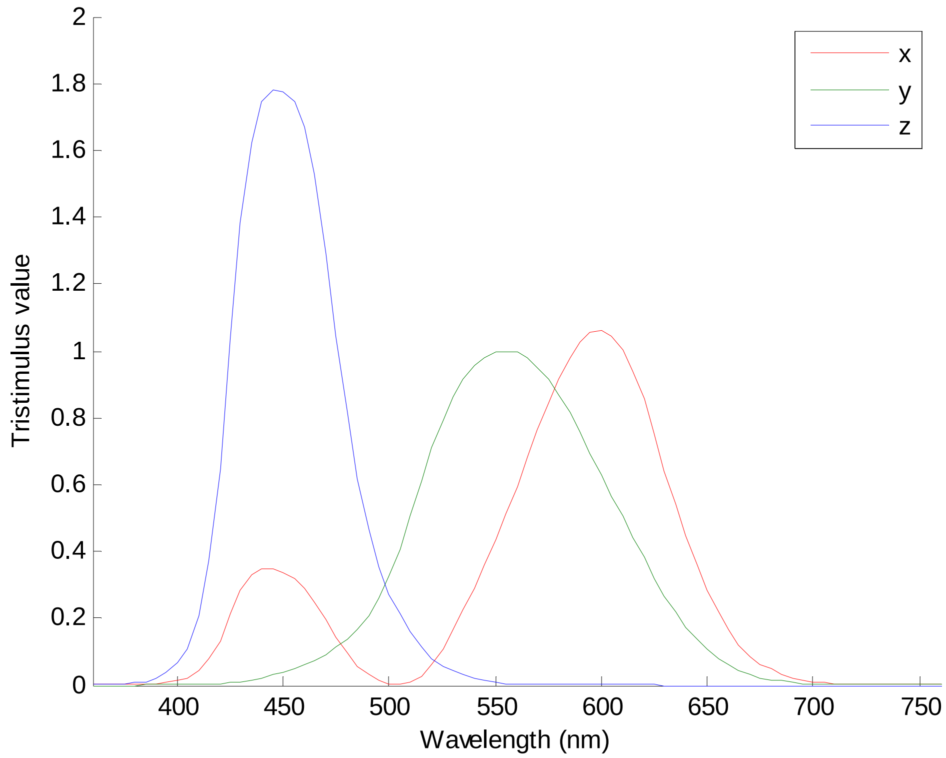

Figure 2-3. Spectral tristimulus functions of the CIE 1931 standard colorimetric observer (2°) [15]

CIE 1931 XYZ tristimulus values are calculated using Equations 5-7. In these equations k is a normalizing constant, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the color matching functions seen in Figure 2-3, and $\Phi(\lambda)$ is the spectral power distribution of the stimulus. The CIE defines that when calculating tristimulus functions wavelength λ is from 360 nm to 830 nm in 1 nm increments. But as noted before, in this case implementation is made with wavelength range from 380 to 800 nm in 1 nm increments. [11] [15]

$$X = k\int_{\lambda} \Phi(\lambda)\bar{x}(\lambda)d\lambda \qquad (5)$$

$$Y = k\int_{\lambda} \Phi(\lambda)\bar{y}(\lambda)d\lambda \qquad (6)$$

$$Z = k\int_{\lambda} \Phi(\lambda)\bar{z}(\lambda)d\lambda \qquad (7)$$

The normalizing constant k used in equations 5-7 is defined differently for relative and absolute colorimetry. In absolute colorimetry in order to make the system compatible with photometry k = 683 lm/W. For relative colorimetry k is calculated from equation 8, where $S(\lambda)$ is the relative spectral power distribution of the light source or illuminant. [11] [15]

$$k = \frac{100}{\int_{\lambda} S(\lambda)\bar{y}(\lambda d\lambda)} \quad (8)$$

For relative colorimetry this results tristimulus values from 0 to 100.

2.3.3 Interpolation, extrapolation and smoothing of spectrum

Hence we will use a term *optical resolution* to characterize a resolution of wavelength axis, *interval* to define a distance [*nm*] of measurement points and *A/D resolution* to define detector's resolution in each point. Because the optical resolution of used color matching data is 1 nm the best practice would be that the measured spectral radiance data would have the same optical resolution. Unfortunately in reality spectrometers have different optical resolutions and different wavelength ranges. For instance Ocean Optics' USB2000 spectrometer has ~0.44 nm and USB4000 ~0.25 nm optical resolution and some devices' optical resolution is poorer than color matching data's. To solve this problem different solutions are possible. For example, we could use nearest neighbor interpolation method for spectrometer data. This means simply that for each color matching function's wavelength value we would use the nearest spectrometer value. This method has its risks because some lamps' spectrums have very sharp peaks, narrower than few nm (for example RGB lamps seen in Figure 2-8). This is why the nearest neighbor could hit or miss these peaks thus distorting the result. In order to remove this phenomenon spectral radiance data should be averaged to 1 nm optical resolution. Also because natural spectra and the tristimulus functions are smooth averaging represents the reality better. In equation 9 I_λ is the average intensity around wavelength λ and I_i are the *n* intensity values of the spectrometer data which fit to the ± 0.5 nm range. [16] [17] [18]

$$I_\lambda = \frac{1}{n} \sum_{i=\lambda-0.5}^{\lambda+0.5} I_i \quad (9)$$

On the other hand, if spectrometer's data has optical resolution smaller than 1 nm linear interpolation method is used to find the corresponding value from the color matching data. [16]

If the spectrometer wavelength range is less than 380-800 nm, for example 400-700 nm, the data must be extrapolated. However, because extrapolation is risky and the color matching function has very small values at the both ends CIE recommends to use most extreme data. In practice this means that the data after 700 nm would have same value as 700 nm had and it would be generated using same optical resolution as the color matching data. [16] [19]

2.3.4 Chromaticity diagrams…

As stated earlier the human interprets colors as an overall response to three channels, known as the trichromatic theory of color vision. If the functions for CIE 1931 standard colorimetric observer are used the calculations will produce three values; X, Y and Z. To present these coordinated a three dimensional tristimulus space would obviously be needed. To provide a two dimensional representation, the chromaticity diagram, they have to be normalized and luminance information removed. Equations 10-12 are needed to calculate CIE 1931 chromaticity coordinates and Figure 2-4 illustrates values plotted to a diagram. [1] [8] [11]

$$x = \frac{X}{X + Y + Z} \quad (10)$$

$$y = \frac{Y}{X + Y + Z} \quad (11)$$

$$z = \frac{Z}{X + Y + Z} \quad (12)$$

Equation 12 above is however unnecessary when calculating CIE 1931 chromaticity coordinates. Even though value *z* is lost, it can also always be recalculated by noting that the *x*, *y*, and *z* always sum to unity. [8] [11]

$$x + y + z = 1.0 \quad (13)$$

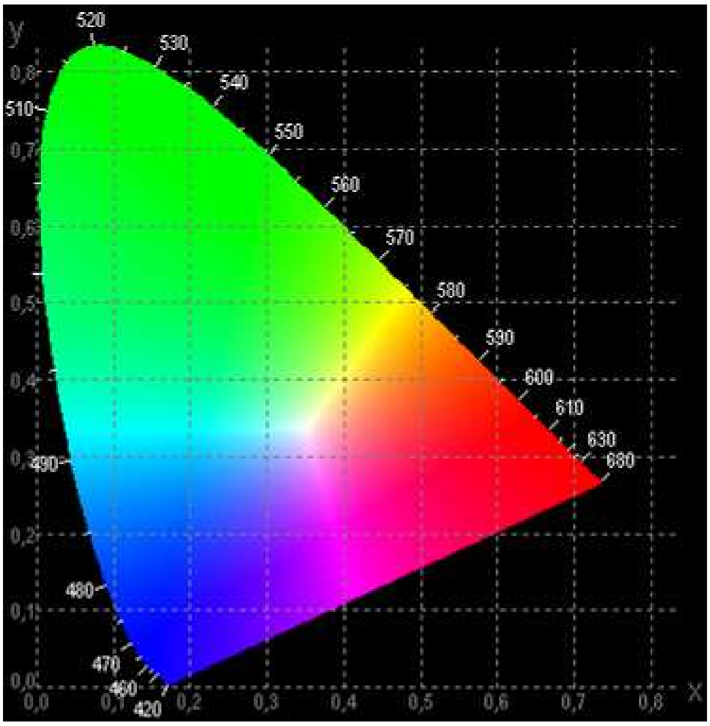

Figure 2-4. CIE 1931 chromaticity diagram [20]

Because chromaticity coordinates have only two variables commonly tristimulus value *Y* is reported among with coordinates *x* and *y*. Tristimulus value Y is chosen since it represents the luminance information of the stimuli. This comes very relevant when we try to control the chromaticity and the luminance separately using geometrical approach in order to acquire a certain color. This is described later more closely in chapters 5 and 6. [11]

According to Saarelma one reason behind removal of one color space's dimension may underlie in the year 1931. More than 70 years ago measured color was usually the reflection of a certain surface, color television and LCD panels were not even under development. A surface reflects a specific amount of light in every lighting condition and does not change while illumination intensity changes. For example, a paper sheet is as relatively bright under sunlight as it is under an incandescent lamp. [8]

Basic CIE 1931 has other flaws too. The target has been that a fixed numerical distance in *xy*-diagram should respond to equivalent visual color difference. The smallest detectable color difference should form a circle with a certain radius no matter what the *x* and *y* coordinates were. Unfortunately the reality is not even close to that, tolerances are different kind of ellipses for different colors. For basic CIE 1931 chromaticity diagram those are called MacAdam's ellipses (seen in Figure 2-5). [1] [8]

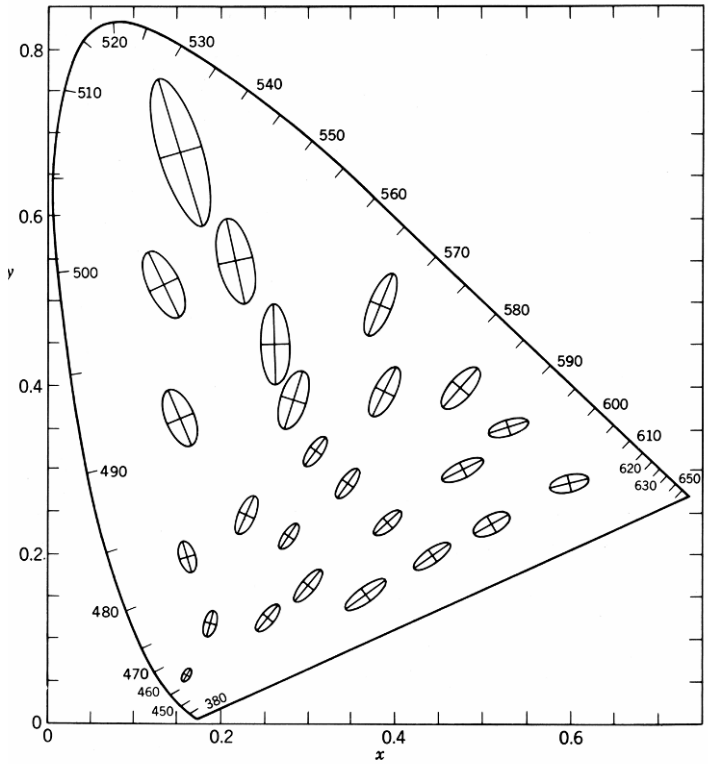

Figure 2-5. MacAdam's ellipses are experimental values that represent the smallest perceivable difference for a standard observer. Ellipses are 10 times their actual size. [14]

From a controlling point of view this non-uniformity is very unfortunate. In order to use chromaticity coordinates as controlling or tolerance values it is crucial that the visual and the numerical equivalency is maintained for different colors. That's why certain improvement for CIE 1931 has been made. For chromaticity diagrams there is CIE 1976 Uniform Chromaticity Scale (UCS) diagram (hence abbreviated CIE 1976) whose general use is recommended by CIE. For color spaces there are the CIELUV and the CIELAB which take adaptation (light/dark and chromatic) into account, those are described more closely in chapter 2.3.5. Equations 14-15 are the CIE 1976 equations. [1] [8] [11]

$$u' = \frac{4X}{X + 15Y + 3Z} \tag{14}$$

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

The CIE 1976 diagram is stretched so that the MacAdam's ellipses come closer to circles of equal radius, using it can better chromatic uniformity compared to CIE 1931 be achieved. This makes the CIE 1976 more suitable for light controlling. Diagram itself can be seen in Figure 2-6.

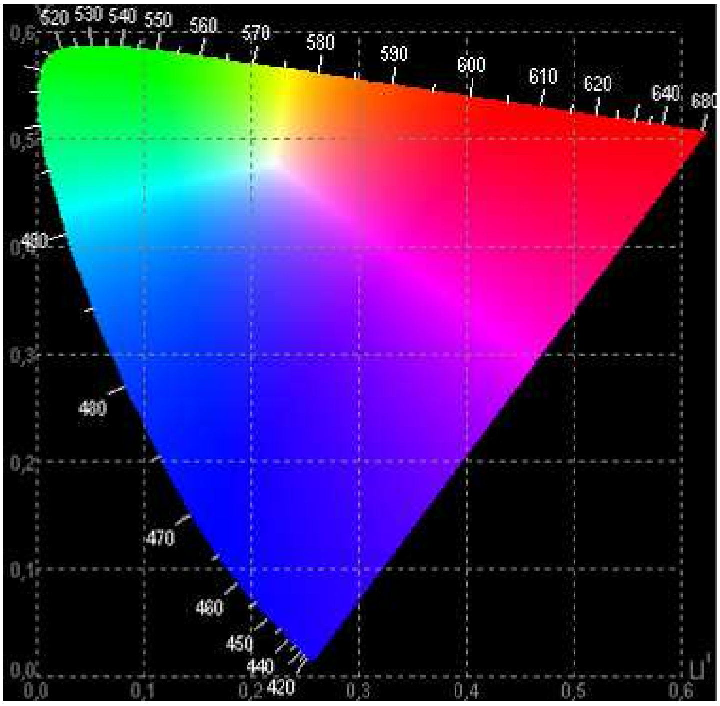

Figure 2-6. CIE 1976 chromaticity diagram [20]

2.3.5 *…and color spaces*

The use of color spaces over chromaticity diagrams is well justified because an idea of representing a three dimensional phenomenon in two dimensions is quite unrealistic. As mentioned earlier the main goal to develop these spaces was to find a way how to measure color differences. It is the same reason why we use these, to determine whether the target is reached or lost while the controlling of color is done in chromaticity diagram. Most common color spaces, both developed in year 1976 and based on the complementary color theory, (aka. the opponent-colors theory) clarified in chapter 3.1, are CIE 1976 (L* u* v*) (hence abbreviated CIELUV) and CIE 1976 (L* a* b*) (hence abbreviated CIELAB). Because CIEDE2000 color difference formula is based on CIELAB it makes CIELUV unnecessary from this thesis' point of view and it will be willfully left out. [1]

The CIELAB equations 16-18 are used to construct a Cartesian color space seen in Figure 2-7. [11] [21] [22]

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16 \tag{16}$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \tag{17}$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right], \tag{18}$$

where

$$f(I)=\begin{cases} I^{1/3} & ;I > 0.008856 \\ 7.7871+\dfrac{16}{116} & ;I \le 0.008856 \end{cases} \tag{19}$$

In equations 16-18 $L*$ is lightness, $a*$ is redness-greenness and $b*$ yellowness-blueness. X, Y and Z are the tristimulus values of the current stimuli and X_n, Y_n and Z_n are the tristimulus of the reference white, also known as the white point where the chromatic adaptation is at the moment. To form the reference white the values of it are scaled according to that Y_n = 100, this is fairly reasonable when we think $L*$ as the lightness extending from black to white (0 – 100). [11] [21] [22].

There are a few more equations (20-21) which alongside with $L*$ are needed to form a cylindrical representation of the same color space.

$$C*_{ab} = \sqrt{\left(a*^2 + b*^2\right)} \tag{20}$$

$$h_{ab} = \tan^{-1}\left(\frac{a*}{b*}\right) \tag{21}$$

Where $C*_{ab}$ is chroma and h_{ab} hue. Equations 20-21 are also needed later on when calculating the CIEDE2000 color difference if chapter 2.3.6. [8] [11] [14] [21] [22]

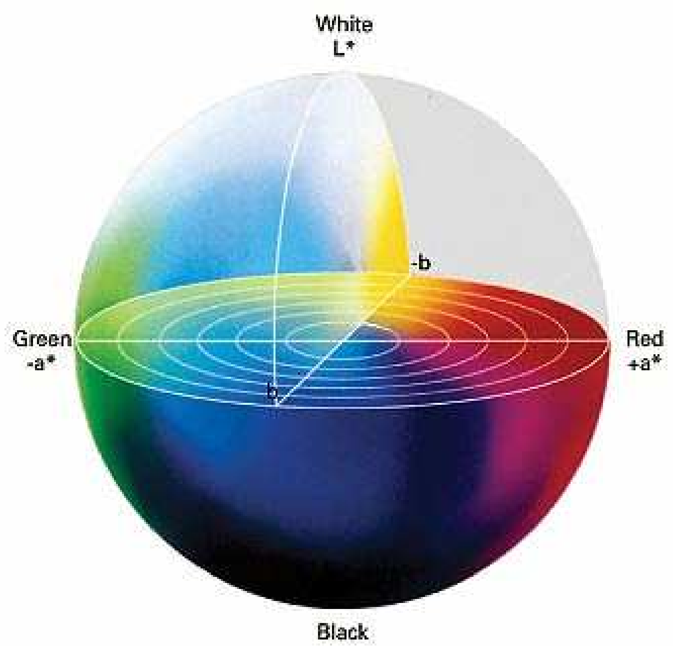

Figure 2-7. CIELAB color space [23]

These partially correct the problems occurred with CIE 1931 even they are not completely distortion-free. Both the CIELUV and the CIELAB are so called rubber sheet operations where the coordinates are stretched, however this fact does not reduce their usability. [8] [11] [21] [22].

2.3.6 Color difference

As stated earlier when perceived color difference is the case a two dimensional chromaticity diagram is not sufficient, color appearance is a three dimensional phenomenon where luminance is also present. The aim of developing color difference models was that one unit geometrical difference in any location should give a corresponding perceived color difference, the space should be uniform. Unfortunately CIELUV and CIELAB equations did not perform sufficiently, which led to the evolution of the CIEDE2000 color difference formula based on CIELAB. [8] [21]

The CIEDE2000 was adopted by CIE as the new color-difference equation in 2001. Besides including lightness, hue and chroma it also performs better in the blue and the gray region. Even though equations of CIEDE2000 are substantially more complex than a straight geometrical distance in the CIELAB color space its effectiveness and CIE recommendations make it the most suitable in this case also. The progress of the CIEDE2000 is gone through step by step in equations 22-41 where the goal is to achieve the color difference ΔE_{00}. [21]

Step 1. Calculate CIELAB *L*, a*, b* and C** as done in equations 16-21.

Step 2. Calculate *a', C' and h'* as follows:

$$L' = L^* \tag{22}$$

$$a' = (1+G)a^* \tag{23}$$

$$b' = a^* \tag{24}$$

$$C' = \sqrt{a'^2 + b'^2} \tag{25}$$

$$h' = \tan^{-1}\left(\frac{a'}{b'}\right), \tag{26}$$

where

$$G = 0.5\left(1 - \sqrt{\frac{\overline{C^*_{ab}}^7}{\overline{C^*_{ab}}^7 + 27^7}}\right) \tag{27}$$

where

$$\overline{C^*_{ab}} = \frac{(C^*_{ab})_1 + (C^*_{ab})_2}{2} \tag{28}$$

Step 3. Calculate $\Delta L'$, $\Delta C'$ and $\Delta H'$ as follows:

$$\Delta L' = L'_b - L'_s \tag{29}$$

$$\Delta C' = C'_b - C'_s \tag{30}$$

$$\Delta H' = 2\sqrt{C'_b\, C'_s}\,\sin\left(\frac{\Delta h'}{2}\right) \tag{31}$$

where

$$\Delta h' = h'_b - h'_s \tag{32}$$

Step 4. Calculate CIEDE2000 ΔE_{00}:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)} \tag{33}$$

where

$$k_L = k_C = k_H = 1 \tag{34}$$

$$S_L = 1 + \frac{0.015\left(\overline{L'} - 50\right)^2}{\sqrt{20 + \left(\overline{L'} - 50\right)^2}} \tag{35}$$

$$S_C = 1 + 0.045\overline{C'} \tag{36}$$

$$S_H = 10.015\overline{C}T \tag{37}$$

where

$$T = 1 - 10.17\cos\left(\overline{h'} - 30°\right) + 0.24\left(2\overline{h'}\right)$$

$$+ 0.32\cos\left(3\overline{h'} + 6°\right) - 0.20\cos\left(4\overline{h'} - 63°\right) \tag{38}$$

$$R_T = -\sin(2\Delta\theta)R_C \tag{39}$$

where

$$\Delta\theta = 3\exp\left\{-\left[\frac{\overline{h'} - 275°}{25}\right]^2\right\} \tag{40}$$

$$R_C = 2\sqrt{\frac{\overline{C}'^7}{\overline{C}'^7 + 25^7}} \tag{41}$$

Even though we now have the formula to calculate the color difference we still need the tolerance for the numerical value, after which we can speak of Just-Noticeable Difference (hence abbreviated JND). JND is a unit that states whether the difference of two stimuli is noticeable. In paired comparison of two stimuli with JND of 1 stimulus will be separable by 75% of observers. Fortunately the ΔE_{00} is meant to give the value of JND, $1JND \cong 1\Delta E_{00}$, so by that we get some real-life interpretation for color difference equation's output. Now we must emphasize that in the ambient light controlling case we are not speaking of pair comparison because there is no point of comparison for the viewer. This will give more loose tolerances for the controlling. [1] [11] [21]

The reason why CIEDE2000 deserves this much visibility is the logic behind when the target can be considered as achieved. It also works as a switch when deciding whether chromaticity or luminance has a greater affect on the perceived color difference. These are dealt more closely in chapter 5.

2.3.7 Metamerism and reproducing colors

As the underlying concept of this thesis is to reproduce a certain perceived color using different lamps without a need to reproduce the spectrum, it all comes down to *metamerism*. As stated earlier when any number of color stimuli with different spectral power distribution produce a same tristimulus value those stimuli are *metamers*. [14]

Almost everyone has faced metamerism, for example while comparing two pieces of cloth under a light of a clothing store. The color of those two clothes might have been a perfect match but when taken outside the colors can be totally different; indoors those formed a metameric pair but outdoors not. Normally metamerism is formed by three components; a light source, a reflecting surface and an observer. In this scenario we will rule out the reflecting surface and use a spectrometer with wavelength range reaching over the visible spectrum as a "perfect" observer, in other words examine the light source itself. [11] [14]

The actual case why metamerism is so interesting from this thesis' point of view is RGB lamps of the test environment. The idea of those is to be able to produce any color inside the existing color gamut of the RGB lamps by combining the right amount of each color; saturation makes these lamps more versatile than others but also means a spiky spectrum as seen in Figure 2-8. It must also be highlighted that the lamps do not necessarily have to be RGB lamps, any lamps can be used as long as the target fits inside the color gamut constructed by those. [11] [14]

The color gamut, hence referred as the gamut, itself means a certain subset of colors that can be represented by a certain output device, in this case by SimOne lamps. The gamut is explained more closely in Chapter 5.1.1 and illustrated in Figure 5-2. [11] [14]

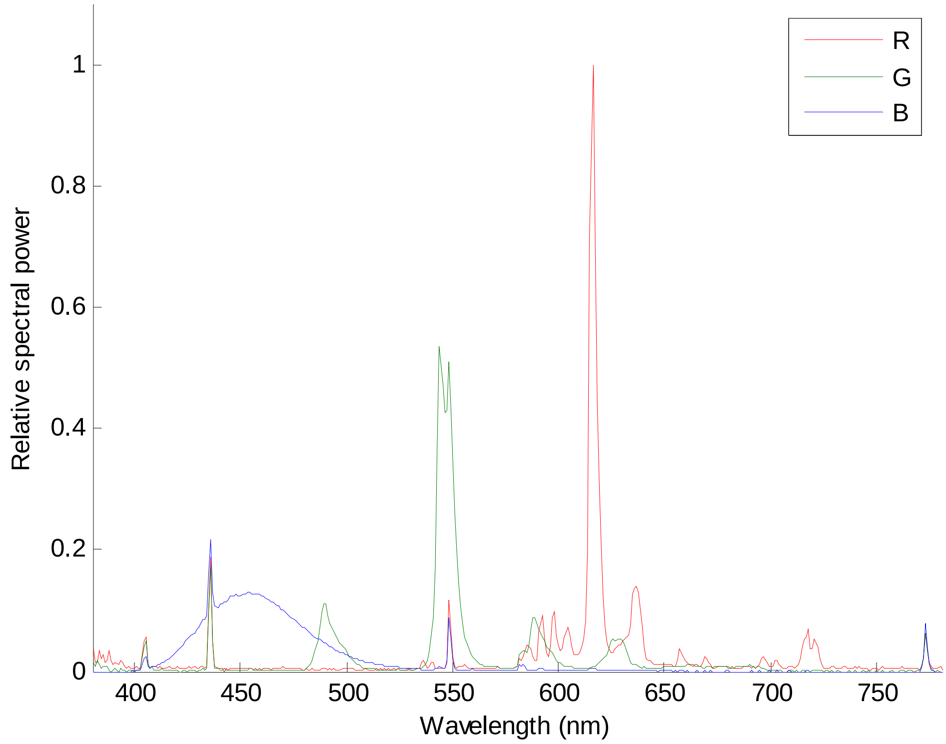

Figure 2-8. The relative spectral power distribution of RGB lamps used in SimOne

The mathematical explanation of metamerism can be understood by examining equations 5-7, while the spectral radiance is weighted with the CIE 1931 tristimulus functions we can have infinite number of different spectral radiances which all construct the same tristimulus values X, Y and Z. In Figure 2-9 two different relative color stimuli that produce the same chromaticity coordinate as an equal energy spectral power distributor are seen(in the CIE 1931 x = 1/3 and y = 1/3). All stimuli, except the equal energy, are created and measured in the SimOne test environment. The first one is constructed adjusting only the RGB lamps and the second by using an external halogen alongside with the RGB lamps, the third is the equal energy spectrum. [14]

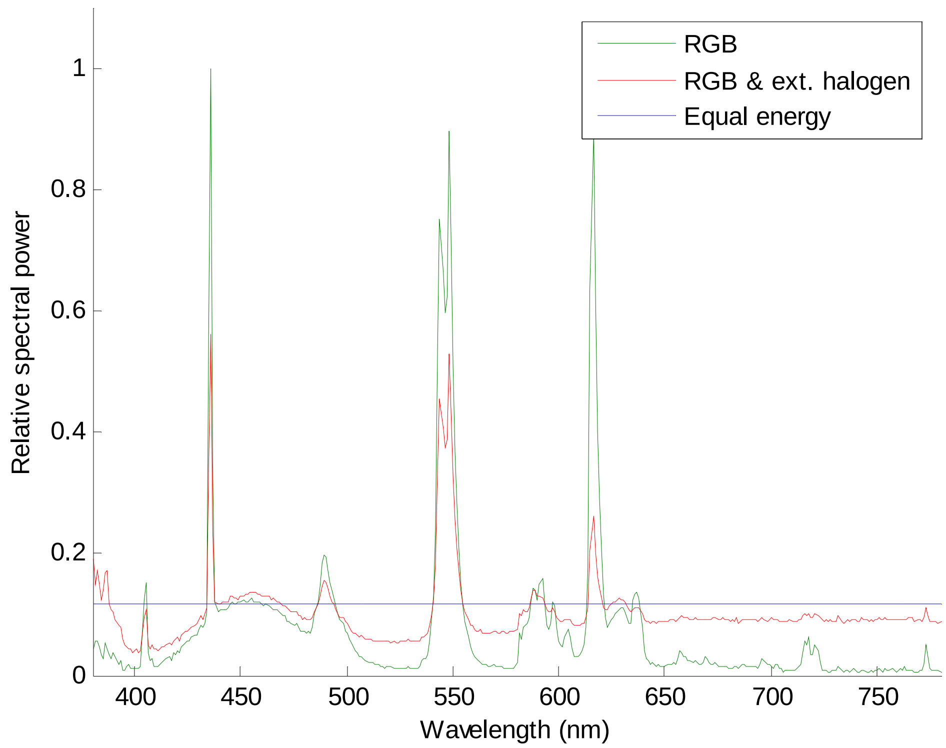

Figure 2-9. Three different relative color stimuli that are metamers

This reveals a bit of the logic how the wanted chromaticity coordinate and illuminance level is reached in the testing environment. The scenarios in Figure 2-9 were actually real-life scenarios and were constructed by using the controlling software itself by only giving the wanted target.

