Low Cost Colour Measurements with Improved Accuracy

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Abstract

Colour measurements are usually performed by measurement devices in the range of 1,000 to 100,000 €. We have evaluated the low cost approach with the MAZET MCTS 2 colour system regarding absolute accuracy and usability for display applications.

The USB-powered sensor is available with standard software which is capable to measure absolute colour co-ordinates with an universal calibration. Additionally, this software allows calibrating the sensor to a special target (display, light source) with reference images or high end colour measurement devices.

Because the original software is more dedicated to perform various measurement tasks rather than display relevant applications, two programs were developed by us. One is for automatic calibration with a YOKOGAWA colorimeter, the other one captures the most relevant optical PC-monitor parameters (max. luminance, dark room contrast ratio, gamma values, colour co-ordinates and gamut) by just one click.

The accuracy of the MAZET MTCS 2 was evaluated in two ways: First, measurements and calibration with the original software and second by using of well known calibration algorithms in our own software. All programs show nearly the same results for measurements of PC-monitors: the absolute accuracy (with common calibration) we achieved is about $\Delta E^* \approx 10$ - 15 and, if the sensor is calibrated to the display, $\Delta E^* \approx 1$ - 3 (ΔE^* is the colour difference acc. CIE 1976 LUV). Therefore the MAZET MCTS 2 shows an excellent performance when calibrated to the display under test. For absolute measurements its accuracy is however limited.

1 Introduction

Colour measurements are necessary in many applications like evaluating of specifications as well as calibration of displays and control of colour light sources (e.g. LED backlights of LCDs). In multimedia systems usually device-dependant colour co-ordinates like RGB are used (e.g. stored in a file) and this leads often to colour shifts when displaying this on another device-dependant system like a monitor. So a better way is paved by device-independent colour systems like CIE. As a consequence of this, RGB-based devices have to be measured for grey scale, colours and gamut with standard colours (e.g. GRETAGMACBETH COLOURCHECKER) in order to generate corrections files (ICM).

In display metrology it is always a task to find the right balance between accuracy and costs. There are several colour measuring instruments available, but high accuracy means also high price. On the other side, many applications require a colour measurement capability that is cost-effective and has a sufficient accuracy. The latter can only be achieved with low cost sensors that are calibrated to the specific display (target). In this article we focus on the cost-saving task by evaluating the accuracy of MAZETs [1] low-cost colour sensor MTCSICS on a new (2006) evaluation board (MTCS 2).

2 Hardware

The MAZET MTCS Colorimeter 2 board (Fig. 1) is an USB based system to test and evaluate the colour sensor MTCSICS. The sensor ‘looks’ through a hole of a black plastic box to limit the acceptance angle to about 10°. The currents of the three photodiodes are amplified by a transimpedance amplifier and digitized (10-bit) by a microcontroller for signal processing. Reference data are stored in an EEPROM and a USB interface is used for data transfer from/to a PC and for power supply.