3 HUMAN VISUAL CAPACITY

Human vision has a notable role in this thesis and it is easy to understand why. Because the underlying purpose of this light control system is to serve persons in real-life test situations the human visual capacity must constantly be kept in mind. It also gives some boundaries and limitations for the controlling: when the target could be considered reached, when lost, how long are the adaptation times and so forth. Most of these black spots will be covered in chapters 2.3 and 5.1, but not from the human vision point of view. Also the physiology of human vision deserves closer examination.

3.1 Human vision

Human vision's simplified model can be seen as an optical system where sensor, known as the eye, is linked to the processors, the brain, where the color appearance takes place. Because all the issues concerning colors used in this thesis are formed from the basis of human vision it is essential to know the most basic functions of it. I willfully bypass most of the anatomy of the human eye (seen in Figure 3-1) and only ponder human vision from perception's viewpoint.

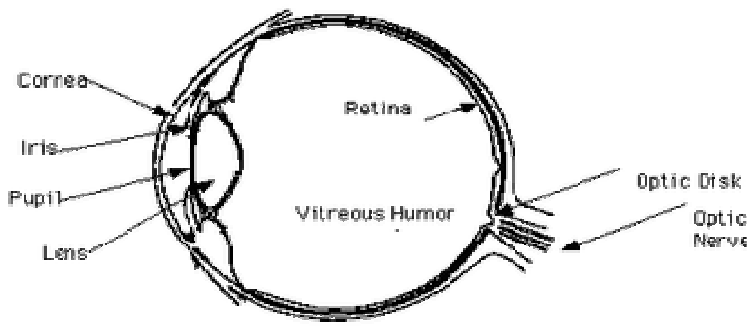

Figure 3-1. Anatomy of the eye [25]

Basically the human eye can see electromagnetic radiation's wavelengths approximately between 360 nm and 830 nm, known as the light. The cornea, the iris, the pupil and the lens together form the optics of the eye, more or less in the same way as camera lens. From these four the iris has a hole in the middle of it, known as the pupil, through which light passes to the retina. The pupil has its own part in adaptation, which is dealt more closely in chapter 3.2. From color appearance point of view the retina, the fovea and the optic nerve are more important. [11] [15] [24]

The retina is the surface where the optical image formed by the front of the eye is projected. The retina has photosensitive cells which transform the optical image to signals that can be transmitted to the brain via the optic nerve. The fovea is a structural area of the retina where we have the most effective color and spatial vision and it covers approximately two degrees of total visual angle. It is not a coincidence that the CIE 1931 standard colorimetric observer is also defined for the 2°. [11] [15] [24]

What interests us more are the photoreceptors in the retina, known as rods and cones. In one eye there are approximately 100 million rods and 6 million cones and only 1 million nerve fibers. Because of this ratio some visual information is already lost before it reaches the brain. The rods activate when illuminance level is low and cannot sense colors at all. Whereas there are three types of cones (long, medium and short) while each of them is sensitive to certain wavelengths, generally red, green and blue. In the brain the ratio of these three signals is combined to form the color appearance. This phenomenon is known as the trichromatic color theory. Any color can therefore be reproduced using these three basic colors. [11] [24] [25]

The perceived color of the light is not physically computable from the spectrum but a subjective perception, so it must be done using a standard observer tristimulus values introduced earlier in Figure 2-3. The color vision is an individual trait while some people by comparison distinguish hundreds of thousands of colors the number for others can be significantly lower. The proportion of people with different color defectiveness for men is approximately 8% and for women 0.43%. [8] [26]

In spite of all there is another theory in addition to the trichromatic known as the opponent-colors theory, which was introduced by a German physiologist Ewald Hering. He stated that the three receptors were bipolar and responded to red-green, yellow-blue and light-dark. The fundamental idea was that a color perception is never reddish green or white and black. [27]

Hering’s theory did not achieve fully acceptance and it was more or less undervalued until the middle of 20th century when the modern opponent theory of color vision started to form. Because the CIELAB color space is based on this theory it is well justified to give attention to it as well. The three signals formed by long-wavelength (L), medium-wavelength (M) and short-wavelength (S) cone cells are not transmitted directly into the brain. The neurons of the retina encode these three signals to the opponent signals which can be summed (L+M+S) to produce the photopic luminous efficiency function $V(\lambda)$, when each factor is weighted with the relative portion of each cone type. The chromatic responses are constructed by separating these signals (red-green = L-M+S and yellow-blue = L+M-S). This procedure is also illustrated in Figure 3-2. [11]

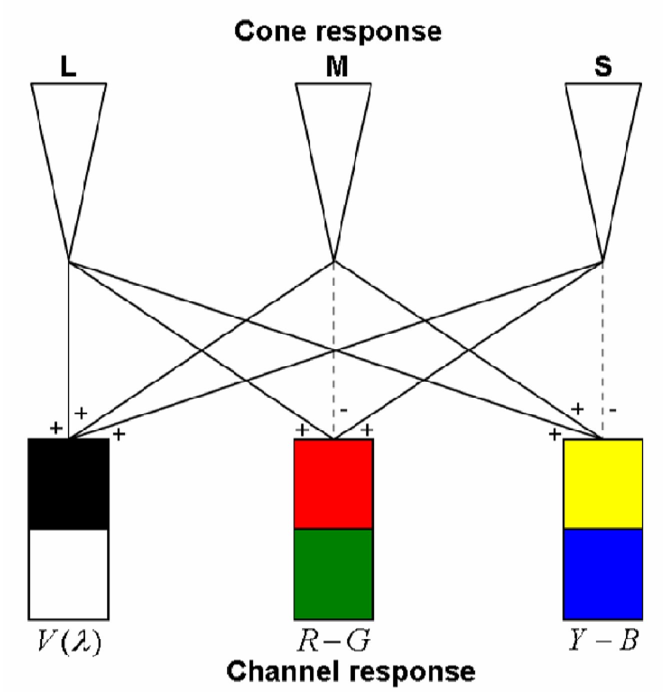

Figure 3-2. Illustration of the opponent-colors theory [11]

3.2 Adaptation

Adaptation is an ability to change the visual sensitivity to a stimulus, the response to changed stimulation conditions. Adaptation does not just mean dilatation and constriction of a pupil (Figure 3-1), because its capacity (diameter between about 3 and 7 mm) is not sufficient for normal lighting conditions. Therefore some of the adaptation must be produced by neural mechanics. According to Mark D. Fairchild the most crucial adaptation mechanisms ranging from sensory to cognitive are the following: [11] [28]

- Pupil dilation / constriction: The pupil is a hole in the middle of the iris. It has a capability to dilate and constrict from ~3mm to ~7mm in diameter by prevailing lighting condition. This means approximately five-fold change in the pupil area.

- Depletion and regeneration of photopigment: The biological changes in the retina.

- The Rod-cone transition: The break when rods will become more sensitive than cones and vice versa, part of light and dark adaptation.

- Gain control in the receptors and other retinal cells: Changes in the dynamic range of each receptor type.

- Spatial and temporal opponency: The affect of spatial and temporal characteristics of a stimulus to its color appearance.

- Gain control in opponent and other higher-level mechanisms: Independent changes of each cone type's sensitivity in order to reach the same relative cone responsivity.

- Response compression: The photoreceptors do not signal the absolute intensity of the light but a relative difference to previous lighting condition.

- Cognitive interpretation: Memory colors and object recognition among others, for example the orange color of Fiskars' scissors is a good example of a cognitive interpretation for Finns.

- Variation of pooling regions across photoreceptors

- Neural feedback

The following list is long and its purpose is almost solely to give some viewpoint to the very tricky world of adaptation mechanisms.

There are different types of adaptation, most relevant to the color appearance are *dark, light,* and *chromatic adaptation*. [11] [28]

3.2.1 Dark adaptation

Dark adaptation means a change in a person's visual sensitivity when the level of illumination decreases. For example, this kind of an event can be experienced when one sits in a closet and suddenly lights are turned off. At the beginning nothing can be seen but as time advances objects begin to take shape.

Figure 3-3 shows the change of visual sensitivity when the illumination (equal-energy white) changes from extremely high to extremely low. Dark adaptation is a two-pronged process representing the duplicity theory of vision. Below circa 1 cd/m^2 vision is scotopic (involving the rods) and above circa 100 cd/m^2 photopic (involving the cones, rods are effectively saturated), there are also mesopic range between these two values when both the rods and the cones are operating together. In spite of all we only show interest in the photopic and the mesopic vision because the level of the scotopic vision, also known as a night vision, is too low to measure and even less to control. [11] [24]

What interests us more is the adaptation time. As we can see from Figure 3-3 the visual sensitivity first increases quite fast and then the curve levels off after about 8 minutes and remains quite stationary until 10 minutes. After that the rods which have a longer recovery time start to take control. The curve becomes asymptotic after about 30 minutes. The adaptation curve changes if the spectrum is biased. Bias in longer wavelengths makes the rod-cone break in Figure 3-3 smoother, this can be easily understood when studying Figure 3-5 about rods and cones spectral sensitivity. The effect of this phenomenon to the adaptation time is nonetheless quite minimal. [11] [24]

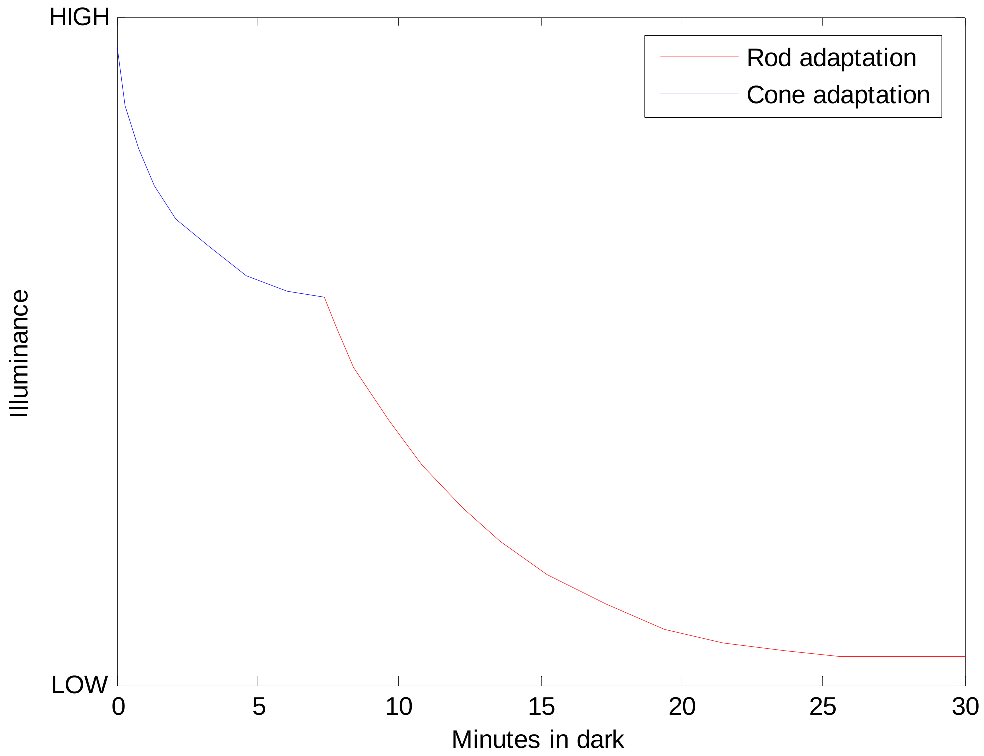

Figure 3-3. Dark adaptation curve, rod-cone break is illustrated as a break in the curve [11] [24]

3.2.2 Light adaptation

Light adaptation can be seen as an inverse to dark adaptation, although it must be considered separately because the properties of those two differ. A person experiences light adaptation for example when he or she exits a shadowy room and enters into a bright daylight. [11]

The mechanisms of light adaptation do not differ from dark adaptation but the visual performance between those two is different. The most important thing in this case is the time course of adaptation which can be seen in Figure 3-4. We can speak of tens of seconds, or according to Fairchild a maximum of 5 minutes, rather than the 30 minutes time span of dark adaptation. Because of this much shorter time course light adaptation is notably more interesting of these two when sorting the lighting scenarios in order to minimize the sum of the adaptation times. Same rules concerning biased spectrum in dark adaptation also apply to light adaptation. [11] [24]

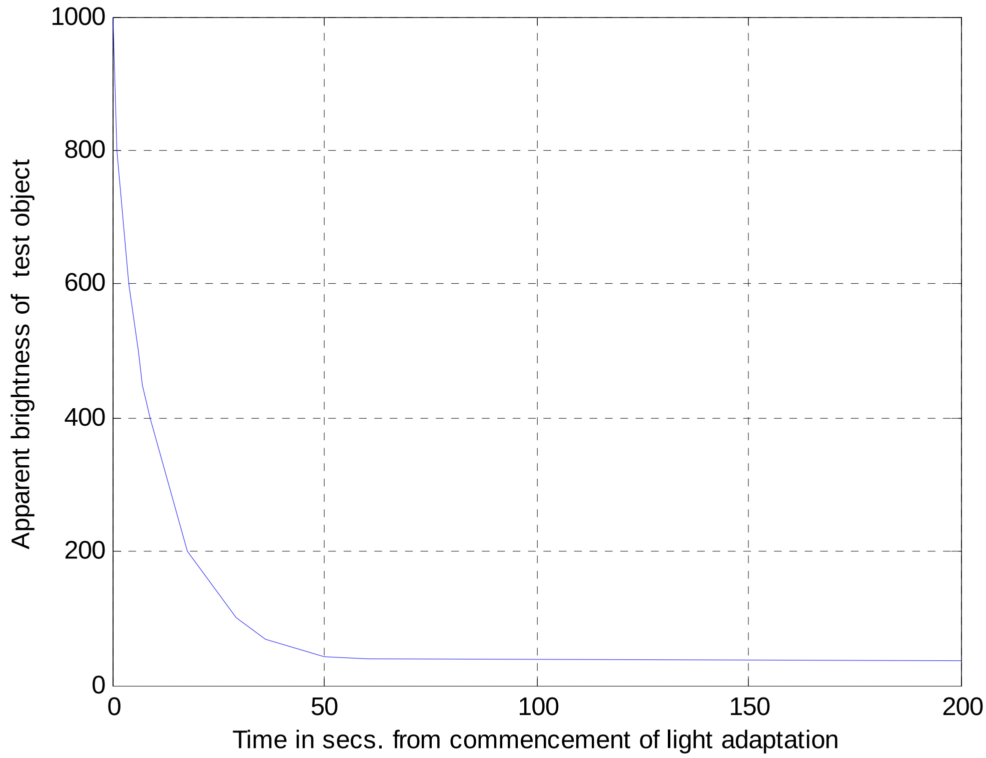

Figure 3-4. Light adaptation curve after a bleaching exposure [24]

3.2.3 Chromatic adaptation

When light and dark adaptation referred to the overall responsivity of the receptors, chromatic adaptation is often considered as an independent responsivity of the three types of cone receptors. Although light and dark adaptation has an impact on the color appearance, chromatic adaptation can be seen as more important. For example, chromatic adaptation can be experienced when looking a plain sheet of paper first in a reddish and then in a bluish light. After adaptation the paper looks white in both conditions regardless of the fact that the energy reflected from the paper has changed. We can understand the white point as a center around which other perceived color are scaled. Quoting Wyszecki and Stiles; *"White is the attribute of a visual sensation according to which a given stimulus appears to be void of any hue and grayness"*. Therefore it has an impact on the other perceived colors and the color difference as well. [11] [14] [24]

The reference white used in color difference calculations is determined by chromatic adaptation's current white point. The chromatic adaptation is happening on the very limited viewing sector, the foveal area of the retina. If the current focus in on a fully lit transmissive display with white content the current white point is determined or at least affected by that. However if the display has reflective characteristics the white point could be determined by the current illumination. Same occurs if person's focus is on a diffusive back wall. Unfortunately defining the white point on the run is a somewhat impossible scenario so we use two different options; current measured system state and D65. The mathematical usage of reference white in color difference calculation is explained in chapters 2.3.5 and 2.3.6. [14]

The other important feature of chromatic adaptation affecting this study is the time period. In constant luminance the sensory mechanics of chromatic adaptation are 90% complete after 60 seconds. According to Fairchild this can be seen as a good general rule for minimum adaptation time for a test person before he or she can make decisions. This time span can increase a bit if variations in luminance occur simultaneously, although in most cases this is not relevant because adaptation time during luminance level change is usually equal or greater. [11] [25] [29] [30]

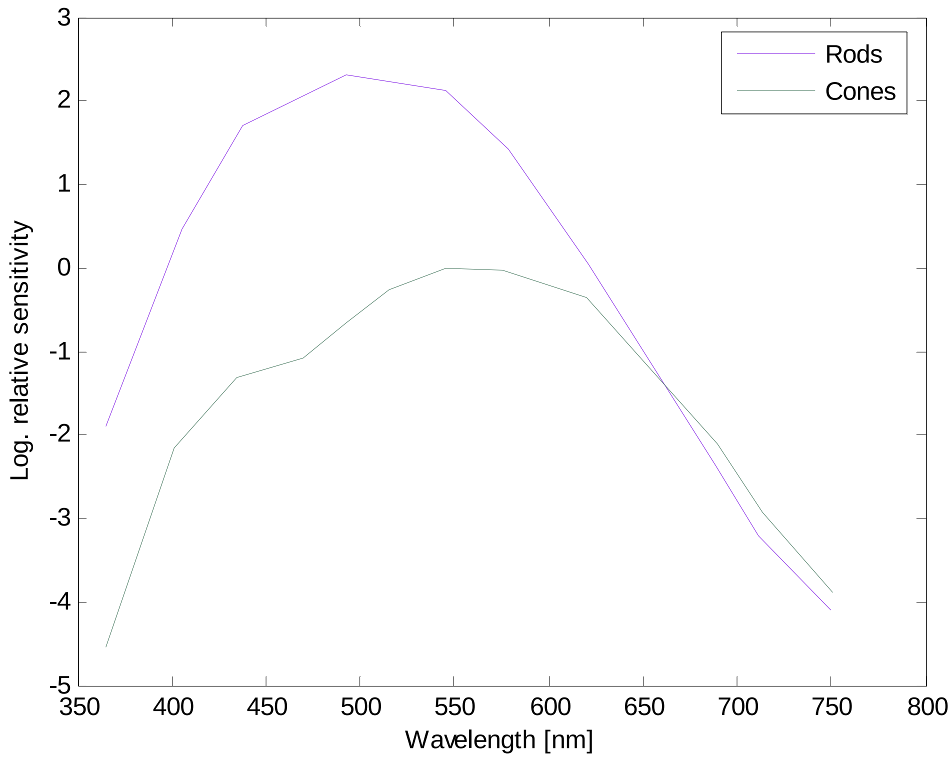

Figure 3-5. Rods and cones spectral sensitivity function [24]

3.2.4 Adaptation times and conclusions

While according to the spectrometer the target color and illuminance is reached the human eye might not yet have been adjusted to the lighting, because it is not a static measuring device. This results in a biased test result if the same lighting condition would be repeated later with a different adaptation level. Also as mentioned earlier the illuminance region where the test would be made strains the photopic or the mesopic vision.

The time span of different adaptation mechanisms is very broad, lasting from milliseconds to days or even years. It might be needless to say that in this case a reasonable maximum adaptation time is a minute or two rather than days. Even somewhat exact adaptation times are almost impossible to calculate so the approach would be to use suggestive adaptation time values when deciding if a test person is capable of making decisions. A finite patience of the test person is also a limiting factor. If the sum of adaptation time (the total time period of the test) raises too high the test person’s concentration could be enervated thus lowering the meaningfulness of the test.

In spite of all this, while constructing a series of different lighting scenarios adaptation times should be taken into account. Sorting different scenarios into the best possible order to minimize the sum of adaptation times is not a simple task. The lowest used levels of illuminance involving both the rods and the cones are more complicated because of the longer adaptation times. A typical scenario could be simulating a parking lot at night. Sequencing scenarios’ dominating criterion should be ascending illuminance level and after that the shortest distance in the used chromaticity diagram.

To overcome the problem of the shifting white point the tolerances for the color difference should be strict enough. The color difference is also the main criterion when judging the quality of controlling.

4 ENVIRONMENT OF USE AND EQUIPMENT

4.1 Colorimeters and Spectrometers

A tristimulus-filter colorimeter is a lighting measurement instrument which has a same relative spectral response functions as CIE standard colorimetric observer. These devices are simple, robust and cheap to buy but lack in accuracy. Normally tristimulus values obtained by a spectrometer combined with computation outperform values provided by a colorimeter. The problem of building a tristimulus-filter colorimeter is to develop filters that relatively match to CIE standard colorimetric observer through the visible spectrum. In some colorimeters there is a fourth receptor that only has a high- and low-pass clear filter in order to maximize transparency and measure illuminance level in low lighting conditions. [14]

Besides tristimulus-filter colorimeters there are two other colorimetric instruments which are a part of the spectrometer family: the spectrophotometer and the spectroradiometer. These two share the same detector types, dispersion methods and other requirements. The distinguishing feature is the source of measurement. Spectrophotometers have an internal calibrated stable light source and are designed to measure spectral transmittance and reflectance of objects. On the contrary spectroradiometers have an external light source, or at least they measure external active objects' radiometric quantities as a function of wavelength. Spectral radiant power distribution is a physical measurement and it contains, but does not by itself tell, colorimetric quantities. Those quantities are derived from it by using formulas given in chapter 2.3. [1] [14]

4.2 Used spectroradiometers

The system state has to be measured, crucial information about the state are CIE 1931 tristimulus values. Although a colorimeter would have been sufficient the decision was to use a spectroradiometer. There was a good candidate available and the spectroradiometer would also provide better accuracy and full spectral power distribution, thus opening new development possibilities. The criteria for the measurement device are specified in chapter 4.2.3.

4.2.1 USB4000

USB4000 Spectrometer is Ocean Optics' latest miniature spectrometer and is based on USB2000 Spectrometer. With certain components and an internal light source USB4000 can be transformed into a spectrophotometer, but in this case when a cosine corrector is used the device is characterized as a spectroradiometer. USB4000 features 16bit A/D resolution, spectral range from 200 to 1100 nm, Toshiba's 3648 pixel CCD array (with a few non usable pixels) which provides pretty good optical resolution of ~0.25 nm. The device itself is connected to a computer via USB where it also provides its power, or via RS-232 and external power supply. In this implementation the used interface was USB. Simplified USB4000 cross-section is seen in Figure 4-1. [18]

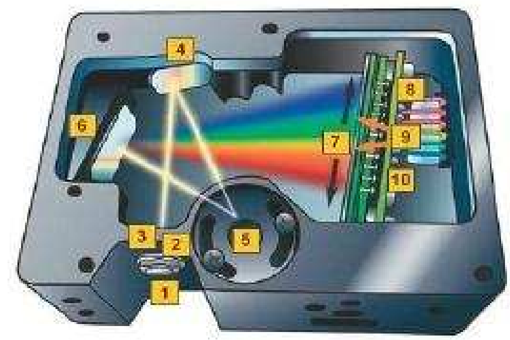

Figure 4-1. Simplified USB4000 cross-section [31]

In spite of its handiness USB4000 suffers from a flaw which is quite disturbing from the controlling point of view. When changed illuminance between two measurements requires integration time changes the device may report way too small or big illuminance levels. Most of that wrong data is filtered by the following procedure: if integration time is changed and sequential measurements vary significantly from each other the measurement result is discarded and a new measurement is made. This of course lengthens the controlling time span. This problem is measurement device based and thus could not be removed.

4.2.2 PR-650

P-650 SpectraScan Colorimeter seen in Figure 4-2 is a portable light measurement device provided by Photo Research Inc. It has a 128 pixel CCD detector with spectral range from 380 to 780nm, hence resulting in quite a poor optical resolution of ~3.5 nm. When used as such PR-650 equipped with a cosine corrector functions as a colorimeter giving illuminance and chromaticity parameters. When connected to computer via RS-232 a full spectral power distribution of measurement is achievable thus transforming colorimeter into spectroradiometer. PR-650 equipped with a cosine corrector was pre-calibrated and used as a master device during calibration. It has smaller optical resolution and narrower wavelength range than the target device, but when the calibration light source’s spectral power distribution is smooth it can be compensated using linear interpolation and most extreme data. Also PR-650 is temperature compensated, portable, accurate and easy to use. [32]

Figure 4-2. PR-650 SpectraScan Colorimeter [32]

4.2.3 Criteria

The controlling of illumination is dependable of a proper feedback from the system state. In this study the used measurement device is Ocean Optics USB4000 spectroradiometer which is calibrated using PR-650 spectroradiometer. The main criterion when choosing the device was size, prize, interface, speed, dynamic and wavelength range. The size and the price are self-evident arguments, the interface aspect went closely hand in a hand with the price, from modern computer interfaces the USB was a logical choice.

The speed was essential because it directly corresponds to a longer response time. While remembering that the used AC frequency is 50 Hz the optimal integration time for one sample would be 20 ms, when detector's over saturation requires shorter integration time the sample should be averaged from multiple samples with integration time sum 20 ms or greater. This can be seen as a precautionary measure if lamps that can flicker with 50 Hz frequency are used. Otherwise if the sampling time was shorter than the wavelength we would get distorted flickering illuminance levels for high luminance lamps, for example. So the requirement for the shortest integration time was 20 ms and for the longest the decision was to use 3000 ms. These values gave the requirements for a dynamic range; using 3000 ms integration time it would be able to measure as close to low illuminance levels as possible with reasonable saturation, later on this level was found to be close to 10 lux, and with 1ms the detector should not over saturate in 100000 lux. The wavelength range requirement was 380-800 nm which the USB4000 passed with flying colors. In addition to this the cosine corrector would have a certain transmittance affecting to the speed and dynamic range, wielded more closely in chapter 4.2.4. [18] [33]

4.2.4 Cosine corrector

When measuring illuminance, a cosine corrector, also known as a diffuser, is needed. From now on when a cosine corrector is attached to our spectrometer, it functions as a spectroradiometer. The cosine corrector is made of hazy material; when light passes into it along its normal, the material scatters the light evenly to all directions. And as inversion it collects the light coming from different angles. A perfect corrector would follow the cosine curve from 0 to 90 degrees and distribute the light evenly thus making the device effectively an illuminance meter. [34]

The unfortunate fact is that better cosine characteristics come with poorer transmittance. Ocean Optics supplied also the cosine corrector CC-3-DA which had great cosine characteristics but a poor transmittance (~20%) which lengthened one sample integration time and thus also the whole controlling time and therefore had to be discarded. [34] [35]

A new diffuser had to be made; the first step was to measure the chosen material. The measurement procedure consisted of a stable collimated light source, a mirror, a sample, a spectroradiometer that could be tilted from 0° to 70° and a measurement table that could be rotated around a vertical axis. The measuring arrangement is seen in Figure 4-3. The sample was measured using eight tilt angles (theta) from 0° to 70° with an interval of 10°; this was repeated with four different rotation angles (phi) which were 0°, 90°, 180° and 270°. [36]

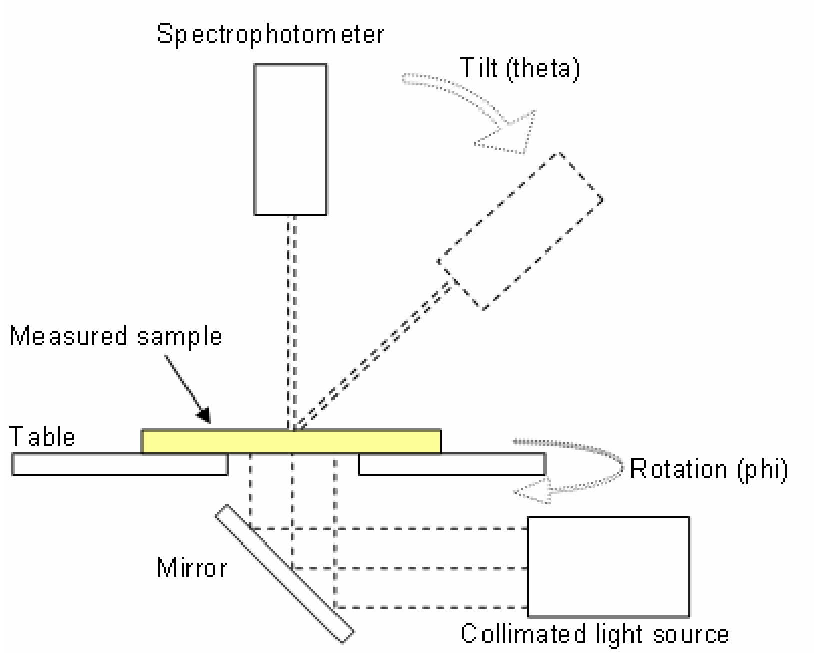

Figure 4-3. Cosine corrector's measuring arrangement

The measurement arrangement was quite simple. The light source had to be collimated so that all beams would pass through the material along its normal, the diameter of the beam was 30 mm and its luminous flux was evenly distributed. When the spectroradiometer was tilted its area of sight still fit to the alight region because of this. The spectroradiometer had a tube (diameter 1 mm) that measured luminance of the material from different angles. Perfect cosine corrector's measured relative luminance would be the same from each phi and theta angle. Although perfect results were not expected, the main concern was that the tristimulus values proportions would change differently with different theta angles thus affecting the chromaticity values. As seen in Figure 4-4 the relative tristimulus values decline quite smoothly and the CIE 1931 chromaticity coordinates seen in Figure 4-5 are practically not changed. As the better transmittance of 61 % was essential the decision was to use this material as the cosine corrector. [36]

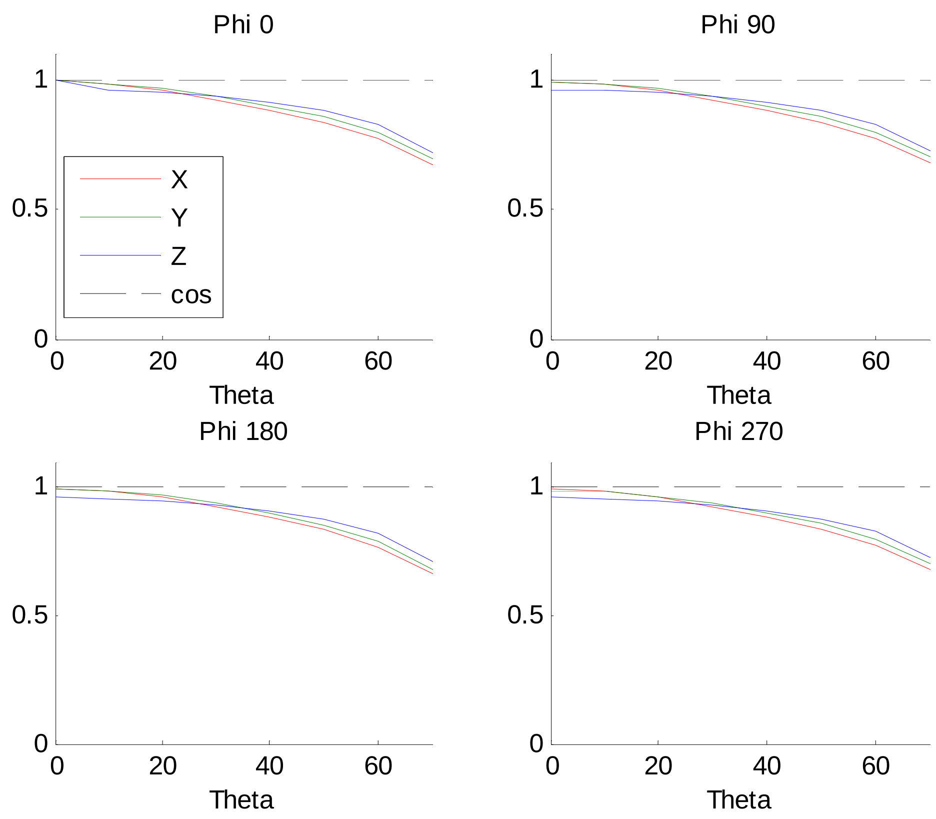

Figure 4-4. Cosine corrector's measured relative tristimulus values as a function of phi and theta using a PID light source

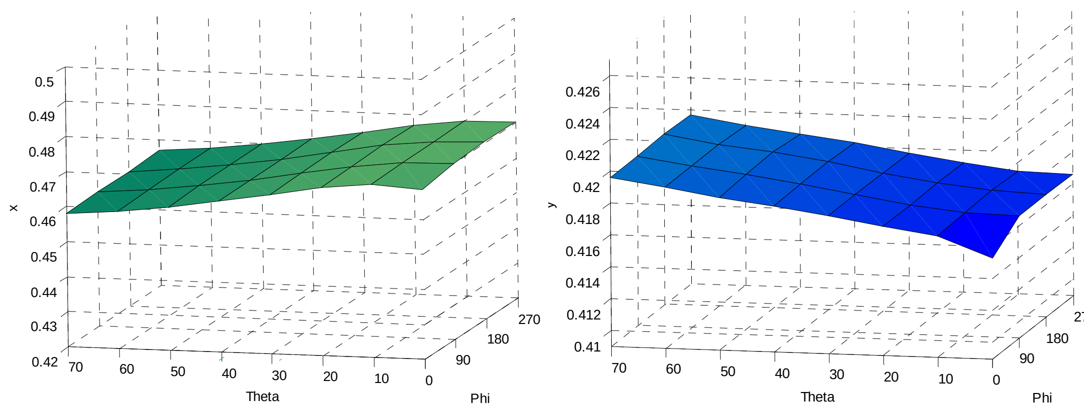

Figure 4-5. Cosine corrector's measured CIE 1931 x and y values as a function of phi and theta using a PID light source

4.2.5 Dark current

All spectroradiometers as well as spectrophotometers also have a characteristic feature called dark current (or dark noise), this means a constant response of a detector over a time event when no light passes to the detector. It can be seen as a white background noise in the measurements and must be eliminated before any other spectral operations can be applied. CCD arrays' dark current varies as a function of temperature and measurement time; in this case because USB4000 is rather well temperature compensated thermal changes are quite minimal when compared to other disturbing factors. Because of that we treat the dark current as a time dependent phenomenon. [37]

In order to eliminate the dark current it must first be measured. USB4000 has Toshiba's detector (TCD1304AP) which has a two shift register (even and odd). As a result of this, the raw dark current seems thick because each shift register has a slightly different offset level. In order to eliminate this difference we cannot use electrical dark current or other constant value for the dark current. USB4000 also has an internal boxcar calculator for signal averaging; boxcar calculation simply averages *n* pixel values from each side of a given pixel and can be used in cases like this when the observed spectral structure is broad. Unfortunately this calculation is also done for the dark current, in other words the dark current cannot be removed before spectral operations. [18] [37] [38]

This gave us foundation and boundaries for the dark current measurement. The boxcar averaging is a nice-to-have feature because it reduces the signal-to-noise ratio and levels off unwanted sharp spikes. USB4000 dynamic range is insufficient if only one integration time is used; integration time must change on-the-fly during a controlling cycle. That is why dark current intensity's integration time dependency obliged us to take different samples with different integration time. Dark current calibration can be understood as a two dimensional matrix where rows are boxcar values and columns different integration times at certain intervals. When we limit the used integration time range between 1 and 3000 ms, have the first dark current sample at 1 ms, the second at 10 ms and each one after that with 10 ms intervals the total number will be 301 samples for one boxcar value. When the integration time changes we will use the nearest dark current spectrum. All the measurements in this study are done using boxcar value 1, but it could be any other. That is why in the implementation itself each boxcar value will have its own calibration data file. [18] [37]

The actual dark current measurement is done by blocking the detector using a metallic cap and starting the dark current measurement run which automatically measures the needed 301 different dark current spectral power distributions. From these measurements a dark current calibration file for a specific boxcar value is constructed.

4.2.6 Calibration

The spectroradiometer equipped with the new cosine corrector and the dark current data over the used wavelength range is not sufficient and does not provide us corresponding measurement values. The measurement device has to be calibrated in order to find the relationship between values indicated by CCD array and real world spectral power distribution. [1] [39]

In order to make the calibration procedure easy the decision was to use spectral calibration and calibrate the measurement device against a calibrated measurement device, PR-650 spectroradiometer.

The intention is to measure a light source with a target device (USB4000) and a calibrated master device (PR-650), and from these values calculate calibration coefficients for the target device. Because the target device has far better optical resolution (~0.25 nm) than the master device (~3.5 nm) the used light source should have a smooth spectral power distribution. Since post processing of the spectrum is needed, the calibration coefficients should have the same optical resolution and the wavelength range as the used color matching data (1 nm and 380-800 nm). [1] [32] [39]

Because now we have a bunch of different wavelength ranges and optical resolutions we need to manipulate the measured spectrum as mentioned in chapter 2.3.3. The steps are as follows (where *t* is target device's used integration time):

1. The calibration light source's spectral response is measured with the target device, resulting $S_{T\_raw-t}(\lambda)$, and the master device, resulting $S_M(\lambda)$.

2. The specific dark current, $S_{dark-t}(\lambda)$, is subtracted from target device's raw spectral response, as in equation 42, resulting $S_T(\lambda)$.

3. Target device's raw spectral response, $S_T(\lambda)$, is averaged to match 1 nm optical wavelength using equation 9.

4. Master device's raw spectral response, $S_M(\lambda)$, is modified to match 1 nm optical wavelength using linear interpolation. Data between 781 and 800 nm is constructed by extrapolation using most extreme data.

5. Calibration coefficients, $CC(\lambda)$, are calculated using equation 43

6. When an unknown light source is measured with the target device (integration time *t*) and operations in steps 2 and 3 are applied, it yields a non-calibrated spectral response $U_T(\lambda)$. The calibration coefficient data is used to convert it to calibrated spectral response $S_{real}(\lambda)$ by using equation 44.

$$S_T(\lambda) = S_{T\_raw-t}(\lambda) - S_{dark-t}(\lambda) \tag{42}$$

$$CC(\lambda) = S_M(\lambda) / \left(\frac{S_T(\lambda)}{t} \right) \tag{43}$$

$$S_{real}(\lambda) = \left(CC(\lambda) * \frac{1}{t} \right) \times U_T(\lambda) \tag{44}$$

When the calibration coefficient file is constructed using these operations any measured raw spectral response can be converted into usable calibrated data. The calibration coefficient file is always device-specific. [1] [39]

This calibration method assumes linearity of target device's photometric area, meaning that the output quantity is always in proportion to the input quantity. This assumption is made because there are a lot of other error sources, and linearity calibration would require fairly heavy workload when compared to payback. Kallio's study also states that spectral calibration has the greatest impact and by also using linearity and wavelength calibration more reliable results were not achieved. Usage of a smooth spectral power distribution halogen lamp was as well emphasized, even though its intensity in blue end is low as can be seen in Figure 4-7. This will cause uncertainty in wavelengths below 400 nm, which is however acceptable because eye response in that end is quite poor as well. [1] [39]

The calibration procedure itself is seen in Figure 4-6, the used light source was a symmetrical halogen lamp, both measurement devices were positioned symmetrically so that a probe distance from the center of the light source (*a*, 2.5 cm) would be the same for both. The cosine corrector surface's distance from light source (*b*, ~1.5 m) was also same for both and orthogonal to the light source's normal. This kind of measurement scenario is easy to arrange and it is not dependable on a special kind of light source. Because both devices measure the spectral response at the same time (in a 125 ms time window) the light source does not have to be totally time stable and thermal effects are not disturbing factors. The measured raw spectral response before and after dark current subtraction, as well as the spectral power distribution of the calibration light source, is seen in Figure 4-7.

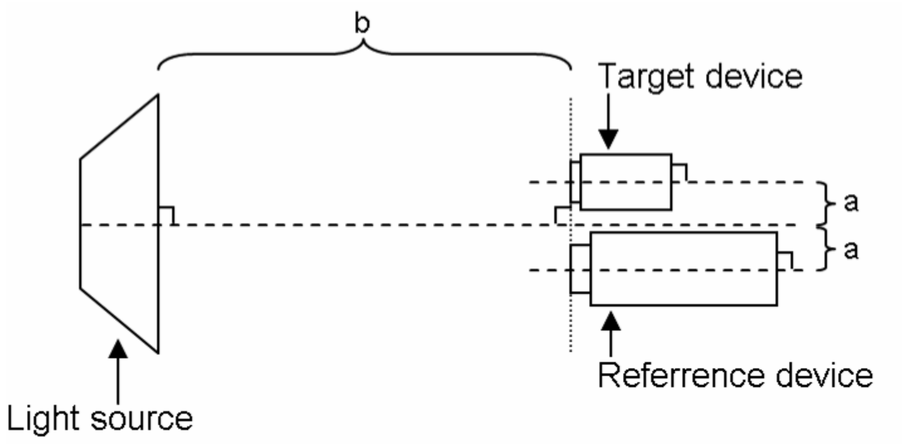

Figure 4-6. View of spectrometer calibration procedure

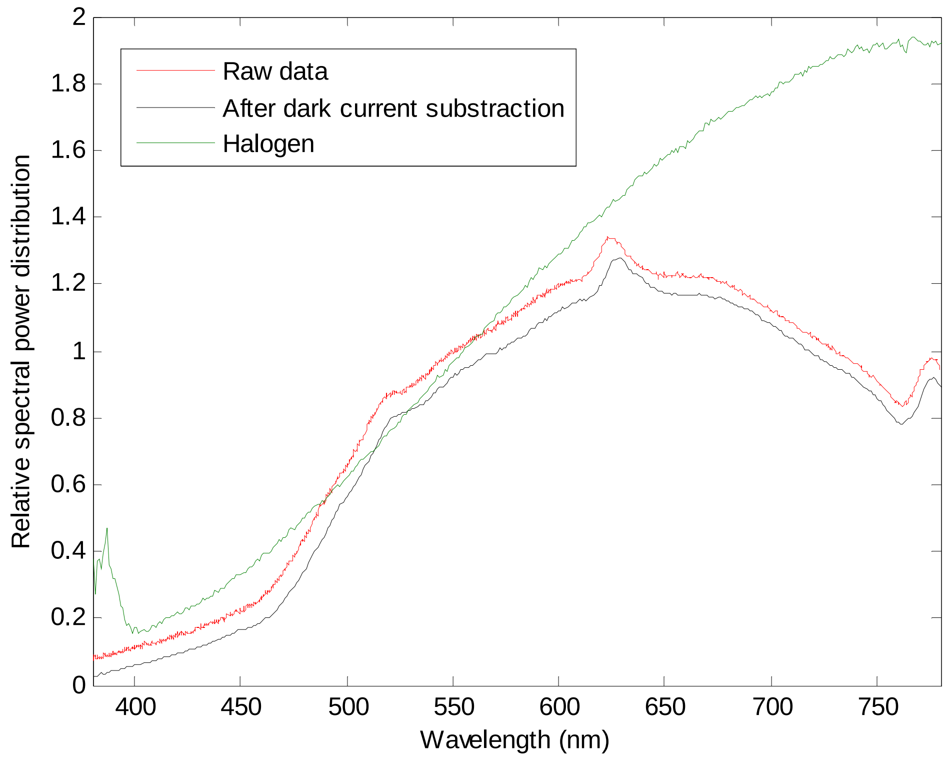

Figure 4-7. Relative spectral response before and after dark current substraction and prior to calibration, and relative spectral power distribution of the used calibration light source (same as the relative specral response after calibration)

4.3 Environment

4.3.1 Overview

As mentioned earlier the used test environment hardware, henceforth called SimOne, had been previously constructed and can be seen in Figure 4-8, curtains from one wall are obviously removed when the picture was taken. A rough visualization of the lamps and the whole test environment's structure is seen in Figure 4-10. The numbers of lamps or dimensions seen in the picture are not same as in the real scenario but it gives some indication about the construction. [5]

The environment itself consists of an aluminum framework which supports the lamp structure on the top of it, under the lamps there are two glasses covering the whole area. The first one is an opal glass that diffuses the light coming from above and under that is a shatter proof glass for safety reasons. The opal glass enables the usage of RGB lamps by diffusing their light more evenly and its diffusing effect can be easily seen when comparing pictures taken from the same conditions above and under the ceiling.

The lamp structure above the glass ceiling is seen in Figure 4-9. It consists of RGB and other fluorescent lamps, in addition to these there are high luminance metal halide lamps which are used to create high lux level scenarios, like daylight conditions. Below the glass ceiling on the left are on/off type lamps that are meant to be used as such, these are for example high and low pressure sodium used on roadsides and parking lots. On the right there is a movable direct light cart which consists of a few tubes and glides on rails. In front, on both sides, there are side lights which can be used to create a certain lighting condition. Under the high luminance lamps there is seen a tube gap which allows more light to pass into the room and to the table level.

The room itself is surrounded and covered by curtains that are impervious to light. These curtains are mat white from inside and mat black from outside. A fan unit is located on the roof and is used to circulate the air and remove the heat extracting mostly from the high luminance lamps. Inside the tent is a worktable and a test person’s chair as well as a controlling computer and air conditioning units. In the picture the measurement device is located on the table, in spite of that it is not bound to any position, but the place is natural and commonly used because the illumination on the table level is a logical measured condition.

Figure 4-8. SimOne from inside at a time when all the RGB lamps were used

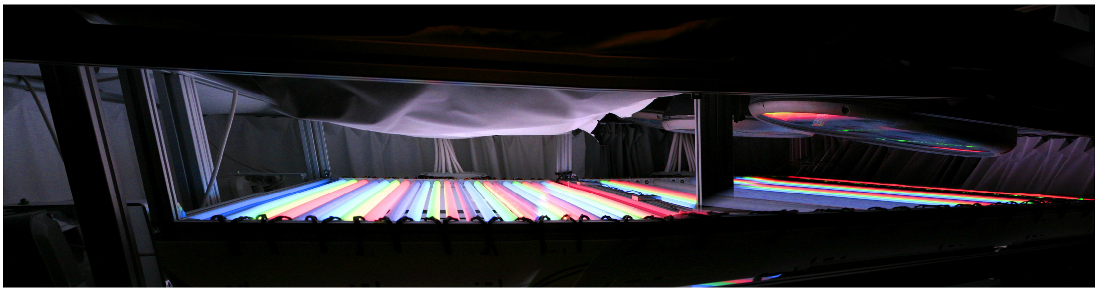

Figure 4-9. SimOne lamps above the ceiling

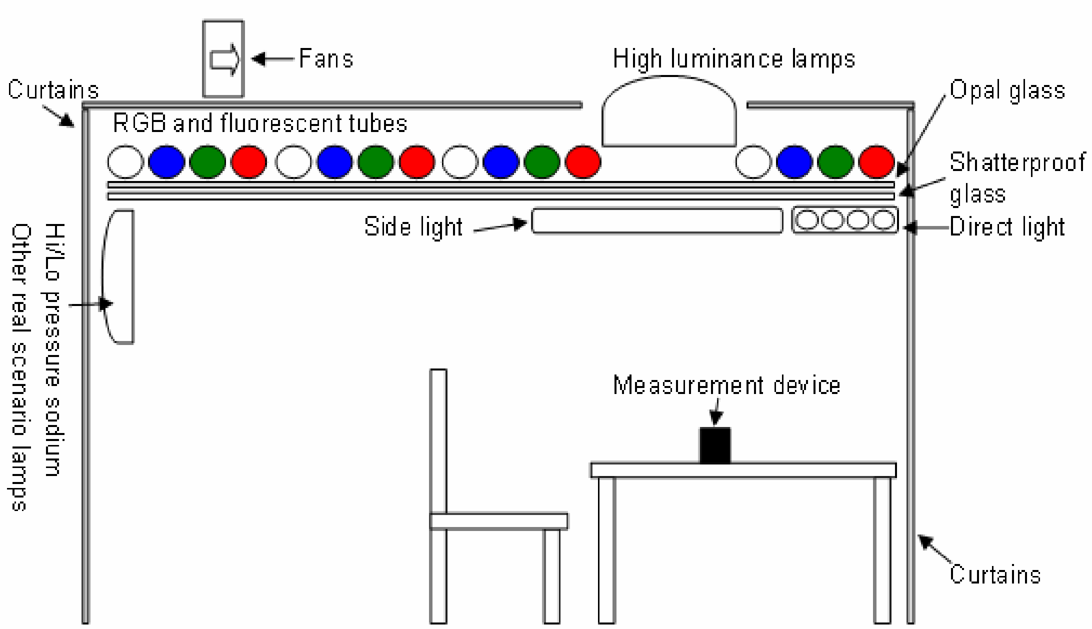

Figure 4-10. SimOne structure

4.3.2 Lamps and performance

From a controlling point of view the lamp has a few interesting characteristics. Some lamps are on-off type which means that those are driven with full voltage or not at all. These lamps are not usable for real-time controlling but can rather be used to boost illuminance level; good examples are high luminance lamps. Lamps that can be driven with different voltages add one degree of freedom to the system, thus being more practicable for controlling. Although it is possible to drive fluorescent lamps with low voltage values, there is a certain controlling voltage below which lamps start to flicker annoyingly and become unstable. In Table 4-1 lamps of a certain SimOne are listed, though it must be noted that the controlling method and implementation are not bound to this specific configuration, but were successfully introduced to other SimOnes with different configurations. Although the measurements and UI pictures related to this thesis are constructed using this specific lamp configuration.

Table 4-1. A certain SimOne lamp configuration

Name	Lamp type	Controlling type	Length x dimater (mm)	Quantity/channel	Channels
Halogen	Osram Trispot 5x20W	Voltage	1500x26	2	1
F12	Osram L 58/31-830	Voltage	1500x26	1	2
F11	Osram L 58/21-840	Voltage	1500x26	1	2
D65	Osram L 58/72-965	Voltage	1500x26	1	2
Red*	Osram L 58/60	Voltage	1500x26	1	8
Green*	Osram L 58/66	Voltage	1500x26	1	8
Blue*	Osram L 58/67	Voltage	1500x26	1	8
Direct Light		Voltage	1500x26	4	1
Side Light		Voltage	-	2	2
Metal Halide 1000W		On/Off	-	1	2
Metal halide 400W		On/Off	-	1	1
Low Pressure Sodium		On/Off	-	1	1
High Pressure Sodium		On/Off	-	1	1
Mercury		On/Off	-	1	1

*RGB lamps are arranged to "banks", a bank has one of each lamp type

As seen there is a great variety of lamps that can be controlled in order to achieve a target lighting condition. As generalization it can be said that the halogen, the F12, the F11 and the D65 are used to create typical indoor lighting conditions with certain illuminance level. Same for outdoor conditions applies for the mercury and the high and the low pressure sodium with the exception that these are not controllable at all. The direct and the side light can be used to create certain scenarios and change lighting balance between the back and the side walls. The RGB lamps are the most saturated thus giving widest gamut and biggest impact to chromaticity controlling. As mentioned earlier the metal halide lamps are used to achieve high illuminance levels, however all the voltage controlled lamps can and should be used to boost the level even further. In this kind of scenario the RGB lamps are used to shift chromaticity coordinate into a certain value.