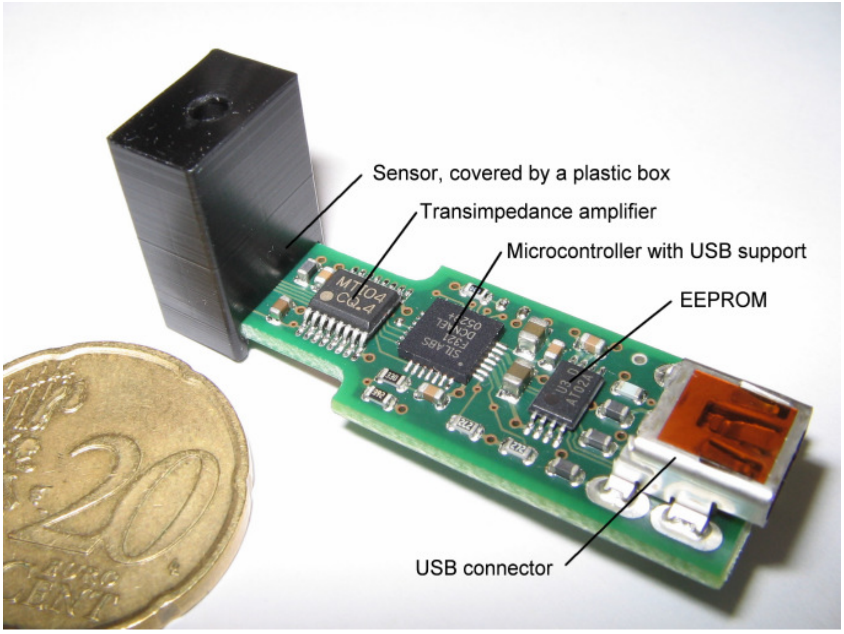

Fig. 1: MAZET MTCS Colorimeter 2 evaluation board

The MTCSICS sensor’s principle is to use three photodiodes with dedicated filters so that their spectral sensitivity is close to the standard colour matching functions (DIN 5033). It is furthermore optimized for high lifetime, temperature stability and a fast data acquisition.

A dedicated software for this sensor system is available from MAZET (see §4) which enables visualisation and logging measurement values in the CIE colour systems XYZ, 1931 Lxy, L*a*b* and L*u’v’. In addition, the sensor can be calibrated on the basis of colour targets.

3 CIE Colour Spaces

In colour measurement and colour management it is necessary to describe colours independently of the human perception in an objective way by an electronic device. Because of these needs the CIE (Commission Internationale de l’Eclairage) has established some standardised colour systems (colour spaces) which were improved over the time like 1931 Lxy, 1976 UCS and 1976 LUV. The so-called Tristimulus values X, Y and Z with Y as luminance are the basic CIE measurement parameters. They are usually transformed to CIE colour spaces (s.a.) to obtain colour co-ordinates. Furthermore, Tristimulus values are the only basis for calculations with more than one light source and for calibration.

To obtain Tristimulus values from a spectrum (intensity of light related to wavelengths) it has to be multiplied with the Colour Matching Functions (CMF, see Fig. 2) for each wavelength and all those products are summarized over the visible wavelengths.

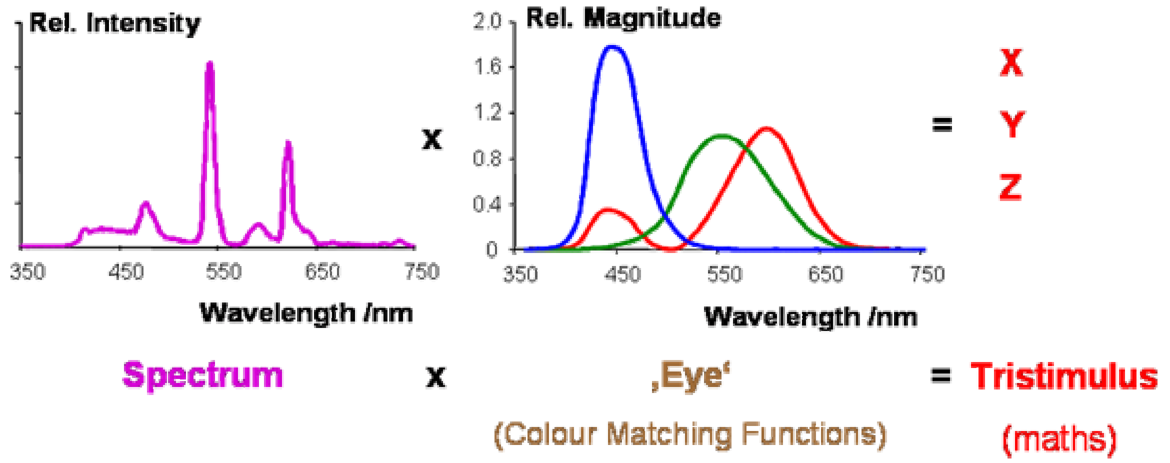

Fig. 2: Colour matching functions (CMF) [3]

This approach is used by monochromators and spectroradiometers. The other way to use at least 3 photodiodes with dedicated filters so that a spectral sensitivity of the colour matching functions is achieved. This is however difficult as the spectral response of photodiodes is completely different from the CMFs. The MAZET sensor characteristic are said to be very close to the CMFs and the device is therefore named as colorimeter.

For visualisation it is convenient to use a 2D representation of a colour space like CIE 1931 Lxy (see Fig. 3 left). In this colour space every colour has an x/y-coordinate which only contains the information about colour and not about the luminance which could be shown in the third dimension.