4.3.3 Measurement device and test person positioning

Adjustments to the system state are made according to measurements of the used measurement device. Because of this one momentous question is arrangement of a test person and the measurement device. Tested objects', which are mostly small displays or cell phones, natural placement is on the table or in the hand of the test person. This and ergonomics define the test person to sit in a normal more or less cozy office chair that has adjustable height. The test person also unwillingly affects to the prevailing lighting conditions, as different clothes cause different reflections, the upper body or a hand can easily cast a shadow to the table level, or the test person can willingly overshadow samples in order to make them more readable. This kind of movement should not be seen as an interference that must be compensated by controlling, because it is natural and also happens in real-life user cases. However the measurement device cannot distinguish it from real interference, so a light controlling compensates it in order to regain a current target.

One other thing to consider is the illuminance square law, when the distance is halved the illuminance level is raised to a power of two. This means that user's eye level is adapted into a different illuminance level than that which prevails on the table level. In some conditions, if the user is tall, the eye level illuminance can be double compared to the table level. Consequent upon this some reference location should be specified. In this thesis the middle of table ~0.5 m from the leading edge is proposed as a reference location, this location is also used when measuring data of this thesis. The location is far enough that the user will not accidentally overshadow the device or cause other interference, but near enough that the illuminance condition on the front of the table is comparable to the measurement. Another logical measurement point would have been the eye level. [9]

4.3.4 I/O cards

The system uses three National Instruments' PCI-6703 analog output cards to control relays and inverters, when voltage is set to 0 V relays cut of the power. Each card has 16 16-bit voltage analog outputs and 8 digital I/O lines. Analog outputs operate at voltage level between -10 and 10 V, but it is self-evident that only positive values can be used, in fact values below 3.4 V cause flickering so it can be considered as the minimum voltage. The cards themselves are located in an operating PC and are controlled using NI-DAQ software and drivers [40].

5 LIGHT CONTROLLING THEORY

In an early phase it became clear that the environment was impossible to model because the dynamics between different lamps became impossible to solve. The lamps' luminance varied as a function of their age and operation temperature, adjacent lamps affected to the temperature as well as did the ventilation. The lighting conditions of course also varied when the environmental conditions changed, a test person sat in different location, a measurement device position was changed, and so forth. The fundamental idea was to model each controllable lamp somewhat robustly, and have a proper feedback from the system state onto which the controlling steps would be based on.

The system's adjustable lamp configuration (and therefore input quantity) changes from minimum one to over thirty. Output variables can be illuminance, chromaticity or both resulting in one to three output variables. Because of this we can definitely speak of a *multivariable control system*. [41]

The block diagram of the closed loop control system is seen in Figure 5-1. As itself it is fairly simple having desired output on the left, controlling loop in the middle and resulting outputs on the right. The process has its interference of which the sources are listed in chapter 5.1.

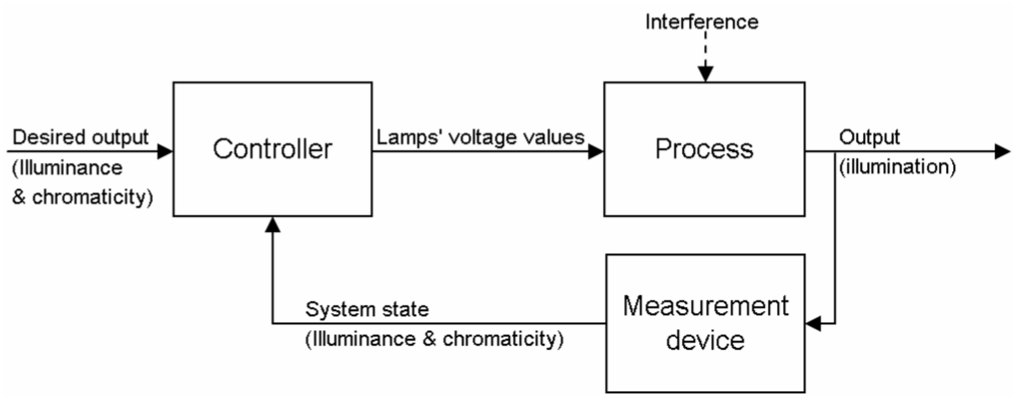

Figure 5-1. Control system

5.1 Chromaticity and illuminance as a target of control

Ambient light controlling has two different aspects: chromaticity controlling and illuminance controlling. Illuminance controlling is rather simple because it is one dimensional, increasing lamp's control voltage level will most likely cause increase in the illuminance level as well and vice versa, unless lamp is already saturated. With proper feedback a classical controller can be designed to control the system state. After this when speaking of lamp voltages it will refer to the controlling voltage which has the same range as National Instrument's PCI-6703 analog outputs' positive voltage level, 0-10V, and which must not be confused to the lamps real operating voltages that are subsidiary from the controlling point of view.

Chromaticity whatsoever is a much more diverse controlling problem, because it has two dimensions instead of one. As known chromaticity coordinates are derived from spectral power distribution and are not uniform in any state. Ambient lighting's chromaticity controlling has following problems and facts:

- When combining two light sources with known chromaticity and illuminance values the resulting chromaticity value cannot be calculated without knowing the spectral power distribution or measuring the system state.

- Lamps spectral power distribution does not increase evenly in proportion to the controlling voltage.

- Lamps spectral power distribution is affected by thermal effects, whereas adjacent lamps heating, air condition and airflow cause thermal effects to the system.

- Aging also affects the spectral power distribution.

- External light sources and lamps aging also affect on the spectral power distribution and thus the perceived color.

- Lamp position and distance compared to the measurement device change if the device is moved, this is why the illuminance intensity response as a function of control voltage is hard to predict. Solutions where the measurement device is bound to one specific place (usually during lamp calibration) were ruled out.

- Because of metamerism there is an infinite number of different spectral power distributions that create the same perceived color. This is also an advantage which makes the whole project possible.

The only self evident thing was this: for example if a red lamp proportion is increased the measured chromaticity coordinate shifts towards red. In other words that lamp functions as a gravity point.

5.1.1 Dynamic range and gamut

Dynamic range of a lamp defines the usable illuminance range. There is a certain maximum brightness with each lamp type, but majority of lamps also have a minimum voltage with which the lamp can be controlled without flicker. Because of this the dynamic range of a lamp does not start from 0 lux, but from somewhere above that, with halogens close 20% of the maximum illuminance level. This why when a lamp is turned on or off it inflicts a step response to the system state. Magnitude of this step depends on the following aspects:

- Lamp's minimum illuminance in proportion to system's current illuminance level.

- Distance between the lamp's and the system's chromaticity coordinates.

The target chromaticity and illuminance is a combination of different light sources that will form the *gamut* inside which the chromaticity coordinate is located. The solid line in Figure 5-2 illustrates a possible color gamut that is constructed by RGB lamps. Colors inside this gamut can be obtained as a combination of red, green and blue. However because of the minimum illuminance level of the lamp there are certain *sub-gamuts* inside which the target chromaticity is truly achievable. In Figure 5-2 the dotted line represents a possible sub-gamut that is constructed when one red, one green and one blue lamp is in use. If only two of those three lamps are in use the chromaticity coordinate is located on an edge of the gamut.

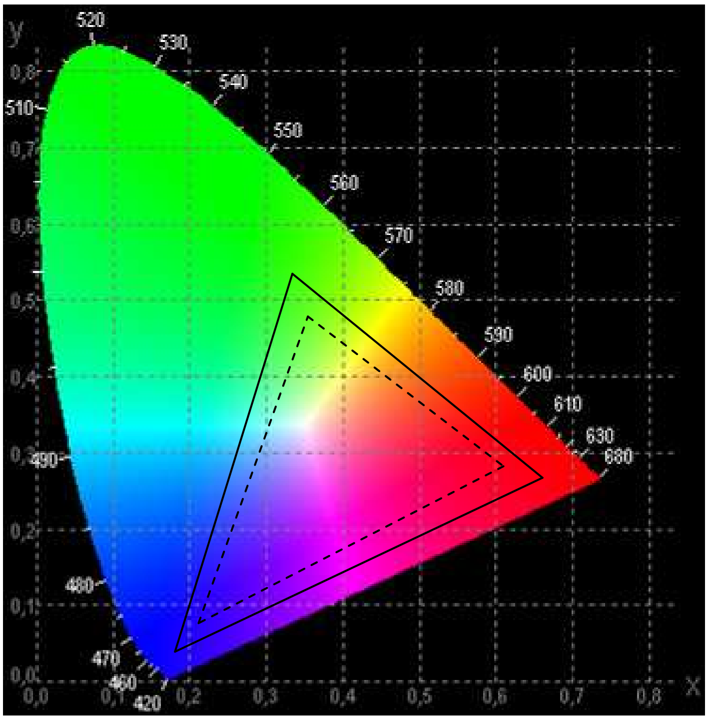

Figure 5-2. Illustration of a gamut and a sub-gamut

In an example scenario if the red lamp is turned fully on and the blue and the green lamp are lit using minimum voltage level the gamut shifts to the reddish corner of the sub-gamut leaving behind a portion which is unreachable. When blue or green lamp's proportion is increased the chromaticity shifts towards it on the edge of the sub-gamut. When quantity of RGB lamps is increased the sub-gamut approaches the gamut.

When illumination is a controlling target alongside with the chromaticity it decreases the sub-gamut even more. Normally this sub-gamut problem is present when the target illuminance level is low and only few RGB lamps can be used. The sub-gamut is smallest when the target illuminance equals the sum of one red, one green and one blue lamp minimum illuminance, in that case it is a point-sized somewhere near the equal energy (white). On the upper end of the lamps dynamic range the sub-gamut undergoes a same type of problem, when the target illuminance equals the sum of lamps' maximum illuminance the sub-gamut is point-like. Figure 5-3 illustrates this phenomenon with CIE 1931 based 3D image which was constructed using one red, one green and one blue lamp. All chromaticity coordinates and illuminance levels inside this 3D gamut are theoretically attainable using one green, one red and one blue lamp.

The sub-gamut is widest when operating in the middle section of each lamp's dynamic range. When the illuminance is also controlled, the problems are hard to predict without testing the lighting scenario.

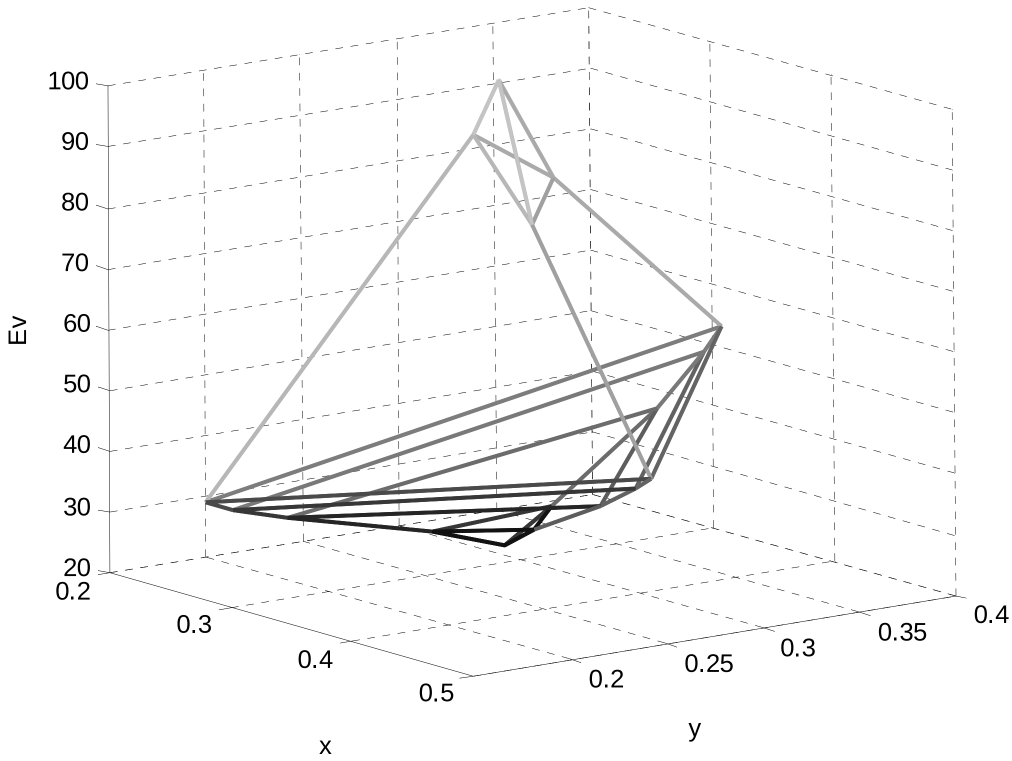

Figure 5-3. Relative CIE 1931 color gamut with different illuminance levels

Although RGB lamps were used to describe the sub-gamut problem those could have been any three lamps with different chromaticity coordinates, thus forming a different and maybe a smaller gamut.

5.1.2 Controlling requirements, facts and terms

In controlling scenarios one fundamental question is the required controlling criteria. In ambient light colorimetric controlling case where we have maximum of three output variables the other question is which value is the best to represent goodness of controlling or which values have the greatest affect on the perceived color. How do we decide whether the target is achieved or not when the target is an adapting human eye? For this problem CIEDE2000 color different formula presented in chapter 2.3.6 brings the solution. Colorimetry and mostly the human visual capacity were used to explain the interconnection between these controlling criteria and system requirements. Because the system and the environment were the first of their kind strict numerical values for the criteria were hard to give. [11] [21] [33] [41]

Acceptable (steady-state) error. Some sort of error must be acceptable because the system cannot be tuned to achieve the target perfectly. For this CIEDE2000 Just Noticeable Difference (JND) is used to determine whether the target is reached or not, $\Delta E_{00} \leq 1.0$ is the requirement for controlling when the target illuminance $E_{v\_target} > 700$ and $\Delta E_{00} \leq 2.0$ when $E_{v\_target} \leq 700$. These values are based on trial runs and the fact that JND 2.0 is still strict enough when pair comparison is not present. Loose tolerances on low illuminance levels have a positive effect on rising and settling time as well. [1] [11] [21] [41]

System state. The measured and controlled system state consists of tristimulus variables *X*, *Y* and *Z*. Using those desired colorimetric variables, described in chapter 2.3, can be calculated.

Saturation. When a human visual system is adapted into certain lighting, sudden changes in it can be noticed much more easily than slow ones. Because of thermal effects, the output parts from the target slowly. If $E_{v\_target} > 700$ and $\Delta E_{00} > 2.0$ or $E_{v\_target} \leq 700$ and $\Delta E_{00} > 4.0$ the system state requires corrective procedures. This criterion gives us the limit when an achieved target is considered as lost. [1] [11] [21] [41]

Rising time. Light or dark adaptation commences when the illuminance level is changed and the adaptation speed is in proportion to the magnitude of exposure. This why it is essential to set the dynamic range and illumination close to the target as quickly as possible, in other words minimize the rising time. Because color difference is always a positive variable rising time is the time when color difference first time goes under the saturation level. [11] [41]

Settling time. As noted before the settlement requirement was $\Delta E_{00} \leq 1.0$ or $\Delta E_{00} \leq 2.0$. It was hard to give precise settling time requirements, the quicker the better. At the end one minute for each target inside lamps' dynamic range was the reference maximum time and the target was as quickly as possible. [11] [21] [33] [41]

Overshoot in illuminance was not that crucial because it could be easily corrected and higher illuminance levels would make shorter integration times possible. Over 100% overshoot in illuminance would however disturb adaptation and hence was not desirable. After the target is achieved for the first time overshoot caused by corrective measures must be minimized in order to create an impression of steady lighting. [11] [41]

Stable system. The system is stable because any input will result in a bounded output. [41]

Sampling period. System controlling is based on a feedback from the system state and one measurement is done after each controlling loop. The sampling period is comparable to spectroradiometer's current integration time and can vary from a few milliseconds to several seconds. [18] [41]

Time varying system. Because of thermal effects and lamp aging the system is time varying, this affects to the spectral power distribution and thus to chromaticity and illuminance. [41]

Robustness (robust control). The main target was to design accurate control while significant uncertainty was present. One of the main system criteria was to design a robust controller that would perform in a predictable manner in each controlling scenario, also when the target would be unreachable because of hardware constrains. As well as controlling this was also an implementation criterion. [41]

Tradeoffs. When pondering the tradeoffs the most crucial one was that after the system state has settled overshoot, the step-like responses must be avoided even if it results in a longer rising time during procedures. Step and overshoot can distract and annoy a test person during ongoing test. Before the target is achieved overshoot is acceptable if it provides a shorter rising time. [41]

5.2 Previous approach

The old approach to solve the ambient lighting controlling problem was based on a pre-calibrated method. In this method the idea was to measure a great variety of different lamp configurations with small and high voltage levels. Using this information a matrix was constructed. Rows and columns were the chromaticity coordinate and cells had the information of each lamp configuration and its dynamic illuminance range. When a certain target was requested the system chose a lamp configuration that matched the chromaticity most closely and where the illuminance target was at the middle of the dynamic range.

This controlling method did not take in count lamp aging, thermal effects, changes in the test environment or interfering light sources. The calibration procedure was also long, lasting several hours and after the calibration the measurement device was to bind into the specific place where it had been during the calibration.

The old pre-calibrated method was abandoned because it did not provide enough confidence for further development.

5.3 New approach, chromaticity controlling theory

First there were the facts, targets and limitations concerning the system and the controlling. Based on those the development of a new controlling method took place.

Controlling the illuminance was not a problem even in the first place. The system was stable because any bounded voltage input would result to bounded illuminance output, inside lamps' dynamic range any illuminance level could thus be achieved using feedback loop and a simple controller. A much more challenging task was to control the chromaticity.

The profound idea of the new controlling method was to comprehend each lamp as a gravity point. This idea originated from the fact that if portion of, for example, red is increased the whole sensation must turn more reddish rather than bluish or greenish. The shade of the color was not so important; all reddish lamps would generate some kind of reddish sensation. Also the color sensation of the lamp was one of the only things that were not affected by the thermal effects or aging.

5.3.1 Illustration of the chromaticity controlling method

As mentioned earlier in the new approach each lamp was treated as a gravity point. Increasing point's gravitation, also known as illuminance, would draw the center of the gravity (system state) toward the point and vice versa, decreasing point's gravitation would push the center of the gravity away from it. The idea itself is illustrated in Figure 5-4 where stars represent lamps which are placed to corresponding locations according to their chromaticity coordinate. Each lamp's chromaticity coordinate is measured during the calibration which is described more closely in chapter 5.3.5. For example, axes of the picture can be *x* and *y* or *u´* and *v´* depending on chosen coordinate system.

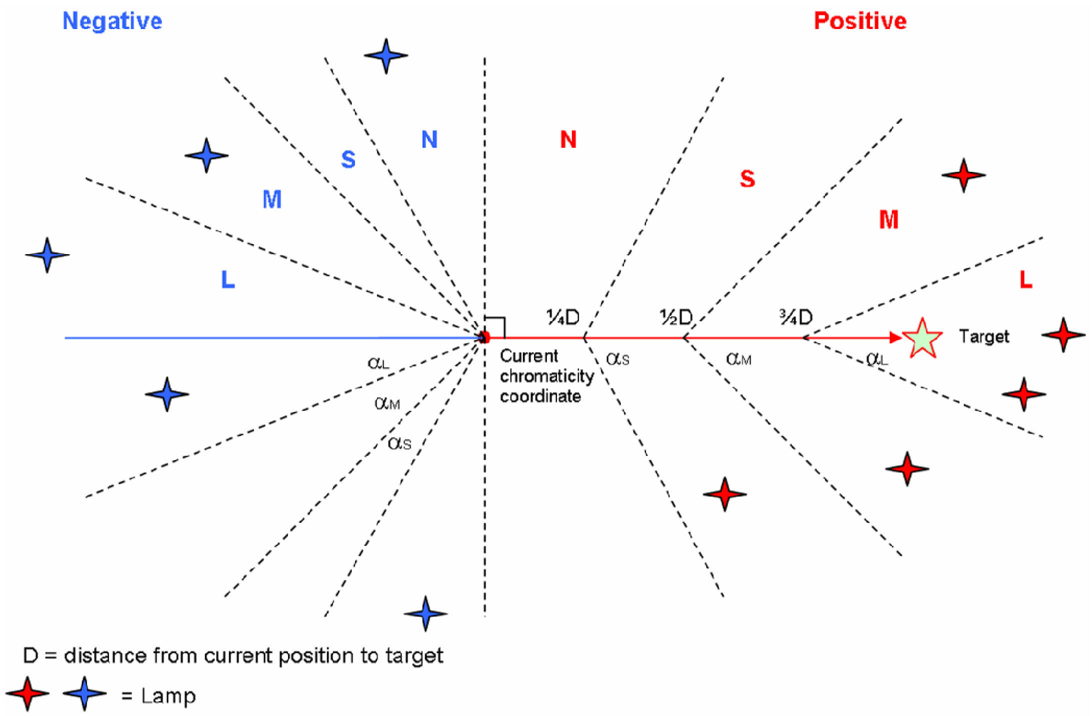

Figure 5-4. Gravity based controlling method which illustrates membership sectors and exemplar lamp locations in the model

As we see in Figure 5-4 the plane is divided into two segments: a negative and a positive. This partitioning is done by drawing a line which is perpendicular to a vector drawn from a current chromaticity location to the target, the vector is henceforth called as the *bearing vector* with a length D. D is the distance from the current chromaticity coordinate to the target. Both the positive and the negative side are divided into four segments, called *membership sectors*. Each of these four membership sectors has a certain *increment value* according to importance: *Large* (*L*), *medium* (*M*), *small* (*S*) and *none* (*N*). These sectors are defined by an angle between the corresponding line and the bearing vector: $\alpha_L = \pi/8$, $\alpha_M = \pi/4$ and $\alpha_S = 3\pi/8$ are used in this implementation. Locating lamps to their corresponding membership sectors is described more closely in chapter 5.3.2.

On the negative side all the membership sectors originate from the current chromaticity coordinate. This is because all lamps on the negative side will always stay on that side no matter how close we get to the target from a direction of an original chromaticity coordinate.

On the positive side the lines separating the membership sectors however originate from four different locations, all located along the bearing vector. The first line separating the sectors N and S originates from a point 1/4D distance from the current location, the second line separating the sectors S and M originates from a point 1/2D distance from the current location and the third one separating the sectors L and M originates from a point 3/4D distance from the current location. This is because lamps located behind or close to the target are the most relevant ones.

During the chromaticity controlling each lamp in the used model is being adjusted and membership sectors define their proportion. There are also four weighting factors (F_{1-4}), described more closely in chapter 5.3.3, which are used to weight the each membership sector's increment value (*L, M, S* or *N*). Because of that the final voltage increment which a lamp receives is a product of the *F* value and the corresponding membership sector increment value (see equation 55). By changing the *F* values system's dynamics can be changed, which is normally done when the target is drawn closer to make system more slow and avoid overshoot. In this implementation membership sectors' increment values were as follows: $L = 1.0$, $M = 0.7$, $S = 0.4$ and $N = 0.25$ Because these values are weighted with F_{1-4} only their relative portion is essential. Here the most significant value *L* is scaled to one. For example, value *S* is only 25% of value L meaning that lamps in membership sector *N* receive only quarter voltage increment when compared to *L* sector's lamps.

Now as we see and can easily imagine the lamps located in the L-sector are the most crucial ones when trying to achieve the target. Reducing negative lamps' voltages and at the same time increasing the voltage of the positive lamps the target coordinate will eventually be reached. As the current point is shifted toward the target the membership sectors and the lamps belonging to them also change after every controlling round and are thus calculated again. The current system state slides to the target with its own dynamics because of positive lamps' suction and negative lamps' thrust. As mentioned earlier the system is stable which eases the controlling a lot. Although the line segment along which the transition to the target is occurred might not be straight the target is always eventually reached (assuming it fits inside the gamut). The whole chromaticity controlling cycle is gone through step by step in chapter 5.5.2.

5.3.2 Equations needed to define lamp's membership sector

In order to define each lamp's membership sector a little vector algebra is needed. The differentiating variable is the angle between vectors drawn from membership area's origin to target and lamp itself. Figure 5-5 illustrates vectors relevant for calculation, *i* is the specific membership sector (*L, M, S* or *N*), D_i is the origin of the specific membership sector and α_i the angle of line separating that sector, θ_n is the angle between two vectors from D_i to the target T and to the specific lamp L_n. If the lamp is on the negative side same equation applies, only bearing vector $\overrightarrow{D_iT}$ is the opposite $\overrightarrow{TD_i}$. [42]

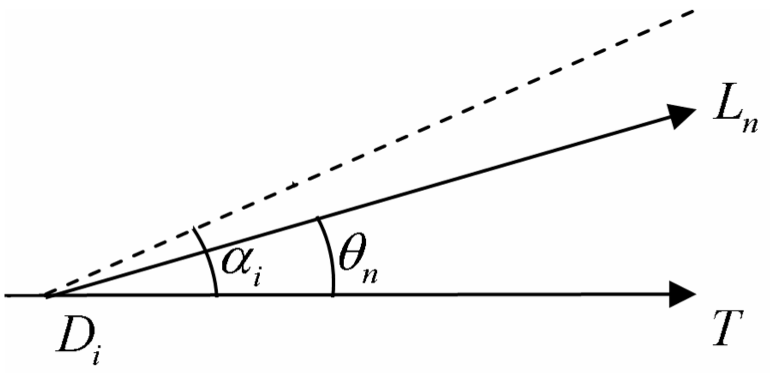

Figure 5-5. Vectors needed to define membership sector

Equations 45-48 are needed for calculating membership sectors. The first equation is used to decide whether a certain lamp is on the negative or on the positive side. [42]

$$\left\|\overrightarrow{AB}\right\| = \sqrt{(B_1 - A_1)^2 + (B_2 - A_2)^2} \tag{45}$$

$$\begin{array}{ll} \overrightarrow{D_i L_n} \cdot \overrightarrow{D_i T} > 0 & ; positive \\ \quad else & ; negative \rightarrow \overrightarrow{D_i T} = \overrightarrow{TD_i} \end{array} \tag{46}$$

$$\theta_n = \cos\left(\frac{\overrightarrow{D_i L_n} \cdot \overrightarrow{D_i T}}{\left\|\overrightarrow{D_i L_n}\right\| \left\|\overrightarrow{D_i T}\right\|} \right) \tag{47}$$

$$\alpha_{i+1} \le \theta_n < \alpha_i \quad ; L_n \in i \tag{48}$$

By this simple calculation lamp L_n can be placed to its rightful sectors *i*. This calculation procedure must be done each time new information about the system state is received.

5.3.3 Factors and increment values

There is variable number of steps that have to be taken before the target is reached. If the target is on the middle of the adjustable lamps' gamut this number is greatly lower compared to a situation where the target is on the edge of the obtainable area. During each iteration step the system state has to be measured, so an integration time of a used measurement device is the most crucial thing affecting the whole controlling time.

Each membership sector has a corresponding increment value that is added to each sector's lamps' current voltage value, on the positive side increment values are positive and on the negative side negative. Obviously L-sector has the biggest increment and N-sector the smallest. Choice for each increment value affects the controlling system's characteristics, bigger increment values will provide faster rising time but also greater overshoot and possibly a longer settling time.

In order to optimize the controlling requirements following simplification is proposed: the system should be fast when target is far away to minimize the rising time and when it is drawn closer it should slow down to minimize the overshoot and settling time. This is done by weighting the factors in portion to color difference ΔE_{00}. The area surrounding the target is divided into four segments with different ΔE_{00} values, each area has its own factor that is used to weight the increment values of different membership sectors. Figure 5-6 illustrates these different sectors.

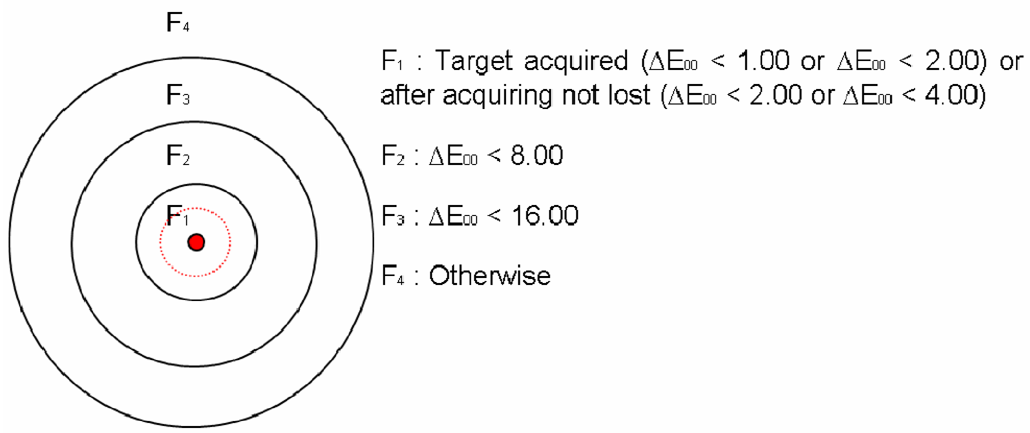

Figure 5-6. F_{1-4} are the weighting factors which change according to distance from the target. Radius of the circles has no real-life equivalency.

Sector F_1 differs from the three other sectors because it defines whether the target is acquired and it also has varying conditions. As noted before when the target is considered as "not-acquired" the conditions $\Delta E_{00} < 1.00$ or $\Delta E_{00} < 2.00$ must be fulfilled in order to transit to "acquired" -state. However if the target is "acquired" it is considered as "not-acquired" after $\Delta E_{00} > 2.00$ or $\Delta E_{00} > 4.00$. It can be comprehended in a way that $F_1 = 0$ means no lamp adjustments are made when the target is reached.

Now we have a group of different controlling parameters that do not have a clear relationship and some of them are even overlapping in some way. Because of this, rather than trying to find the optimum way or mathematical model, a genetic algorithm was used to optimize the parameters, this is handled more closely in chapter 5.3.6.

5.3.4 How to decide whether the target is reachable or not

In some scenarios the target could have been set outside of a possible controlling area or chromaticity-illuminance combination is not achievable, in these cases futile controlling is not desirable. Controlling system should inform the user if the target is not reachable and minimize the color difference ΔE_{00}. A prior geometrical examination can be used to define whether the target chromaticity coordinate is reachable or not, but in order to know if the chromaticity-illuminance combination is also achievable a few iteration rounds combined with geometrical approach are needed.

We have one case and two sub-cases that are needed to make the decision whether the target is attainable. If the answer to the question one is negative target chromaticity coordinate is not reachable in any circumstance. However if it is positive, the two following sub-cases (*a* and *b*) have to be gone through. A negative answer to both of them will result to non-achievable result.

1. Is there any lamp on the region separated by a line passing through the target point and perpendicular to the bearing vector? Illustration of this is seen in Figure 5-7 where this region is marked with a question mark.
    a. Can illuminance of any positive side lamps be increased?
    b. Can illuminance of any negative side lamps be decreased?

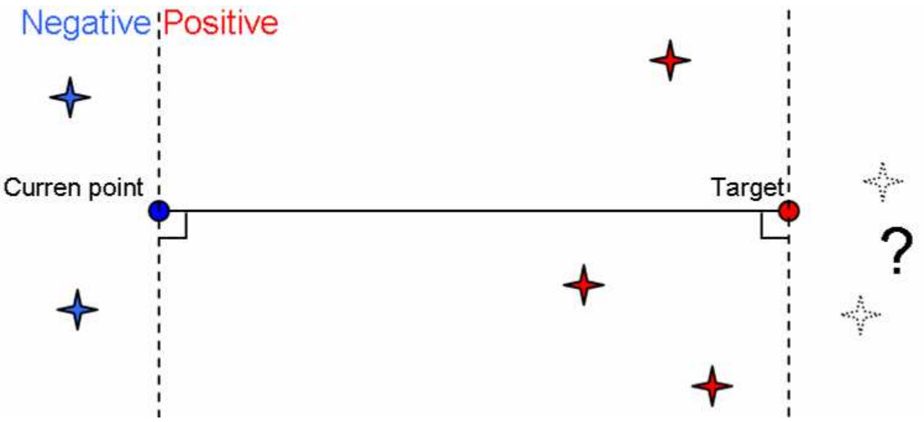

Figure 5-7. Is target reachable or not?

The first question can be made after the system initial state is measured, not beforehand. This can seem strange if we think that the color gamut is constructed by certain lamps and that a target outside that color gamut could not be obtainable. However this is valid only when there are no interfering light sources outside the color gamut. For example, if a very saturated red light source external to the controllable lamps is used, the system initial state can be located outside the color gamut constructed by the controllable lamps. In this case the target could be achievable regardless of its chromaticity coordinate

5.3.5 Calibrating the controlling model and locating lamps' gravity points

Before any controlling can be done the system must be calibrated using a calibrated measurement device, calibration of which was wielded in chapter 4.2.6. Only if the system is calibrated using a calibrated device will it produce accurate results. Although calibration can be done by any colorimetric measurement device it should correspond to the one used during controlling.

As mentioned each lamp is managed as a gravity point, each of which has its location defined by a chromaticity coordinate. The first step is to measure each lamp's chromaticity coordinate and place them into a model based on CIE 1931 chromaticity diagram, CIE 1976 could also be used as well. The lamps are measured one at a time first using maximum and then minimum voltage, measured characteristics are the chromaticity coordinate and the minimum and maximum illuminance value. This data is then saved and the lamps are placed into the model according to their chromaticity coordinate. A typical model after calibration can be seen in Figure 5-8 where unfortunately overlapping gray codes represent chromaticity coordinates of calibrated lamps, the picture itself is taken straightly from SimOne's light controlling software (Autolights) itself.

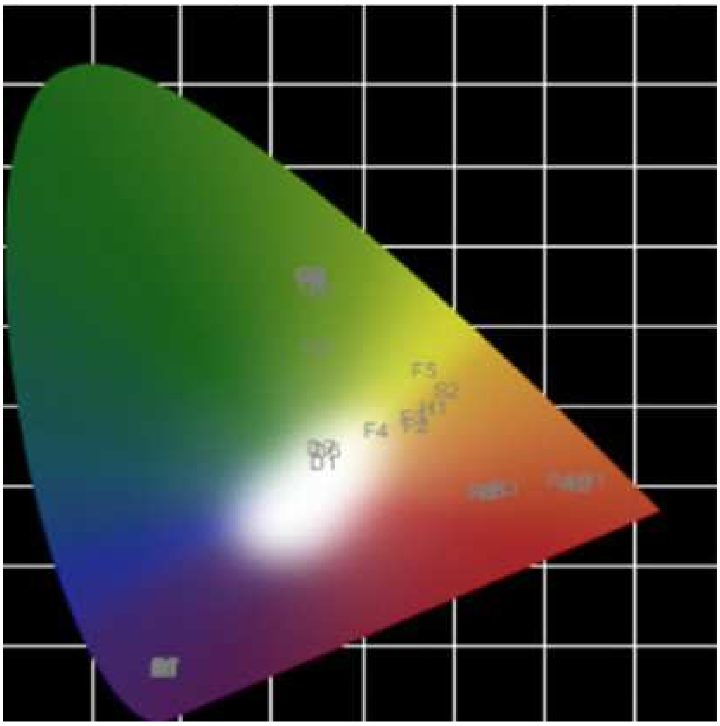

Figure 5-8. CIE 1931 based lamp model after calibration

Before the calibration procedure is started possible interference must be reduced as much as possible. In order to do this the most basic action is to remove the biggest error sources. In order to do that the most basic actions are darkening the test environment, removing any interfering light sources, removing personnel from the test environment and pre-heating the lamps.

5.3.6 Calibrating the control parameters using a genetic algorithm

As mentioned earlier in the chromaticity controlling system there are various controlling parameters and their cross-effects and regularities are hard to predict. In order to solve this optimization problem genetic algorithms are introduced.

Genetic algorithm is a powerful tool to find near-optimum solutions to these kinds of problems. Genetic algorithm itself is based on evolution; combining different parts of good solutions randomly will result to even better solution with high probability. Tuning controlling parameters using genetic algorithm, hence abbreviated GA, should deserve a thesis of its own. This thesis willingly just scratches the surface and explains GA usage in this situation very briefly. If interested the reader should study, for example, the two books used as reference here. [43] [44]

The controlling parameters tuned with GA are the weighting factors F_1, F_2, F_3 and F_4 which are unsigned and eight bits long. Each population member is constructed by joining F_{1-4} together thus forming a 32 bits long member. After GA process these members are decoded back to numerical values F_{1-4}. These factors will define many controlling system characteristics like the rising time and the settling time. Used fitness function is the Integral of the Square Error criterion, hence abbreviated ISE, while ΔE_{00} being the error. Equation 49 resembles ISE criterion which is minimized. [43] [44]

$$Fitness = \int_0^{\infty} \Delta E_{00}{}^2(t)dt \tag{49}$$

Genetic algorithm principle is divided into four main steps which are as follows: [43] [44]

1. Starting: create a new starting population of size *n* randomly. In this case values are limited between 0 and 1.0.

2. Run controlling for each member of the population, this results in fitness values. Here we will use a chosen number of controlling scenarios, diversity of fitness scenarios is as essential as diversity of the starting population. So using both high and low illuminance reddish, bluish, greenish and whitish scenarios for each member of the population are suggested. Fitness value of an individual member is thus the sum of the fitness values of all the scenarios.

3. Remove the worst members of the population according to ISE criterion, in this case 20% of population will face extinction. The percentage could be more or less.

4. If the population is not sparse, such as more than ten, place remaining population into a mating pool and breed them with each other, this is called a recombination. However if population has grown thin the algorithm stops and the fittest individual is the winner.

5. If population is still considerable return to step 2.

In the step four the recombination is done using a *crossover* method which will combine the genes of parents to form an offspring. A new crossover index with same number of bits as a member population's individuals is randomly created during each round. Recombination phase is illustrated in Figure 5-9 where each character represents one bit, two eight bit parents produce one eight bit child. [43] [44]

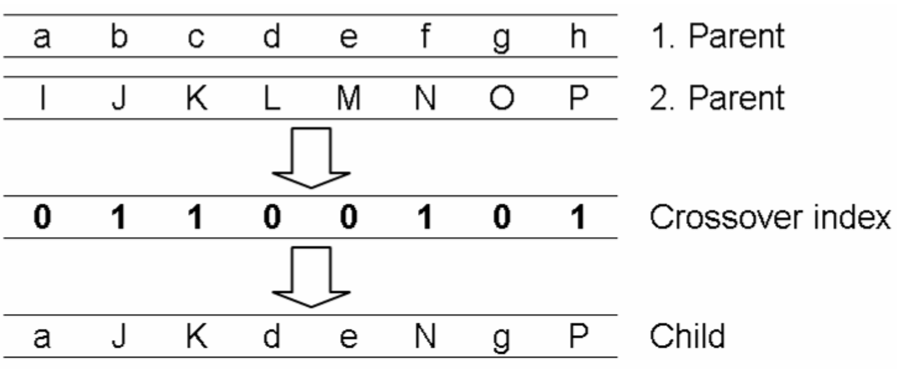

Figure 5-9. Crossover, aka the recombination [43]

Each *F* is represented using eight bits, which result in 256 different values for one factor and a total of 32 bits for one member of the population. The number of bits is kept low because the fitness function is in fact not a normal function, but a real-life controlling cycle which will last for a one minute for each member of the population per scenario. With a starting population of 200, eight scenarios and 20% extinction it can take little over four days to get the population drop below 10. Although one minute is the maximum controlling time, in order to decrease the total time span after five consecutive measurements where the target was acquired controlling will stop and switch to a new scenario or a next member of the population. [43] [44]

Because of a small quantity the starting population should be evenly distributed, after a successful run the starting range of 0.0 to 1.0 should be situated more tightly around the suitable value of each *F* and a new population should be created. [43] [44]

Results of the GA are represented in Chapter 6.4.2 more closely.

5.4 Controlling illuminance

Because the illuminance (E_v) controlling is separated from the chromaticity controlling it is very straightforward and traditional. The system basically is the most common discrete one variable feedback control loop illustrated in Figure 5-10 where y_{ref} is the target illuminance, y the current system state and e the difference between these two. The top system represents the real hybrid flow chart and the bottom one is its normal representation. In this case the digital-to-analog converter is the National Instruments' I/O cards and the analog-to-digital converter is the used measurement device, Ocean Optics USB4000. Because the system was impossible to model mathematically, normal observation had to be left out and concentrate on somewhat intelligent controller parameter tuning. [33] [45]

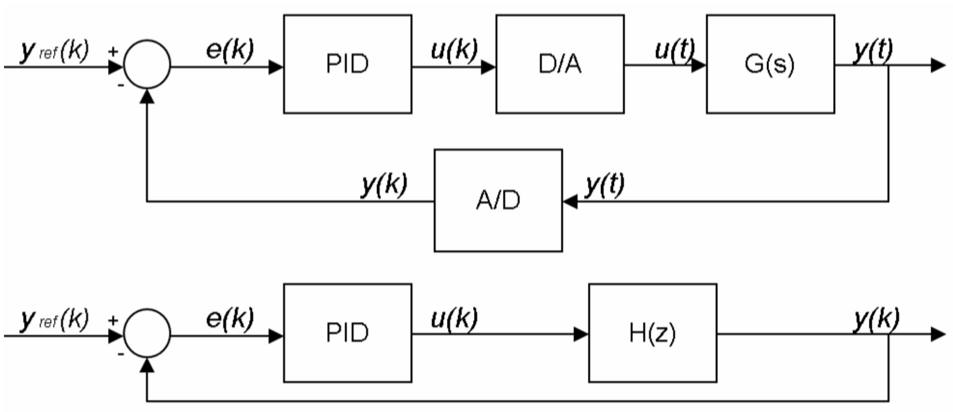

Figure 5-10. Illuminance control system [46]

5.4.1 PID controller

As noticed the system is controlled using a very classical method, the proportional-integral-derivative (PID) controller which covers about 90-95 percentage of all controlling problems. If the reader is not familiar with PID controllers besides this presentation he or she can find a great variety of good literature covering the theory, for example the books used here as references will give extensive viewpoint to the subject. [33] [45]

The PID controller tries to correct error between measured system state and target value using a combination of three separate parameters: proportional (U_P), integrative (U_I) and derivate (U_D). The P term defines reaction to the current error, the I term reaction to the sum of errors and the D term reaction to the change rate of the error. The weighted output changes the controlling term of the process, in this case the voltage, and the system state via it. [33] [45]

The sum of three terms is seen in equation 50 and the terms in equations 51-53 [33] [45] [46]:

$$U(s) = U_P(s) + U_I(s) + U_D(s) \tag{50}$$

Where

$$U_P(kh) = K_p e(kh) \tag{51}$$

$$U_I(kh) = K_i \sum_{i=-\infty}^{k-1} e(ih)h \tag{52}$$

$$U_D(kh) = K_d \frac{e(kh) - e(kh-h)}{h} \tag{53}$$

Sampling period h is directly defined by the integration time of the measurement device and depends on the device saturation to a peak value of a measured spectral power distribution. So the time domain sampling period is constantly changing, because of that we will define sampling period's length *h=1*, no matter what the real-life time was.

Changing target illuminance range (circa 1-50000 lux) and controllable lamps quantity means different reactions to controlling voltages. This is why controller parameters are optimized for a certain scenario (1000 lux), that is used as a reference for intelligent parameter tuning. Because PID-controller value affects to all the lamps equally the output is always limited to 0-10V. The K_P, the K_I and the K_D term are weighted using equation 54.

$$K_{current} = K_{1000lux} * \frac{1000.0}{\sum E_v} \tag{54}$$

Where $K_{current}$ is the current factor, $K_{1000lux}$ is the corresponding factor optimized for case where lamps' maximum illuminance is 1000 lux and $\sum E_v$ the sum of used lamps' maximum illuminance.

The integration term typically saturates especially when the target cannot be reached because it is out of range and lamps need to heat up. To overcome this, a simple anti windup block is used, the integral term is limited to $U_i < 1.0$ and when the target is reached the integration term is set to zero. When both chromaticity (in its own control cycle) and illuminance are controlled, which is the normal case, the integration term is even more dangerous. For example, ΔE_v could exist but although chromaticity could have greater affect to ΔE_{00} and increasing illuminance would cause chromaticity to drift away. During each illuminance controlling round when ΔE_v is present integrator term would be increased and the constant illuminance error ΔE_v would finally saturate the integration term. It is encouraged to keep K_I as small as possible or even set it to zero, as done here, when chromaticity cycle is present. Some simple parameter tuning is also introduced, if $-2.0 > U(s) > 2.0$ controlling factors are halved. [33] [45]

Differing from normal use of a PID controller in this case it will not give absolute or relative controlling value, but an increment or decrement that will be added to every lamp's controlling voltage. [33] [45]

Used PID-controller parameters are listed in chapter 6.4.3.

5.5 Whole controlling cycle

5.5.1 Overview

As mentioned earlier ambient light controlling has two distinguishing features; chromaticity and illuminance. When controlling the chromaticity we can also support the illuminance controlling, if the current illuminance is behind of the target we can help the problem by trying to limit turning lamps off and favor lamp ignition. The other way round is not that simple, when the illuminance is controlled using the

PID controller the lamps are only divided into two groups; adjustable and non-adjustable.

Figure 5-11 illustrates a simple flowchart of the whole controlling cycle. Before the actual control cycle we have a preliminary section (see Table 5-2). The pre-controlling is done in order to set the dynamic range near the target. This is done by first making an educated starting guess; if the same scenario has been previously controlled and achieved, voltage values from that scenario will be used as a starting guess. Otherwise the lamps are presumed to be linear through their operating voltage range and starting voltage levels are given accordingly. If controllable lamps' maximum illuminance sum is lower than 100 lux an exception will be made, which results to the usage of maximum controlling voltage. After that the illuminance is controlled by the illuminance control cycle until the level is approximately the same as the target. The accuracy of this approximation is not that relevant and 15% illuminance level difference is acceptable, and can be seen as a good rule of a thumb. This preliminary section minimizes the rising time and makes sure that dark/light adaptation commences as early as possible. After the preliminary control section system transits into the actual control section and cycle.

First in the main control cycle the system state is measured. Secondly, if the target is achieved or a previously achieved target is not lost the system state will be measured again after a while. If the target is not achieved the system is adjusted. Thirdly, if the target illuminance or chromaticity is not acquirable the user will be notified about that and the controller will minimize ΔE_{00}.

Based on these circumstances the actual light controlling cycle is divided into two different processes; the chromaticity controlling (Chapter 5.5.2) and the illuminance controlling (Chapter 5.5.3). The selection criterion between these cycles is ΔE_{00}, or more precisely the color difference caused by the chromaticity error, ΔE_{00C}, and the color difference caused by the illumination error, ΔE_{00I}. When calculating ΔE_{00C} the current illuminance is set equal to the target's illuminance level. ΔE_{00I} is calculated respectively using the target's chromaticity coordinate for the current system state. By this we can distinguish which parameter has the greatest impact on ΔE_{00} and focus on that. The chromaticity and the illuminance controlling theory are presented in chapters 5.3 and 5.4. Both controlling blocks will result in new lamp voltage values and thus a new system state. Because of lag the system state is allowed to settle before it is measured, this will take a few tenth of a second.

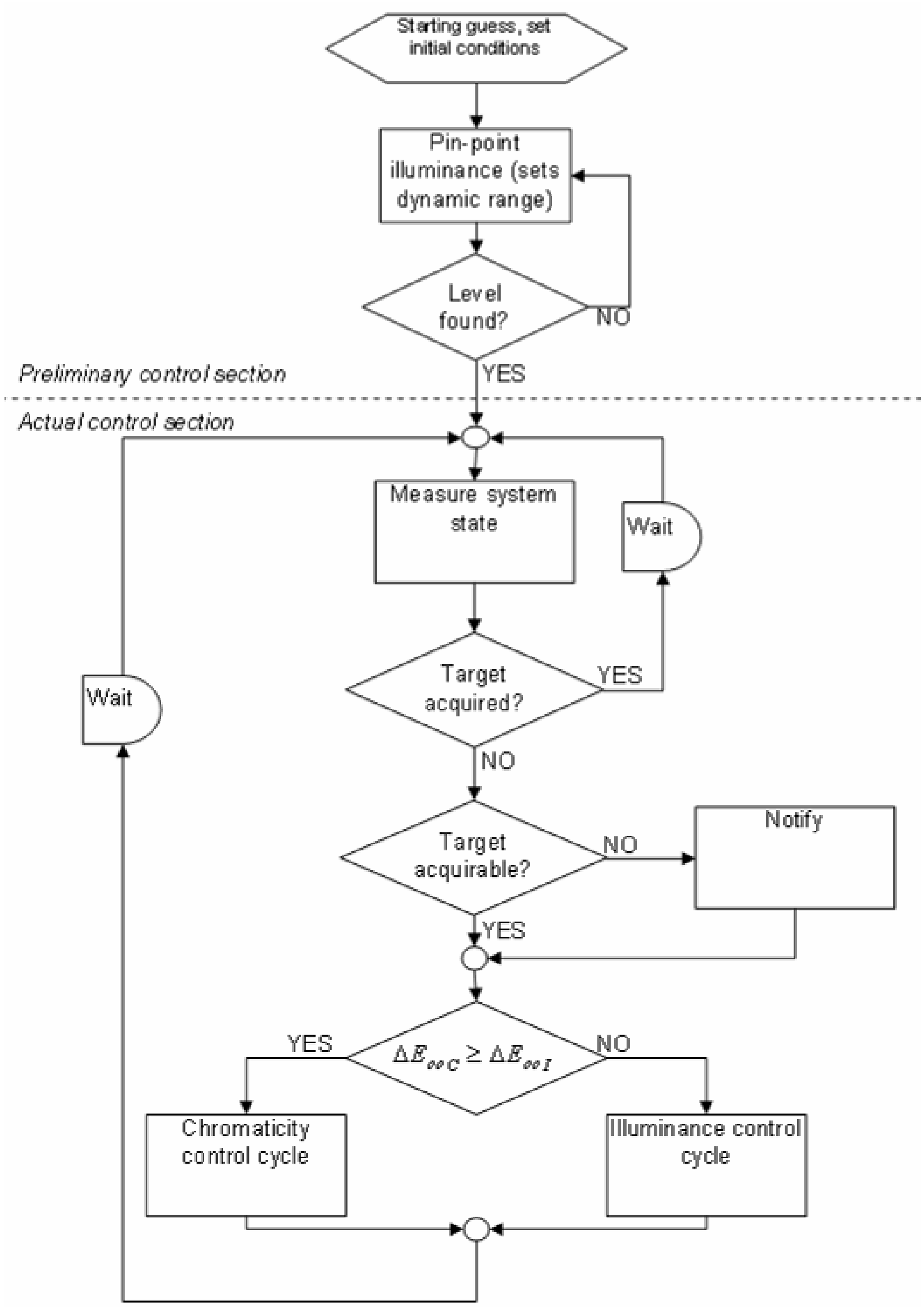

Figure 5-11. Flowchart of the controlling process, chromaticity control cycle is described in chapter 5.5.2 and illuminance control cycle in chapter 5.5.3

5.5.2 Chromaticity controlling cycle

Chromaticity controlling cycle can be divided into five different sequential steps. These main parts are all gone through during the chromaticity controlling cycle. There are also a few sub-steps, some of which are complimentary and depend on preceding conditions. All these steps are seen in a flowchart illustrated in Figure 5-12 and explained more closely in Table 5-1.

The first step is to divide the lamps into three different membership sectors on the negative and the positive side. The dividing itself is previously gone through in Chapters 5.3.1 and 5.1.2.

The second step is not directly a consequence of the first step and their execution order is thus interchangeable. Here the used weighting factor F will be calculated according to the prevailing color difference ΔE_{00}, however value F_1 is not an option because in that case target would have been acquired and this control cycle would have never been reached. This step is based on Chapter 5.3.3.

The third step will calculate new voltage values for each lamp. All the positive lamps will receive an increment and the negative lamps a decrement to their previous voltage value. Lamps' increment size depends on their membership sector and weighting factor F as seen in equation 55.

$$lamp\_increment = membership\_sector\_increment * F_{2-4} \quad (55)$$

After the increments and the decrements are applied, the lamps' voltage values which are out of bounds will be corrected, meaning that if the lamp's controlling voltage is over the maximum or below zero it will be corrected accordingly.

The fourth step will handle turning the lamps on or off. As noted before because the lamps' have minimum operating voltage turning them on or off will result a step response. Because of this we have a set of ground rules on when to allow this kind of action. Switching lamps on and off should also support illuminance controlling.

1. Conditions resulting to turn a positive lamp on
   a. Current illuminance level is smaller than the target, $E_{v\_current} < E_{v\_target}$
   b. All the positive lamps are driven with maximum operating voltage, thus depleting the dynamic range from that end.
2. Conditions resulting to turn a negative lamp off
   a. The current illuminance level is greater than the target, $E_{v\_current} > E_{v\_target}$
   b. All the negative lamps are driven with minimum operating voltage, thus depleting the dynamic range from that end.

If these conditions apply, a lamp from the most relevant negative or positive membership sector with the smallest *order* number will be turned on or off. The order number, described more closely in Chapter 6.1, is used because it will produce more uniform illumination. Smallest numbers are in the front of SimOne and biggest on the back. Hence the laminated region is automatically weighted to the front.

The fifth and the last step will apply newly calculated voltages to each lamp thus changing the system state.

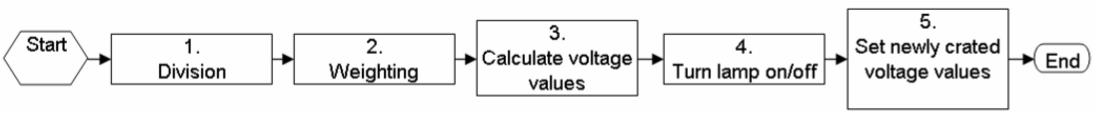

Figure 5-12. Chromaticity control cycle flowchart

Table 5-1. Chromaticity control cycle steps' functions

Chromaticity
1. Division
1.1. Divide lamps according to their membership sectors
1.1.1. Negative and positive (L, M, S and N)
1.1.2. Each sector has its own increment value
2. Weighting factors
2.1. Calculate ΔE_{00}
2.1.1. Select appropriate weighting factor ($F_{2\text{-}4}$)
3. Calculate voltage values
3.1. Calculate new lamp voltage increment/decrement
3.1.1. Increment for positive lamps
3.1.2. Decrement for negative lamps
3.1.3. Values are weighted using appropriate factor $F_{2\text{-}4}$ (*increment value* * $F_{2\text{-}4}$)
3.2. Correct impossible values
3.2.1. If any lamp's new voltage value is > *max* set it to *max*
3.2.2. If any lamp's new voltage value is < 0.0 set it to 0.0
4. Turn lamps on/off
4.1. All positive lamps are driven with maximum voltage or turned off and $E_{v\_current} < E_{v\_target}$?
4.1.1. Turn a lamp belonging to most momentous sector with lowest order number on
4.2. All negative lamps are driven with minimum voltage or turned off and $E_{v\_current} < E_{v\_target}$?
4.2.1 Turn a lamp belonging to most momentous sector with highest order number off
5. Set newly calculated voltage values
5.1 Set each lamp's new voltage value

(Off = 0.0V, On = minimum operating voltage)

5.5.3 Illuminance controlling cycle

Besides the chromaticity there is also the illuminance control cycle. A distinctive feature of this cycle is its different activity in the preliminary and in the actual control section. Figure 5-13 represents the flowchart of the illuminance control cycle and Table 5-2 describes the controlling steps more exactly. The preliminary control section is explained more closely in Chapter 5.5.1 as well.

In the actual control section the illuminance control cycle is founded on the classic PID controller described in Chapter 5.4. Although it has a few correcting steps that are necessary because of the nature of the controlling problem. Firstly a new voltage increment is calculated using the PID controller and summed up to previous lamps' voltage values. Secondly impossible voltage values exceeding the controlling range will be cut out accordingly.

Thirdly, as with the chromaticity controlling, some rules on when to turn lamps on or off also apply during the illuminance control cycle. If the dynamic range has ran out a lamp will be turned on or off. As it can be seen there are few rules when this kind of action will be taken, all sub-conditions must apply when deciding whether to take an action:

1. When to turn lamps on during illuminance control cycle
    a. If all lamps are driven with maximum voltage…
    b. …and there are still lamps that can be turned on
2. When to turn lamps off during the illuminance control cycle
    c. If all lamps are driven with minimum voltage…
    d. …and more than one lamp is still switched on

If both the chromaticity and the illuminance are controlled almost always the chromaticity control cycle takes a care of turning lamps on or off. This is why the chromaticity controlling requirements are not taken into consideration as illuminance was taken during the chromaticity cycle.

The last step is applying the new voltage values resulting in a changed system state.

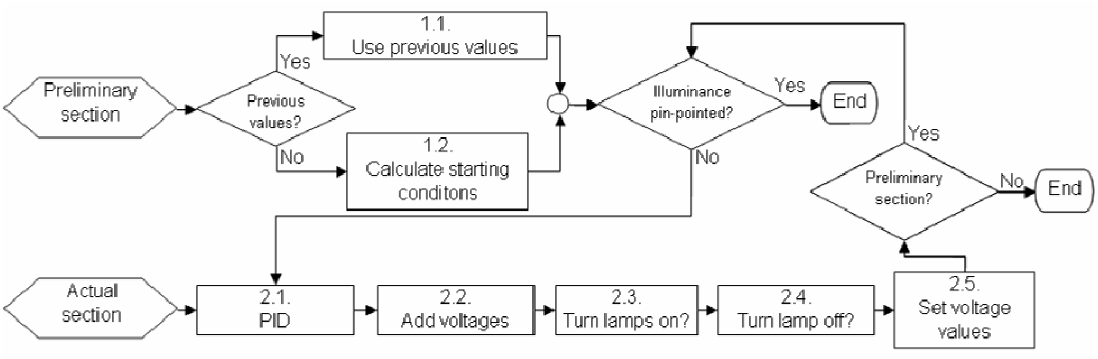

Figure 5-13. Illuminance control cycles flowchart

Table 5-2. Illuminance control cycle steps' functions

Illuminance
1. Preliminary control section, set starting conditions and pin-point dynamic range
1.1. Use scenario's previous voltage values, if any
1.2. If no starting conditions present, all lamps get the same starting voltage
1.2.1. Calculate scenarios lamps' maximum illuminance
1.2.2. If maximum illuminance < 100 lux use maximum voltage
1.2.3. Else: Voltage *value = target illuminance * max. voltage / max. Illuminance*
1.3. Adjust lamps according to step 2 until the illuminance level is pin-pointed
2. Actual control section
2.1. Calculate voltage increment using PID-controller
2.2. Add voltage increment to adjustable lamp's voltage value
2.2.1. If any lamp's new voltage value is > *max* set it to *max*
2.2.2. If any lamp's new voltage value is < 0.0 set it to 0.0

2.3. If all lamps are driven with maximum voltage?
    2.3.1. Turn a lamp with smallest order number on
2.4 If all lamps are driven with minimum voltage and there are more than one controllable lamp
    2.4.1. Turn a lamp with biggest order number off
2.5. Set each lamp's new voltage value according to NI-DAQ address

(Off = 0.0V, On = minimum operating voltage)

5.5.4 Controlling time span

In order to analyze and then minimize the controlling time the controlling cycle must be divided into parts which all have a corresponding time span. By studying this we will have a clue on what is really affecting the speed and what is not. We will assume that code running and calculation time is trivial when compared to the other time-consumers and the target is inside the lamps' current dynamic range, so lamp heating does not take time.

1. We have *n* number of iteration rounds after which the target is reached, each round lasting *t* milliseconds, total time span *X* is a product of these two, $X = n * t$

    a. By reducing iteration rounds *X* might decrease, but not necessarily. Less iteration rounds would mean bigger steps, which would need more reliable guesses. A big step into wrong direction would result to a major drawback.

2. Each round lasts a varying time *t*, which is affected by

    a. Controlling calculations, trivial

    b. Lamps and NI-DAQ response time after new voltage values are set, ~200 ms for halogens and other than high-luminance lamps

    c. Device integration time (sample period) with 50% saturation using the cosine corrector defined in chapter 4.2.4 and an external halogen light source seen in Figure 4-7. Also 50 lux and 3000 ms sample period is used as an example of low illuminance.

        i. 50 lux -> 3000 ms (16 % sat.)

        ii. 500 lux -> 3000 ms (50 % sat.)

        iii. 1000 lux -> 1500 ms (50 % sat.)

        iv. 10000 lux -> 150 ms (50 % sat.)

        v. 50000 lux -> 32 ms (50 % sat.)

Here we can distinguish that the slowest part is not the system response as in common controlling problems, but the measurement device's speed that lengthens the sampling period and thus the whole controlling time span. By using a faster measurement device the controlling time span could be decreased dramatically in low illuminance levels. On high levels (> 5000 lux) differences paybacks would be smaller. It must be stated that 16% saturation, although most of it is caused by the dark current, is enough in this case but to maximize the dynamic range 50% would be the optimum.

6 SOFTWARE AND IMPLEMENTATION

Implementing the controlling algorithm played a significant but also a time consuming role in the whole process. Because the need for light controlling software was one of primary reasons to conduct this thesis, so it deserves a bit of attention as well. Also a real-life implementation was the only way to test the controlling algorithm.

The idea was to make both independent light controlling software and a light controlling module that could be utilized by other programs. In fact the independent software can be seen as a user interface that utilizes the light controlling module and has a few other functionalities. Nevertheless both implementations are called *Autolights*. This chapter emphasizes a viewpoint where Autolights UI utilizes the light controlling module.

Implementation was done using Microsoft Visual Studio 2005 developing environment and .NET framework 2.0, the implementation also required a little bit of C/C++ for measurement device controlling. The decision to use these tools came from the company and the reason was to verify compatibility to the other previously created software components. Although from this thesis point of view the implementation language is irrelevant and totally depends on the developer.

6.1 Terms and data structure

From hereinafter we will use a few terms for data structure that should be clarified. Figure 6-1 represents the data structure.

Calibration data stores each lamp's *chromaticity coordinate* and *illuminance* level with a minimum and a maximum voltage. This is kept separate so that the system could be calibrated without making changes to scenarios.

Scenario is an entity that holds all the information needed to control lighting, excluding *calibration data*. This means following information: *target*, *controller parameters*, *adjusting type* and *lamp data*. For each lamp there is also the following data: *adjustability* in current scenario, *voltage value* (if the lamp is forced on or off) and *initial state* if the scenario has been previously achieved.

Lamp data represent each lamp and holds information about *lamp ID, name, order, I/O address* and *control type*.

Lamp ID is unique for each lamp and distinguishes them from each other.

Name simply means lamp's name in the UI, for example F11, D65, red etc.

Order is lamp's physical location in a lamp row.

I/O address is lamp's address in NI-DAQ software.

Control type has two possibilities; voltage controllable or on/off -type.

Adjusting type means scenario's adjusting, it can have three different values: *illuminance*, *chromaticity* or *both* and refers to controlling cycles presented in chapter 5.

Description holds a free form description for a user about the scenario.

Category is a categorizing term which is used to group the scenarios, for example "office", "home" or "outdoors".

Target holds information about the desired output response: chromaticity (x, y) and illuminance (E_v).

Controller parameters hold the information about different membership sectors' angles, criteria when the target is achieved or lost, and used white point. These are dealt more closely in the previous chapters.

Adjustability can have two values, true or false. It expresses whether a lamp can be adjusted in current scenario or is it left out.

Voltage value of a lamp is an attribute of non-adjusted lamp and means simply the voltage with what the lamp is driven. Normally this is used to force specific high-luminance lamps on.

Initial state holds a scenario specific voltage values for each lamp which are used when scenario controlling is started. Initial state parameters hold information about voltage values with which the target was most recently achieved.

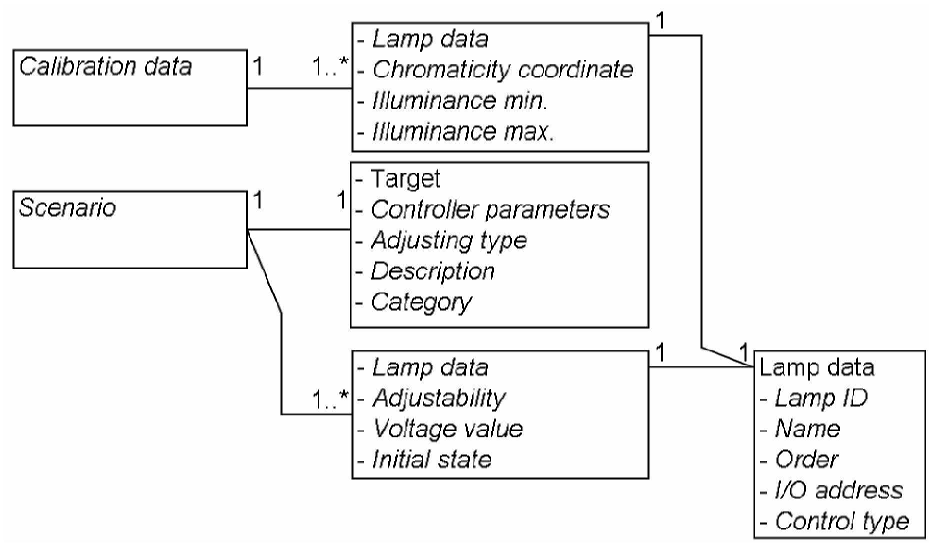

Figure 6-1. Data structure

6.2 Software structure

As mentioned the light controlling software structure can be divided into two levels, here called *the utilizing level* and *the module level*. The utilizing level can be seen as an independent user that utilizes the lighting control module, in this case the user is Autolights software which consists of Manual control and Autolights UI, the module is always Autolights module and its accessories. There are also the third level which is called *the supporting level*, this level consist of programs that support the light controlling, here *Calibrator*, which will calibrate the lights as described in 5.3.5. Figure 6-2 illustrates the software structure.

In the figure arrows represent information and data flow and their direction, while solid arrows are necessary and dotted arrows are compulsory from operation point of view. Dotted rectangles describe a type of a data flow or a type of interaction if it is somewhat unclear. Solid rectangles represent modules that have a specific function.

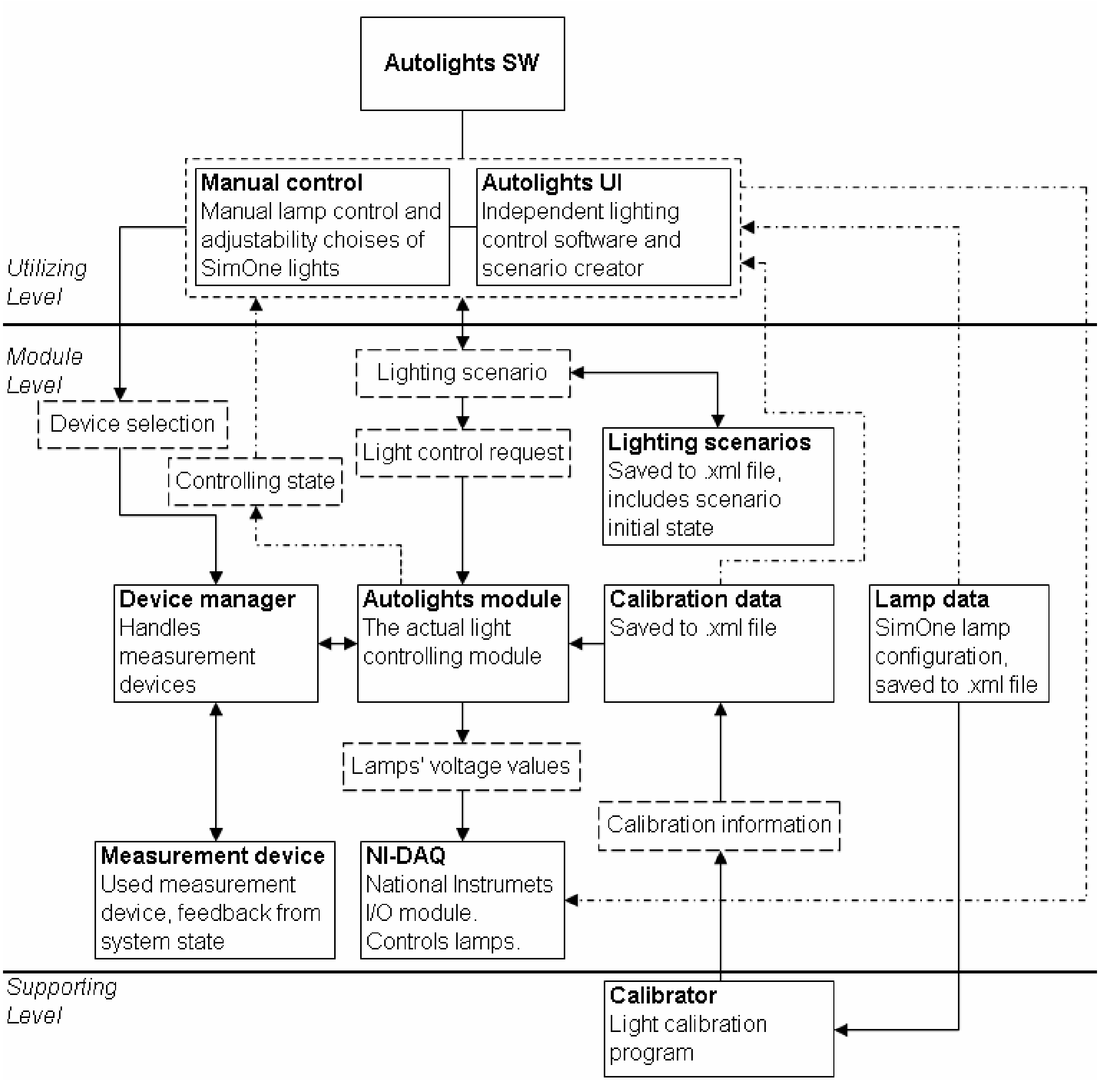

Figure 6-2. Software structure

6.2.1 Utilizing level

On the utilizing level both Manual Control and Autolights UI can be seen forming Autolights Software, although both of them are independent modules that have data exchange. The Autolights SW is used to both manage (create, edit, open and delete) lighting scenarios, control lamps manually, gather controlling data and optimize parameters using GA.

Autolights SW can be seen as an outsider utilizing Autolights light controlling module and therefore it could be replaced by any other program using Autolights module interface. The two compulsory interactions are setting the right used measurement device configuration to the *Device Manager* (i.e. USB 4000) and creating a controlling request based directly on a lighting scenario.

The complementary interactions (which however are used in Autolights SW) are as follows. The *lamp data* is needed in order to create scenarios or control lamps manually, and to visualize the calibration model the calibration data is needed (as seen in Figure 5-8). Also to get controlling information from the Autolights module an action listener must be set, described as *controlling state* in the figure. In order to control lights manually a link to NI-DAQ is needed, controlling is based on lamp's I/O address defined in the lamp data.

6.2.2 Module level

The *Device manager* handles all measurement devices, also the ones named earlier in this thesis. When Autolights module requests specific information of the system state Device manager handles the data interchange with the measurement device and returns the information to Autolights module.

Autolights module can be seen as the heart, all the light controlling functionalities described in chapter 5 are located in this module. The module loads C*alibration data* containing lamps' calibration information and after receiving a proper light control request (lighting scenario) addresses the correct calibration information to the corresponding lamp. In order to change the system state lamps' new voltage values are sent to *NI-DAQ* according to their I/O address.

6.2.3 Supporting level

The supporting level is as necessary as the two other levels but its distinctive feature is invisibility to an everyday user. The main supporting module is *Calibrator* which loads Lamp data and runs the calibration procedure described in chapter 5.3.5. After the calibration run Calibration data is saved into an .xml file.

6.3 Program UI

The part of this thesis' background work was to also implement functional software, here it will be used as an example how the lighting control could be utilized. The following two screenshots are from Autolights Software. The first one seen in Figure 6-3 is taken from Autolights UI advanced controller tab and Figure 6-4 from Manual Control. The three other tabs seen in Figure 6-3 and not represented here are *Device manager* tab described earlier, *Measure* tab to use a current device solely as a colorimeter and *Genetic Algorithm and Data Logging* tab where the GA run presented in chapter 5.3.6 and data logging for chapter 7 were done.

Autolights UI advanced controller tab contains tools to define scenario specific data. *Diagram type* changes the chromaticity coordinate type which is based on the *calibration data*, this change do not affect to chromaticity diagram used in the chromaticity controlling and are solely for the informative purposes preferred by the user. Here CIE 1976 diagram is used instead of CIE 1931. In the diagram the white dot illustrates the target and the red rod current system state. The most recent system state is also displayed in *Measurement values* box. *Controller parameters' used white point* can be chosen from the first radio button. *Target* can be set by entering the numeric values or clicking the wanted coordinate from the chromaticity coordinate. The *adjusting type* can be chosen from *controls* radio buttons. C*ontroller parameters'* information when the target is achieved or lost, incoming illuminance for dynamic range pin-pointing and used membership sector angles is selectable from *controlling values* and *illuminance* boxes. These values are the same as proposed and used in this thesis, changing them via Autolights is considered to be for research and development purposes only. The last textbox is for scenario *description* obviously. Also *scenarios* with corresponding category can be opened, deleted and saved using the respective buttons and textboxes.

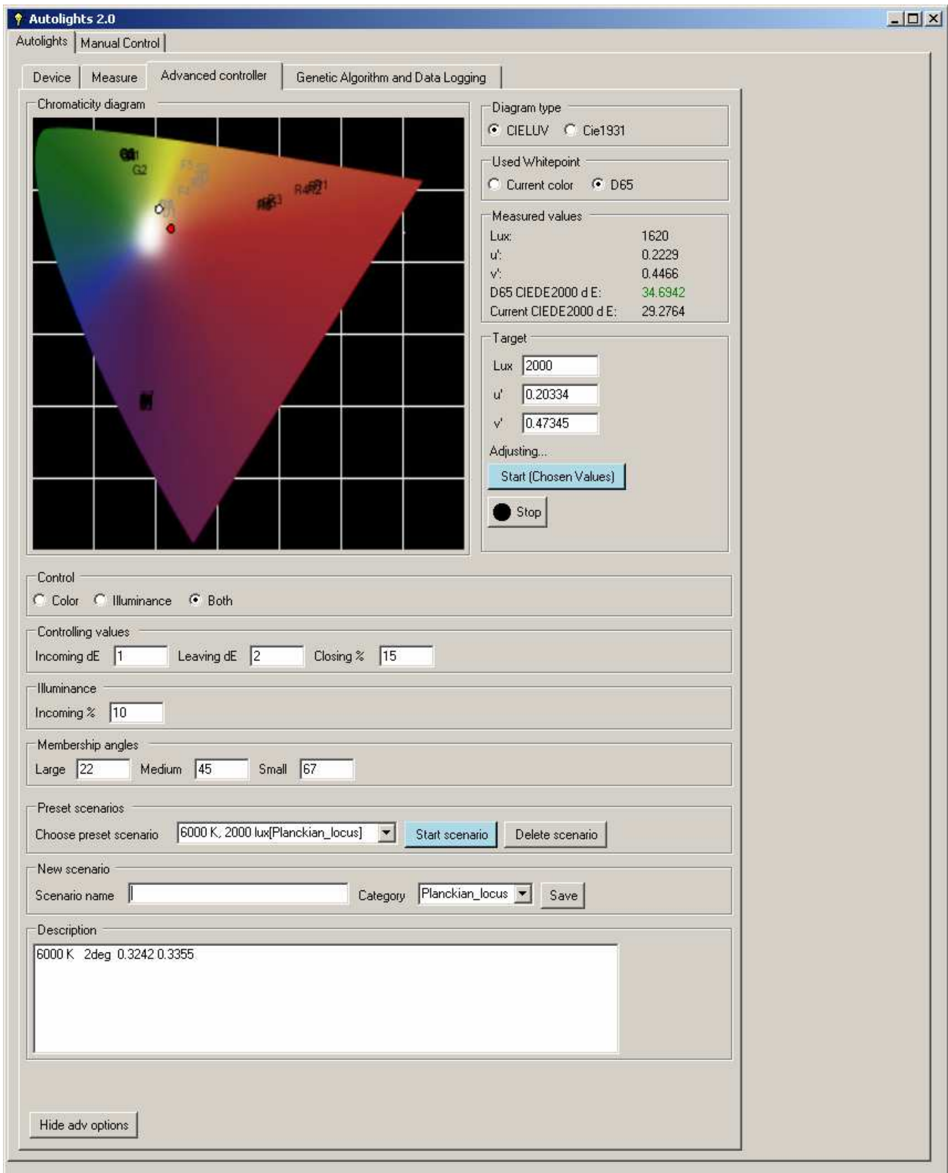

Figure 6-3. Autolights UI

From Manual Control tab each lamp's controlling parameters described in chapter 6.1 can be set. In the UI first checkboxes enable the numeric up-down box for *voltage value* and can be used to force lamp on, if lamp's *control type* is on/off this checkbox sets voltage value accordingly (for example MH1000W). The second checkbox defines the *adjustability* of the voltage controllable lamp. The numerical value tells lamp's current voltage value, here 0.0 for all the lamps.

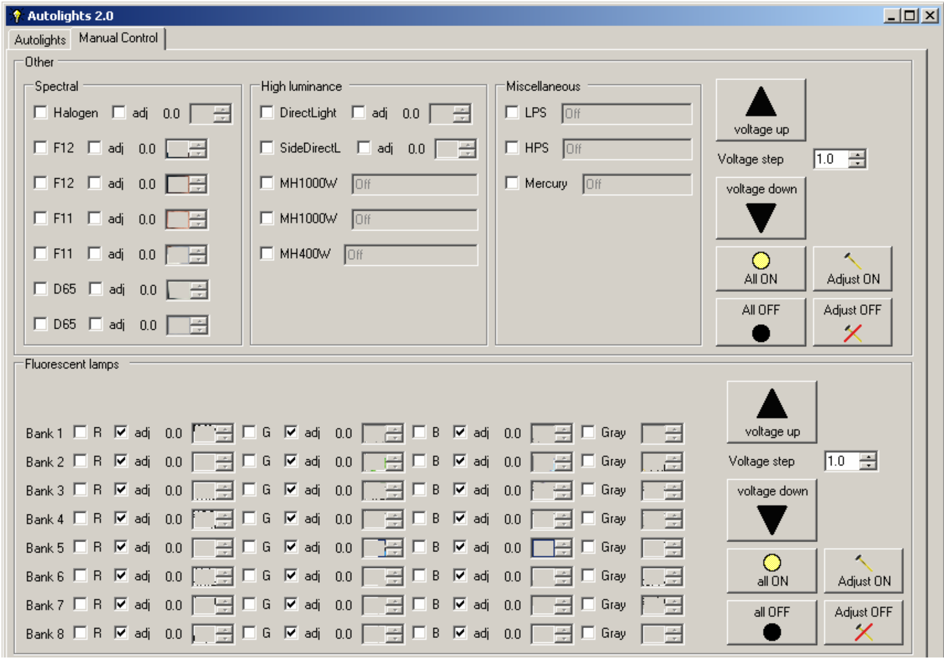

Figure 6-4. Manual Control UI

6.4 Used parameters

As previously mentioned light controlling has a few parameters that can be tuned, in this chapter the parameters used in the implementation are shortly listed.

6.4.1 Chromaticity controller

Although the chromaticity controller parameters were listed in previous chapters they are briefly repeated here.

The used membership sector angles were as follows: $\alpha_L = \pi/8$, $\alpha_M = \pi/4$ and $\alpha_S = 3\pi/8$. The color difference defining use of different weighting factors F_{1-4}: F_1 if $\Delta E_{00} < 2.00 \vee \Delta E_{00} < 1.00$, F_2 if $\Delta E_{00} < 8.00$, F_3 if $\Delta E_{00} < 16.00$ and F_4 if $\Delta E_{00} \geq 16.00$. The increment values weighted with F for both negative and positive lamps were as follows: $L = 1.0$, $M = 0.7$, $S = 0.4$ and $N = 0.25$. And finally the illuminance closing percentage when pinpointing systems dynamic range before actual control section was 15%. Also the used white point in ΔE_{00} calculation is the D65, other option would be to use the current system state as the white point.

6.4.2 GA results

A genetic algorithm was applied using chromaticity controller parameters listed in chapter 6.4.1. GA run consisted of 100 creatures and factors F_{1-4} were weighted around values achieved from a previous run ($F_1 < 0.1, F_2 < 0.125, F_3 < 0.5, F_4 < 1.0$), used scenarios were a red, a blue, a green and a equal energy white and a target illuminance 1500 lux, all the RGB banks were used as controllable lamps. The same test run was once repeated. Results and their relative fitness values are listed in Table 6-1.

As can be noticed also factor F_1 has a value although in chapter 5.3.3 it was stated that when the area for F_1 was reached no controlling was made ($F_1 = 0$). However during the GA run this criterion was not applied which fore chromaticity was controlled also when the target was achieved. All the test runs in chapter 7 as well as the implementation are made using value $F_1 = 0$.

Table 6-1. GA results

Relative fitness	*F_1*	*F_2*	*F_3*	*F_4*
Run 1				
1.0000	0.044	0.061	0.055	0.227
1.0023	0.03	0.046	0.165	0.212
1.0033	0.021	0.008	0.343	0.941
1.0107	0.012	0.017	0.453	0.878
1.0672	0.009	0.016	0.39	0.878
Run 2				
1.0000	0.049	0.112	0.359	0.765
1.1296	0.002	0.04	0.292	0.761
1.2702	0.064	0.098	0.265	0.286
1.2848	0.049	0.112	0.359	0.388
1.3661	0.063	0.098	0.265	0.847

As can be seen in the first run the relative fitness values are almost the same but in the second run much more varying. Results are not straightly utilizable, but give good boundaries what the controlling values should be. Because the starting population (100 creatures) was sparse the results are somewhat biased, bigger starting population would give more "genes" and create a better end population. By interpreting these results the decision was to use following factors: $F_1 = 0.0$ (or $F_1 = 0.03$), $F_2 = 0.07$, $F_3 = 0.15$ and $F_4 = 0.8$. GA also clearly verified the hypothesis that controlling factors should diminish as the distance from the target decreases.

6.4.3 PID controller

The reference controller parameters used for 1000.0 lux were as follows: $K_P = 0.0005$, $K_I = 0.0$ and $K_D = 0.0005$ when controlling both illuminance and chromaticity, $K_P = 0.002$, $K_I = 0.0002$ and $K_D = 0.002$ when controlling only illuminance. Notice significantly smaller values in the first case. The values changed during the controlling as described in chapter 5.4.

6.5 Scenarios

Functional light controlling software would allow repeating the wanted lighting conditions during different occasions and in different locations. While the software gave the tools to fully utilize controlling algorithm, extensive lighting scenarios had to be defined as well. Although these scenarios are not bound to Autolights or vice versa those were used during the software testing and some of them were even used when testing controlling performance and tuning the controlling parameters.

6.5.1 Used scenarios

When defining the scenarios the profound idea was that less is more, number of scenarios should be kept low. The scenarios should cover the most typical use cases in indoors, outdoors and in office, and also the most demanding scenarios in high and low illuminance and when there were maximum reflection. Also more "scientific" scenarios covering the planckian locus were needed, mostly because color temperatures are widely used and well defined, and also those contain great degree of freedom for controller testing purposes.

The scenarios themselves are listed in Table 6-2. Depending on readers background he or she might disagree whether some of the scenarios are necessary, some are missing or some do not represent their purpose well enough. For example, is cloudy day 10000 lux with chromaticity of x=0.295 and y=0.305? However it must be kept in mind that for test repeatability and comparison more important than is office lighting 500 or 700 lux is that lighting conditions are every time the same. [47]

Table 6-2. Used lighting scenarios [47]

Category	Scenario name	Lamp(s)	Illuminance [lux]	Controlling type	CIE 1931 x	CIE 1931 y
Office Light	F11	F11	500	Illuminance	-	-
	F12	F12	500	Illuminance	-	-
	F11	F11	1000	Illuminance	-	-
	F12	F12	1000	Illuminance	-	-
	Precision workstation	Direct light	1000	Illuminance	-	-
Outdoors	Cloudy	All *	10000	Both	0.295	0.305
	Bright day	All *	50000	Both	0.328	0.337
	Cloudy	High luminance & RGB **	-	Chromaticity	0.295	0.305
	Bright day	High luminance & RGB **	-	Chromaticity	0.328	0.337
	Shadow	RGB	1000	Both	0.273	0.279
	Rainy Day	RGB	2500	Both	0.311	0.321
	Road	Mercury	20	None	-	-
	D65	D65	400	Illuminance	-	-
	D65	D65	1000	Illuminance	-	-
Home	Halogen	Halogen	100	Illuminance	-	-
	Bulb	Bulb	30	Illuminance	-	-
Planckian locus	3000-40000K ***	RGB	500	Both	*various*	
	3000-40000K ***	RGB	2000	Both	*various*	

** All but back wall lamps are used, RGB lamps are adjusted and other are forced on*

** High luminance lamps set the illuminance level and RGB lamps are used to correct the chromaticity

**** 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10000, 12000, 13000, 15000, 20000, 25000, 30000, 35000 and 40000 K*

As can be noticed the scenarios cover four categories which are office, outdoors, home and planckian locus. Each category has different typical scenarios offering maximum variety. Some scenarios are duplicated, for example *cloudy* and *bright day*, in other solely the chromaticity is controlled using RGB lamps and in also the illuminance is adjusted. Planckian locus scenarios have two different illuminance levels and cover cases from very cold to very warm. The topmost value of 40000 K is the limit because the color does not significantly change even if the temperature is raised to 100000 K, also values under 2000 K would exceed the possible gamut. [14]

As mentioned earlier the planckian locus scenarios were used to evaluate the controller itself in chapter 7 because they have the greatest degree of freedom and reached quite well over the possible gamut. Scenarios containing high luminance lamps (or other) that need to heat up would not give good overall picture of controlling quality, because the time span would be dependable on lamps' starting temperature.

6.5.2 Controlling scenario order

A typical display validation test case consists of different lighting scenarios that are repeated one after another. Chapter 3.2 wielded the different cases of adaptation and came to a resolution that exact adaptation times are hard to calculate, but it is obvious that light adaptation is much more agile than dark adaptation. Based on these facts in a case of multiple scenarios those should be arranged into an ascending illuminance order. When sequential scenarios have the same illuminance level dominating criterion should be the smallest color difference ΔE_{00}.

7 CONTROLLING RESULTS

As mentioned earlier there is a set of defined lighting scenarios that are intended to cover the ambient lighting needs for mobile display testing. As seen in chapter 6.5 these scenarios consisted of high and low illuminance scenarios, like a clear day or a parking lot at night, office and home lighting scenarios and black-body radiators. Some of them utilize only non-adjustable lamps, some adjust only illuminance level and some both chromaticity and illuminance. As known, the latter ones consists of two kinds of scenarios types: RGB adjustable planckian locus and high illuminance where chromaticity is corrected using RGB lamps. These scenarios have the greatest number of degrees of freedom and most variables, thus being the most interesting ones. In controller testing the idea was that if it could manage a multi variable controlling problem consisting of illuminance and chromaticity controlling side by side, each of them would perform least as well is only one of them would be adjusted. The controlling criteria itself were discussed in chapter 5.1.2. [47]

7.1 What to measure

When all the scenarios presented earlier are implemented there are a vast number of different scenarios. All of them cannot be analyzed here, so the decision was to take an extensive group which would contain relatively high and low illuminance levels from the middle and edge of the color gamut. As earlier have been mentioned planckian locus scenarios were justified for this job because they are widely used and well defined. Table 6-2 defines the used planckian locus scenarios, 34 in total (17 of both 500 and 2000 lux cases).

The light controlling algorithm has a one feature effect of which to the controlling result was obvious: the scenario initial state. This why the results presented later are divided into two categories: the first ones are controlled without lamp specific initial voltage values and the second ones using an initial state. Runs for both the test types and scenarios were conducted three times in a cyclic order. All the results and criteria were calculated using D65 as a white point.

When combined this results to 68 different scenarios and to 204 different data sets which is too many and even unnecessary to present here. This why the decision was to analyze 4000 K scenarios’ controlling runs with and without initial state more closely and count the following key figures using all data:

- Rising time mean value and standard deviation

- Settling time mean value and standard deviation

7.2 How the data collection was conducted

Firstly all the scenarios defined in Table 6-2 were entered into Autolights using its own interface.

Secondly, before the test runs were conducted the measurements device, USB4000, was calibrated as described in chapter 4.2.6 and its dark current was measured as described in chapter 4.2.5. After that the lamps were calibrated as described in chapter 5.3.5 using freshly calibrated USB4000.

Thirdly the data collection took place. It was conducted using Autolights data logging capabilities which controlled all the scenarios for a one minute, the countdown began from the first system state measurement and ended to the first one whose time stamp exceeded 60 seconds. From the each measurement all colorimetric variables including ΔE_{00} were recorded into file that was later on analyzed. During the data logging runs there were no personnel present at the test environment, but the environment setup was the same as it would have been during normal display testing situation. The spectrometer itself was placed onto a designated spot on the table.

7.3 Results and their interpretation

7.3.1 Graphs

In this section totally of four different scenarios are analyzed more closely. The scenarios were 4000 K and 500 lux as well as 4000 K and 2000 lux, both with and without an initial state. Each of these was controlled three times but during different occasions. 4000 K scenarios were selected because those are located quite near the edge of the sub-gamut constructed by SimOne's RGB lamps, which could be a potential problem when illuminance level is relatively low.

The figures itself show the scenario state in two different ways. Figure 7-1, Figure 7-3, Figure 7-5 and Figure 7-7 represent a traditional view, the color difference ΔE_{00} as a function of time. This is the same data by which the controller performance is evaluated. Color difference ΔE_{00} differs from a normal controlling criterion since as a distance it can only achieve positive values, so there is no overshoot, for example. In these figures ΔE *incoming* represents the steady state error and ΔE *leaving* the saturation level.

Figure 7-2, Figure 7-4, Figure 7-6 and Figure 7-8 however represent the system state development (CIE 1931 and illuminance) in a three dimensional graph. Dots in both figure types represent each system state measurement.

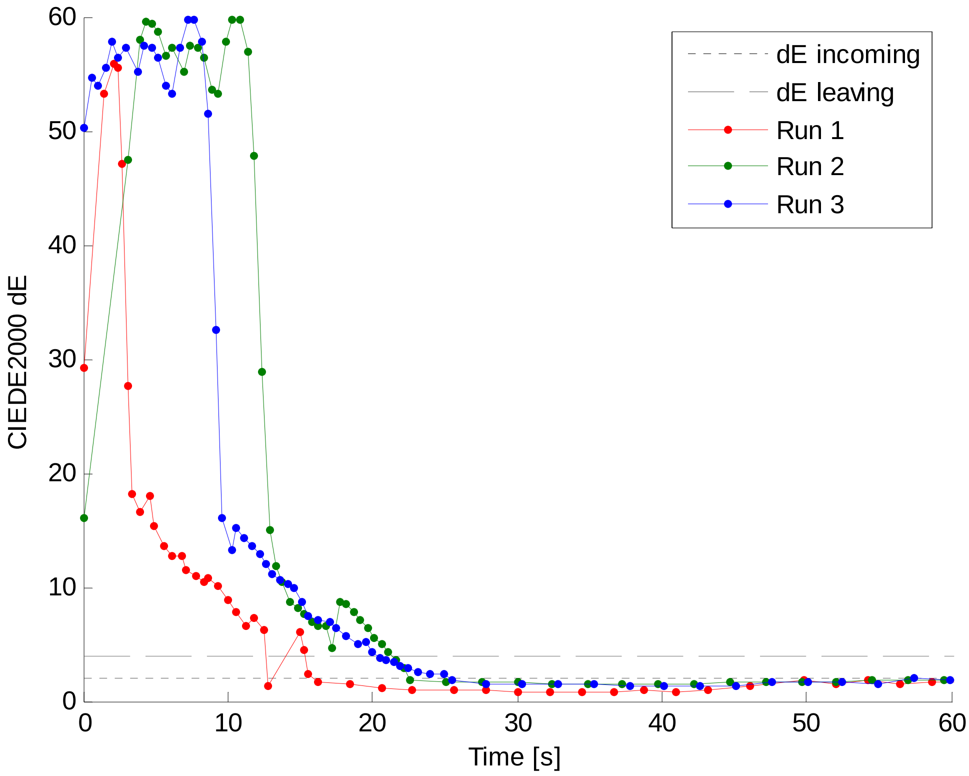

Figure 7-1. CIEDE2000 color difference as a function of time. The target was 4000 K and 500 lux, scenario was run without a previous initial state

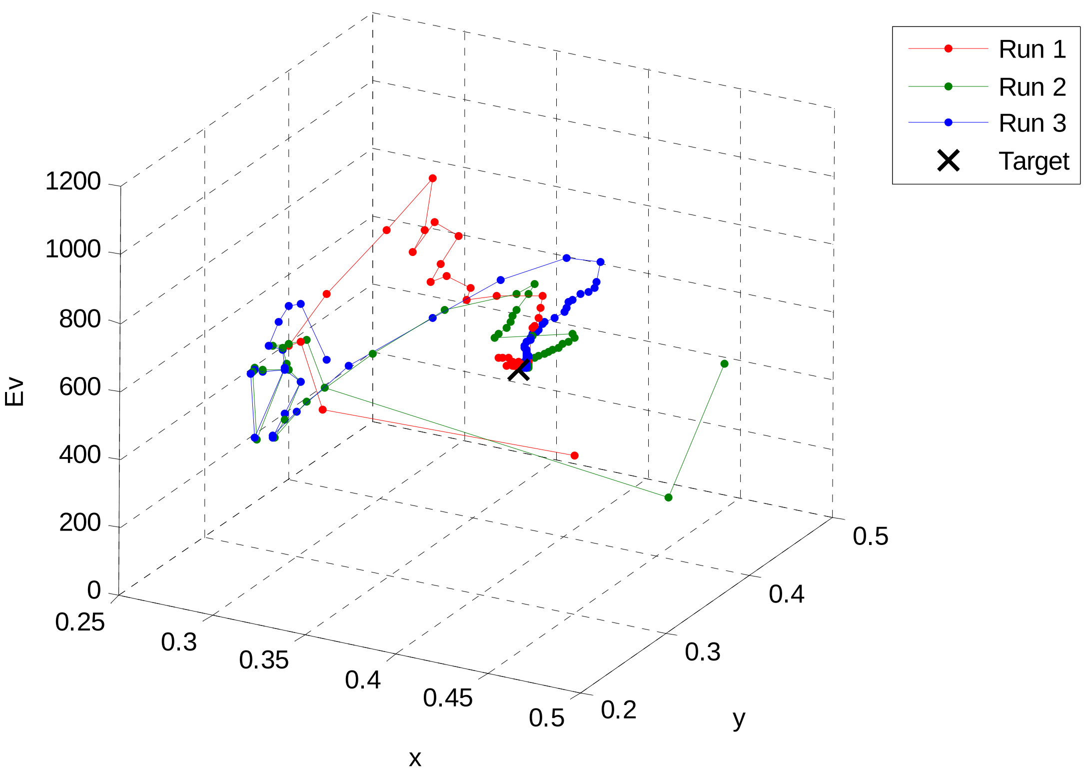

Figure 7-2. Measured colorimetric system state development during three test runs, the target was 4000 K and 500 lux, scenario was run without a previous initial state

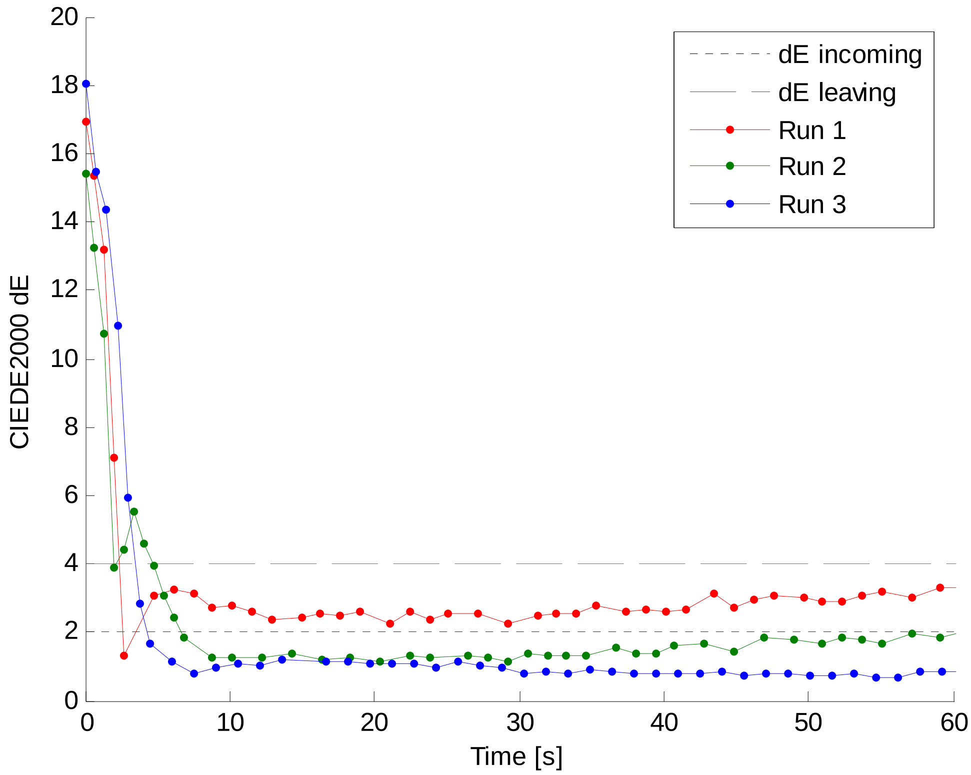

Figure 7-3. CIEDE2000 color difference as a function of time. The target was 4000 K and 500 lux, scenario was run using a previous initial state

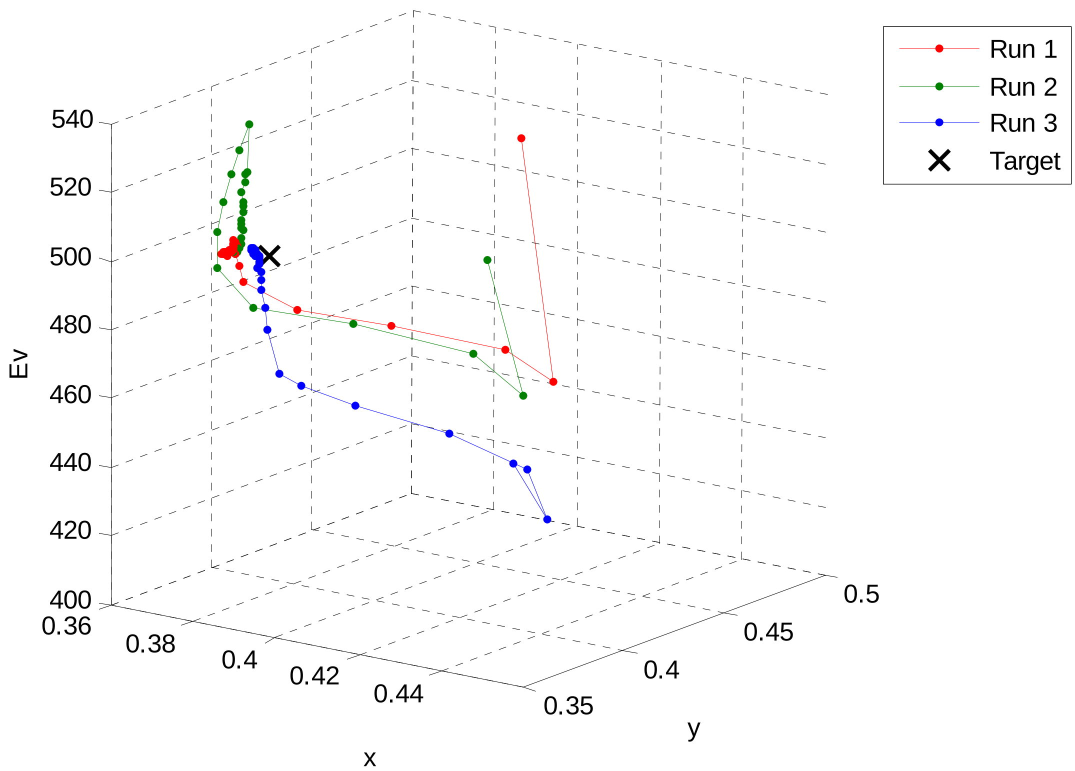

Figure 7-4. Measured colorimetric system state development during three test runs, the target was 4000 K and 500 lux, scenario was run using a previous initial state

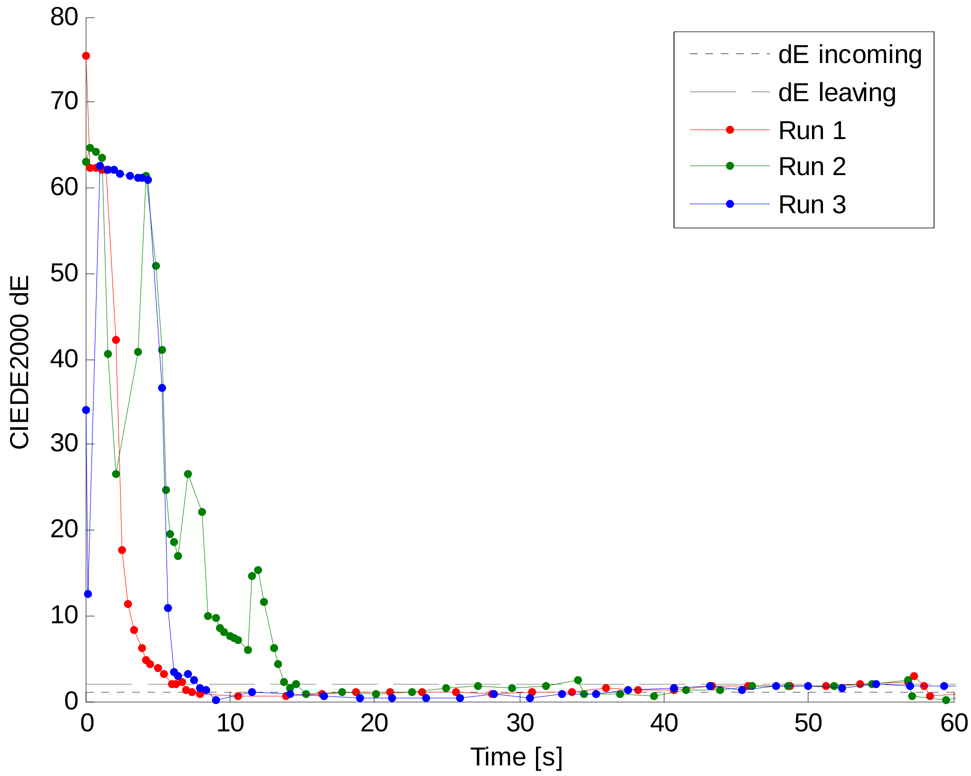

Figure 7-5. CIEDE2000 color difference as a function of time. The target was 4000 K and 2000 lux, scenario was run without a previous initial state

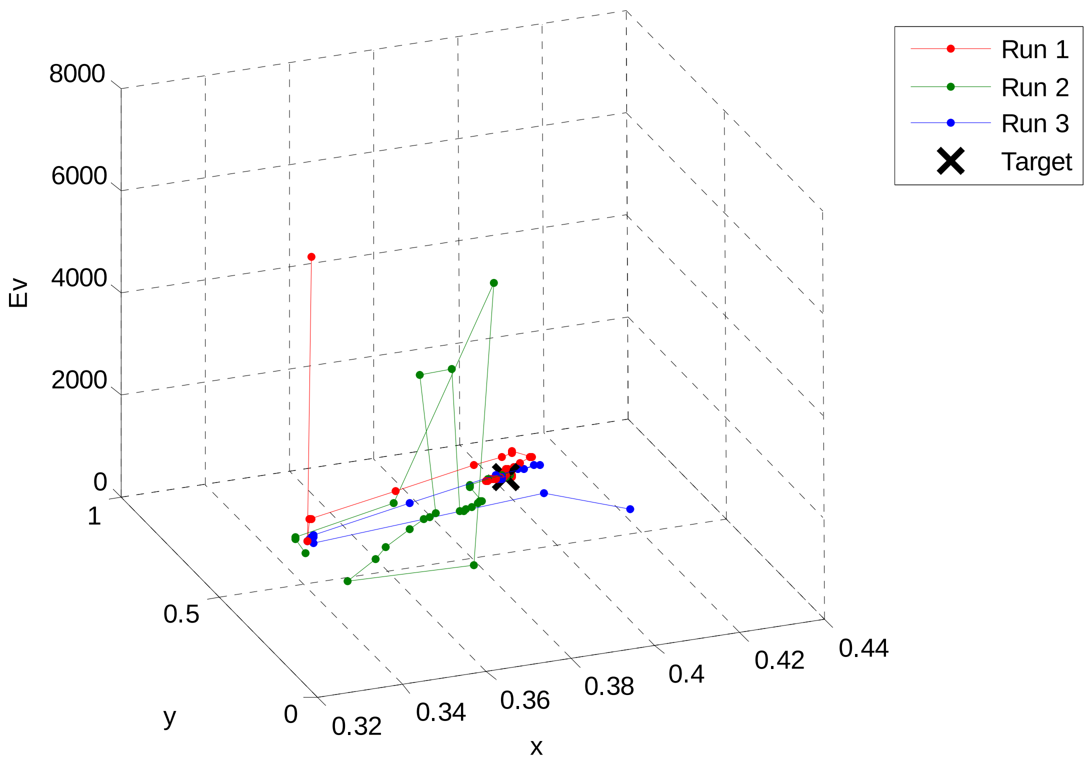

Figure 7-6. Measured colorimetric system state development during three test runs, the target was 4000 K and 2000 lux, scenario was run without a previous initial state

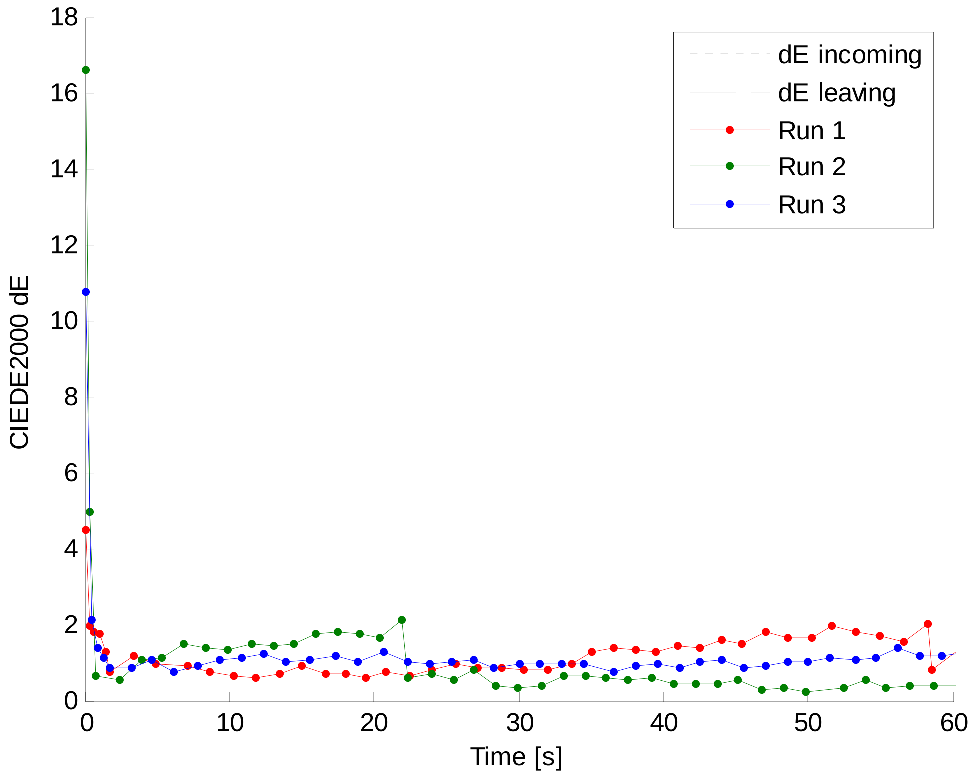

Figure 7-7. CIEDE2000 color difference as a function of time. The target was 4000 K and 2000 lux, scenario was run using a previous initial state

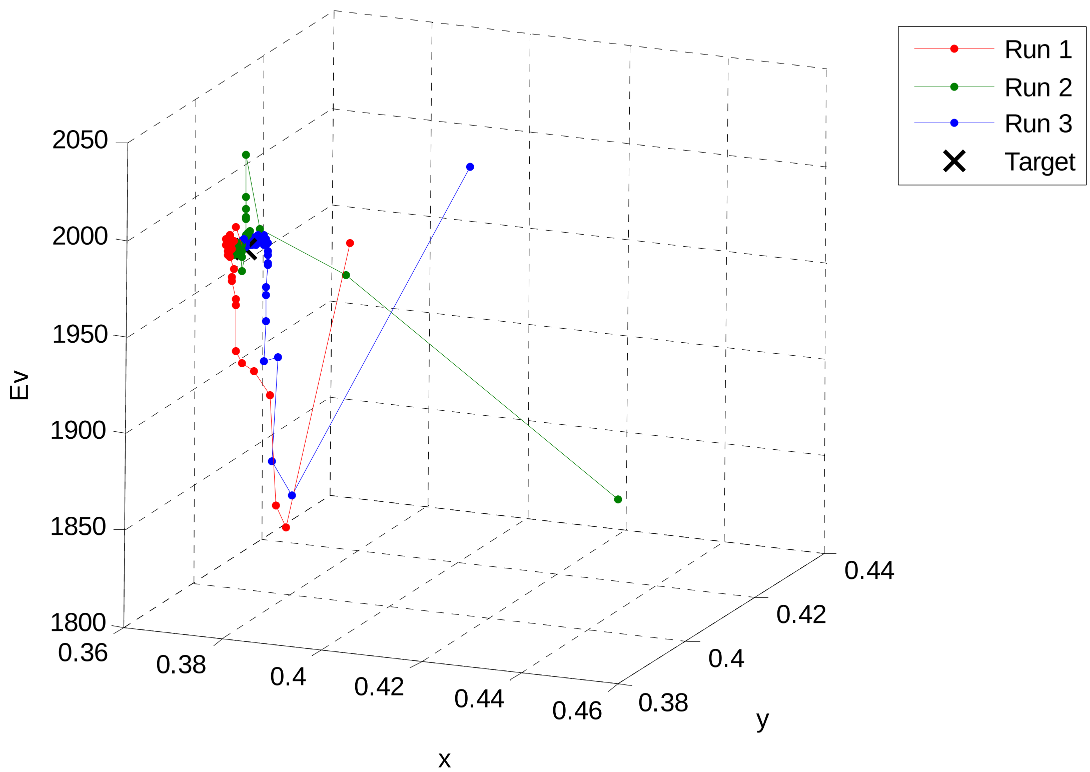

Figure 7-8. Measured colorimetric system state development during three test runs, the target was 4000 K and 2000 lux, scenario was run using a previous initial state

While studying Figure 7-1, Figure 7-2, Figure 7-5 and Figure 7-6 where no previous initial state was used a few notices can be made. The illuminance pinpointing sets the illuminance level near the target quite fast; however the chromaticity coordinate is in a wrong position so the illuminance change is not seen in the color difference, which is still high. After the chromaticity controlling cycle starts the color difference begins to decline more rapidly. In Figure 7-1 and Figure 7-5 can little bumps be seen, those are most probably caused by illuminance control, when the chromaticity is not achieved and lamps relative portions are wrong illuminance increment or decrement causes chromaticity to shift even more. In all the figures a wrong initial condition is the most significant factor. It can be seen as a huge initial color difference which needs drastic controlling procedures.

Figure 7-3, Figure 7-4, Figure 7-7 and Figure 7-8 wields controlling cases where a previous lamp voltage values are used as an initial state. As can be seen this condition causes much more agile performance and smaller initial color difference, which is roughly a quarter when compared to a corresponding scenario without a previous initial state. Even though the initial color difference is most probably wrong in all cases, rising time and settling time are much shorter. This originates from the fact that even though lamps relative portions might not be right in the beginning, the target can most probably be achieved using a same lamp combination as before. Time consuming iteration where lamps are turned on or off is thus minimized.

In Figure 7-2, Figure 7-4, Figure 7-6 and Figure 7-8 can be seen that the illuminance and particularly chromaticity is adjusted first by bigger and after that by smaller steps.

In Figure 7-1, Figure 7-5 and most clearly in Figure 7-7 can the saturation limit exceeding after the target achieving can be seen. When this happens the controller automatically corrects the system state until the ΔE_{00} is smaller than the acceptable steady state error.

As can be seen in all the previous figures the target is eventually reached (maximum rising time ~21 s and settling time ~25 s) although the most challenging and slowest ones are seen in Figure 7-1 (500 lux without an initial condition). The sub-gamut problem explains this behavior quite well. 500 lux illuminance is quite low and at least one of each RGB lamps must be turned on. This means that there are quite a small number of different lamp combinations with what the system state can be reached, and when lamp quantity is small turning one on or off causes a bigger proportional step response. When a previous initial state is used the correct lamps are automatically selected and the controlling problem is limited to their proportional voltage value adjusting. Longer integration time in low illuminance levels is also other explanatory variable for the longer time span.

Faster behavior (maximum rising time ~14 s and settling time ~16 s) seen in Figure 7-5 can be explained by measurement device’s shorted integration time, smaller step responses and greater number of possible lamp combinations, all this is caused by higher illuminance level. However the requirements for the saturation and the steady state error are stricter.

7.3.2 Values

As mentioned earlier because considerable quantity of different controlling scenarios presenting them all here is not necessary. In Table 7-1 the key figures for planckian locus scenarios controlled without a previous initial state can be seen. In Table 7-2 are the same figures for the same scenarios, the discriminating feature is that those were controlled using a previous initial state. Scenarios' rising and settling times used to calculate these values can be found from the appendix.

Because ΔE_{00} cannot have negative values rising time is the time when the color difference first time crosses the saturation level ($\Delta E_{00} = 2.0$ if $E_{v\_target} > 700$ or $\Delta E_{00} = 4.0$ if $E_{v\_target} \leq 700$).

As mentioned earlier the settling time is the time when ΔE_{00} first time undershoots the steady state error ($\Delta E_{00} \leq 1.0$ when the target illuminance $E_{v\_target} > 700$ and $\Delta E_{00} \leq 2.0$ when $E_{v\_target} \leq 700$) and stays under the saturation limit effectively.

Table 7-1. Planckian locus lighting scenarios' key figures, without a previous initial state

	Mean value		Standard deviation	
	500 lux	**2000 lux**	**500 lux**	**2000 lux**
Rising time [s]	16.133	14.020	10.555	6.736
Settling time [s]	19.922	17.863	11.994	9.021

Table 7-2. Planckian locus lighting scenarios' key figures, with a previous initial state

	Mean value		Standard deviation	
	500 lux	**2000 lux**	**500 lux**	**2000 lux**
Rising time [s]	1.896	3.433	2.628	6.375
Settling time [s]	4.612	5.037	3.951	7.755

It must be noted that during all one minute test runs the target was eventually reached and thus none of the test scenarios were un-achievable. As can be seen the mean settling time and rising time values are well under the one minute maximum. By interpreting these values some previous assumptions can be confirmed.

When a previous initial state is not used 2000 lux illuminance scenarios have shorter rising and settling times. The interpreting variable for this is measurement device's shorter integration time in higher illuminance. However this order is inverted when a previous initial state is used. The most probable explanation for this is that higher illuminance scenarios need more RGB lamps thus having more variables that can go wrong and need adjusting.

Also there is an interval between mean rising time and mean settling time is almost identical with both initial conditions (~3.8 s without an initial sate and ~2.2 with an initial state), although a little bit smaller when a previous initial state was used. When compared to rising time difference which is ~8.5 times longer for 500 lux and ~4.1 times longer for 2000 lux scenarios without an initial state.

When the standard deviation is studied some notes can be made. Generally standard deviation is quite high; this mean that different controlling scenarios differ from each other and the target is achieved sometimes quicker and sometimes slower. This is obvious when thinking about the controlling algorithm, a choice in the early stage can direct the controlling course into a different direction during different occasions. In spite of the course the target is eventually reached, which was the main idea of robust controlling. However rising time and settling time standard deviation does not differ inside one scenario type that much, settling time's deviation is a bit bigger (~1 s) which is obvious. This gives a hint that after the saturation level is crossed the target is achieved quite steadily. The biggest difference in time spans is caused in the early part of the controlling procedure.

In 500 lux scenarios when an initial condition is used the standard deviation is quite small even though its relative portion compared to mean rising and settling time is almost twice. In scenarios without an initial condition standard deviation is however quite big, over 10 seconds. When interpreted this can be explained by following arguments: the number of possible lamp configurations is small, thus if the controller manages to choose it correctly the procedure is quick and if not adjusting lamps correctly can take much longer time. Also USB4000 spectroradiometer has a longer integration time in lower illuminance level.

In 2000 lux scenarios the standard deviation is not affected by the initial state condition that much. In scenarios with a previous initial state standard deviation's relative portion compared to mean rising and settling time is quite great. This tells a tale about the fact that if the initial state is wrong the controlling time lengthens drastically and is it is right the controlling is agile.

8 CONCLUSIONS

Constantly developing mobile phone display technology and display requirements have created a need for reliable and comparable visual testing. Measuring displays technological characteristic and comparing those results have been previously studied. However the final decision whether a display is good in its category is done by an end user, the measurement device then is not a spectrometer but the eye itself. Lighting scenarios in which mobile displays are used, and must thus perform, cover the whole scale from a dark room to a sunny day. In order to make repeatable subjective testing feasible a test environment had been constructed. This environment, SimOne, however lacked a proper colorimetric feedback multivariable ambient light controlling which would allow adequate repeatability of the lighting scenarios, illuminance and chromaticity coordinate being the adjusted variables.

As the target was to develop a system that would serve test persons a humane approach had to be taken. Human visual system brought a lot of requirements and thus required also simplifications, among them are the adaptation times. In order to make comparable decisions adaptation has to be completed. Light adaptation is much more agile than dark adaptation, thus the decision was to arrange lighting scenarios to ascending illuminance order, and suggestive maximum light adaptation time span would be one minute. Chromatic adaptation occurs in tandem with light adaptation. Other problem which affects drastically to color difference calculations is white point defining. Because it is almost impossible to do on-the-fly the suggestion is to use some standard, like D65. Also using current system state as a white point could be another option.

Obviously colorimetric theory was as a foundation of the controlling system, because chromaticity controlling is based on metamerism full spectral power distribution was not intended to reproduce. To measure system state's three variables from a human point of view a color difference calculation was needed. CIE-recommended CIEDE2000 color-difference formula being the most advanced one was a logical choice, although it requires heavy calculation. However that was not a problem because sampling period is determined by measurement device's integration time and calculations are thus done at long intervals, ranging from about 20 ms to three seconds.

The environment, SimOne, was constructed before and composed of different kinds of lamps underneath of which were a diffusing opal glass and a toughened glass for safety reasons. RGB lamps were basically the most usable from chromaticity controlling point of view and the environment could be considered to be functional. Lamps' minimum operating voltage and thus minimum illuminance level caused disturbing step responses to the system. Lamps were controlled using I/O cards located in the operating PC. Ocean Optics' USB4000 spectroradiometer combined with a cosine lens measured the system state. The device was calibrated against a pre-calibrated PR-650 SpectraScan Colorimeter using wavelength calibration, a halogen lamp worked as a calibration light source. This arrangement was found to be adequate and first and foremost easy to perform and replicate. USB4000's lack of performance on lower illuminance levels lengthened the integration time with a reasonable saturation levels. The measurement error when integration time changed was also a bothersome flaw.

The chromaticity controlling algorithm which treated each lamp as a gravity point in a chromaticity coordinate based model was found to be a workable method. Each lamp was placed into the chromaticity diagram according to its coordinate, negative lamps worked as “pushers” and positive as “pullers”. Both the negative and the positive side were divided into membership sectors according to their significance. Most extreme lamps, basically RGB, constructed a color gamut but also a sub-gamut because of their minimum illuminance. This made achieving the target near the edges of the gamut problematic, especially on low illuminance levels. Separating PID-based illuminance controlling and chromaticity controlling from each other was a functional idea. Illuminance controlling was thus done using traditional PID-controller. CIEDE2000 color difference worked as a selector between these independent controlling cycles. Because of many and partly overlapping controlling parameters a genetic algorithm was used to optimize weighting factors that were determined by the distance. GA results gave controller parameter guidelines and confirmed a supposition that controlling should slow down when the target was approached.

Implementation played also a significant role in work behind this thesis, resulting to light controlling program called Autolights. The controlling algorithm itself was separated from the program as an independent module but Autolights described its potential and usage quite well. It also worked as a tool with which the controller was tested, optimized and analyzed. Also a group of test scenarios were defined during the process, number of these was kept low but at the same time they had to serve visual testing cases extensively.

The controller was analyzed using pre-defined planckian locus scenarios with two different target illuminance values, 500 and 2000 lux, with and without using previous parameters as an initial guess. During each controlling round rising time and settling time, and their mean values as well, were inside the target limits and could be considered as reasonable. Standard deviation was however quite strong which could be explained by iterative nature of the controller, a wrong early guess lengthens the controlling time span even though the target is eventually reached. 2000 lux scenarios were a bit faster, mainly because of measurement device’s shorter integration time, greater number of suitable lamp configurations and smaller step responses. 500 lux scenarios brought out bigger step responses and the sub-gamut when the target was located near the edges of the color gamut. In overall target chromaticity coordinate’s location inside the color gamut had an impact on the controlling time span.

A good initial guess had the most significant effect on rising and settling time. This is reasonable in two ways. Firstly a good guess obviously locates the system state near the target. Secondly the chromaticity controlling can be understood as a group of iteration rounds whose one purpose is to define the right lamps that can produce the wanted chromaticity coordinate. A good starting guess will reduce this number and the light controlling will thus be responsible for system state correction. Corrective procedures were found to be workable and they corrected drifted system state effectively.

At the end the controlling algorithm, its implementation and software structure were proven to be functional. Also a few targets for development emerged during this thesis work, which are wielded more closely in chapter 9

9 FUTURE DEVELOPMENT

This chapter covers possible enhancements as well as future study and development needs that aroused during the months of this thesis work. Some are closely related to the light controlling and some are ideas that could be utilized to potentially improve the mobile display testing environment.

9.1 Controlling development

During the controller development a few notices were made. Because the system and the controlling for it was unique and developed first time there were some ideas that could have enhanced the performance and quality of both the controlling and the lighting.

PID controller parameter tuning is now done by quite a raw way. Somewhat more intelligent and learning controller could enhance the controlling result. As well the current approach uses only one PID controller to give the same increment for all the lamps. This could be changed to more lamp-specific, if not all the lamps would have their own controller but the lamps could be grouped by their characteristics and one controller would be assigned for each of these groups.

As known chromaticity controlling parameters are tuned using genetic algorithm, however continuous adaptive optimization would help the situation even more. For example, intelligent function that would punish for unwanted effects like an overshoot and a steady state error as well as a step response when the target is already achieved could be effective.

One possible solution in order to improve lighting uniformity on the table level and illuminance uniformity between the eye and the table level could be a usage of two spectroradiometers. Also one of them could be optimized for low and the other for high illuminance, thus their dynamic range would not have to range through the whole illuminance range. This could improve integration time, accuracy and thus controlling performance on low illuminance, which is now one of the major problems. As stated earlier ceiling lighting uniformity can be tricky, now all lamps are weighted to the front of the SimOne to create a proper illusion of uniformity. This is hardest for the RGB lamps that can be distinguished through the opal glass. A web-camera could be mounted to monitor the ceiling and using machine vision combined to the spectroradiometer data there could be possibility to achieve lighting uniformity on the ceiling as well as on the table level.

One real-life target is to make the usage even more user-friendly and thus lower the threshold to use Autolights and SimOne for also other than R&D purposes. The optimal solution could be that only chromaticity and illuminance would be chosen and the controller would intelligently parse lamp with what the best possible solution would be achieved. This would most probably require some more information about the lamps; one possible solution could be a simplified CAD-model of SimOne that would include all lamps’ geometric locations.

As mentioned earlier the initial state guess has a major effect to the controlling time span. Using a previous state as an initial value is well justified and most probably the best solution when the scenario is previously achieved. On the other hand when a previous state is not present initial guess should be done more intelligently. Some kind of simplified CAD-model could provide an aid to this problem as well.

9.2 Environment development

As one of the underlying ideas is the possibility to simulate real life lighting scenarios, for example bright day, lamp construction should be somewhat different. Firstly because the distance to a light source is short when compared to the real world distance, on the eye level illuminance is much higher than on the table level. This causes the eye to adapt into different lighting that prevails on the display level. One possibility would be to use an eye-shade so that these two illuminance levels would be equal.

Secondly lighting uniformity on the ceiling is not complete even though a diffusing opal glass is used; different colored lamps can be distinguished from the ceiling. Replacing fluorescent RGB tubes with light emitting RGB diodes would allow more uniform light distribution. For example, in that case the high luminance lamps could work as a sun and blue or cloudy sky could be constructed using the LEDs. Also LEDs would allow more accurate controlling thus reducing step responses.

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APPENDIX

Appendix 1. Planckian locus scenarios' rising and settling times without a previous initial state

	Rising time			Settling time		
Temp. [K]	**Run_1 [s]**	**Run_2 [s]**	**Run_3 [s]**	**Run_1 [s]**	**Run_2 [s]**	**Run_3 [s]**
500 lux, without a previous initial state						
3000	14.5	60.0	52.0	14.5	60.0	60.0
4000	12.7	21.6	20.0	16.2	22.6	25.0
5000	12.7	20.0	17.6	25.7	20.5	18.1
6000	21.3	14.7	13.4	31.3	23.6	16.8
7000	10.5	15.0	20.3	12.9	18.4	20.3
8000	7.0	14.0	13.6	7.0	21.0	15.1
9000	5.4	11.0	18.6	5.9	14.5	19.7
10000	8.7	11.6	14.1	12.1	12.6	15.0
11000	16.3	7.4	11.7	17.5	9.4	13.7
12000	8.2	11.7	17.0	8.6	14.2	19.0
13000	8.4	9.5	7.4	11.7	13.0	7.4
15000	14.5	11.7	15.1	15.7	12.5	15.1
20000	11.7	9.9	16.5	35.0	12.6	23.0
25000	11.5	23.8	14.5	12.7	27.9	16.0
30000	14.3	13.5	22.9	14.3	15.0	22.9
35000	11.2	15.4	16.4	11.6	16.4	25.1
40000	52.0	8.1	11.9	60.0	18.0	38.9
2000 lux, without a previous initial state						
3000	12.6	21.4	21.6	13.4	24.7	22.3
4000	5.9	14.2	8.0	8.0	15.2	9.0
5000	5.8	6.1	8.1	11.1	10.1	9.5
6000	13.0	18.0	17.4	15.0	21.0	20.0
7000	12.0	8.3	8.2	54.0	33.0	25.0
8000	9.3	8.8	10.1	11.2	8.8	12.8
9000	7.9	11.5	9.0	8.3	14.1	9.0
10000	8.4	12.0	9.4	10.1	14.1	10.9
11000	9.3	11.1	14.1	11.9	14.6	16.7
12000	10.8	9.2	14.0	12.6	12.4	17.7
13000	9.3	24.0	22.0	13.3	26.0	23.2
15000	9.7	15.8	15.6	13.9	19.0	18.0
20000	25.2	9.3	25.8	34.0	13.5	27.4
25000	10.4	8.1	26.1	11.2	8.7	30.4
30000	12.2	27.7	12.2	14.4	27.7	14.6
35000	9.3	12.2	29.0	11.6	13.0	32.0
40000	23.7	20.2	31.7	30.7	20.2	31.7

Appendix 2. Planckian locus scenarios' rising and settling times with a previous initial state

Temp. [K]	Rising time Run_1 [s]	Run_2 [s]	Run_3 [s]	Settling time Run_1 [s]	Run_2 [s]	Run_3 [s]
500 lux, with a previous initial state						
3000	14.0	11.0	10.2	14.0	14.0	16.0
4000	2.7	2.0	3.7	2.7	6.7	4.5
5000	2.2	1.4	2.2	3.7	4.4	3.8
6000	2.2	2.9	3.0	3.7	2.9	3.7
7000	2.2	0.7	1.4	3.0	2.8	2.9
8000	0.7	1.4	0.7	2.2	1.4	4.4
9000	4.3	0.7	0.7	4.3	2.8	2.9
10000	0.7	0.7	0.7	2.2	0.7	2.9
11000	0.7	0.7	0.7	2.1	2.1	2.9
12000	0.7	1.4	0.7	2.2	2.0	2.2
13000	1.4	1.4	0.7	6.4	4.1	2.1
15000	1.3	1.4	1.4	14.0	10.0	7.9
20000	0.6	0.7	0.7	2.7	2.8	3.6
25000	0.7	0.7	0.7	2.7	2.8	2.1
30000	0.7	0.7	0.7	2.8	3.4	2.9
35000	1.4	1.4	0.7	12.0	16.5	4.9
40000	0.7	0.7	0.7	2.0	1.3	2.1
2000 lux, with a previous initial state						
3000	2.1	2.2	0.3	2.5	4.4	1.8
4000	0.3	0.7	0.8	1.8	0.7	1.7
5000	0.4	0.7	1.2	2.3	1.6	2.8
6000	0.7	1.4	1.4	2.4	1.4	2.8
7000	0.4	1.1	0.3	1.5	3.9	2.0
8000	0.9	1.3	0.4	1.6	1.3	1.8
9000	0.4	6.4	0.2	0.4	8.8	0.7
10000	7.2	1.0	6.2	10.2	1.0	12.4
11000	0.4	0.4	25.6	0.4	0.8	28.6
12000	8.3	2.6	0.3	11.4	4.0	1.0
13000	0.3	0.3	0.3	0.6	0.3	0.3
15000	9.6	0.4	0.2	13.7	0.4	0.4
20000	0.3	0.4	12.2	1.3	0.4	15.2
25000	27.1	12.7	8.6	27.9	21.8	17.6
30000	0.4	0.4	0.4	2.1	0.4	1.2
35000	0.4	0.4	0.4	0.4	0.4	1.9
40000	24.0	0.4	0.3	31.1	0.8	0.7