The x- and y-values can be derived from Tristimulus values by a linear transformation (Formula 1, see e.g. [5]).

$$x = \frac{X}{X+Y+Z}; \quad y = \frac{Y}{X+Y+Z}; \quad z = \frac{Z}{X+Y+Z} \quad \text{with } x + y + z = 1$$

Formula 1: Linear transformation of XYZ to CIE 1931

The CIE 1931 standard is very widespread. However display metrology standards refer to CIE 1976 UCS (see Fig. 3 right), which has some advantages over the 1931 standard. The most important one is, that in CIE 1976 UCS colour differences (Mac Adam ellipses) are more uniform. For practical use in terms of noticeable (colour) differences, the colour spaces CIELAB and CIELUV from 1976 provide a formula which is normalized to the 'Just Notable

Difference' of a human observer via $\triangle E^* = 1$. A value for $\triangle E^* = 5$ is the difference that can be easily differentiated by human eye, $\triangle E^* > 20$ is specified in ISO 15008 for minimum colour discrimination. The colour difference $\triangle E^*$ in the CIELUV (1976, non-linear transformation of XYZ) is defined as shown in Formula 2 (see e.g. [5]).

$$\Delta E^*_{uv} = \sqrt{\underbrace{(\Delta L^*)^2}_{\text{Luminance}} + \underbrace{(\Delta u^*)^2 + (\Delta v^*)^2}_{\text{Colour}}}$$

Formula 2: Calculation of the colour difference $\triangle E^*$ in the CIELUV system

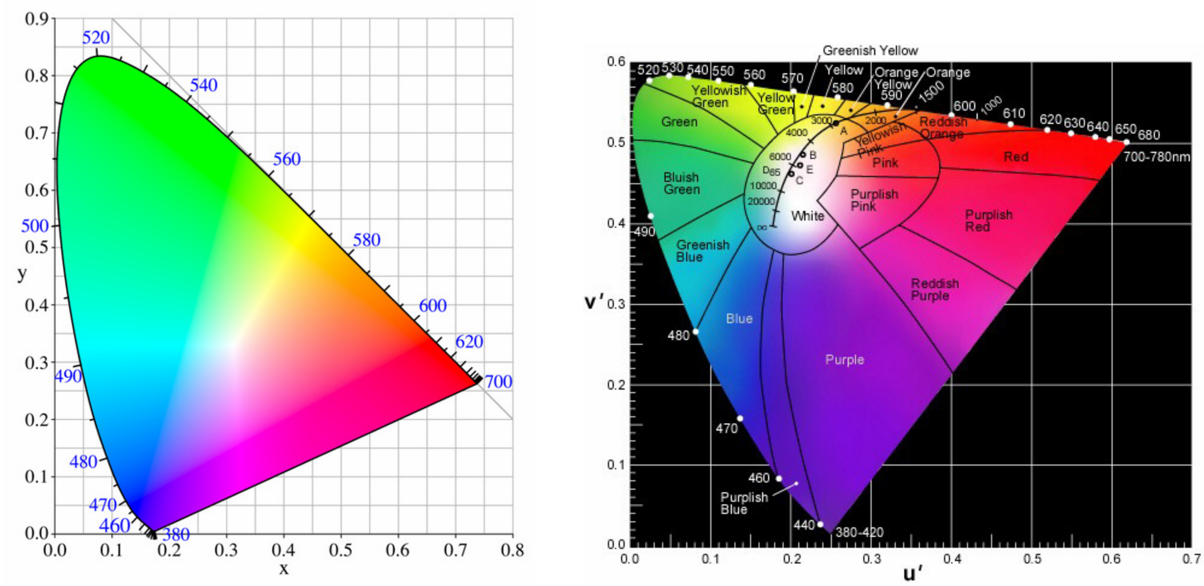

Fig. 3: CIE 1931 Lxy (left, [4]) and CIE 1976 UCS (right, [5])

4 Evaluation of the Sensor Board with MAZET Software

First tests of the low cost sensor were done by using the original software from the manufacturer. After its installation the sensor board is plugged to a PC via USB. The program (screen shot see Fig. 4) allows the user to test and to calibrate the sensor. The sensor is ready to use with standard calibration (via standard correction matrix, see §5) and the output is given graphically and in figures of different colour systems. These data can also be saved to a text file as single values or as series of measurement.

Another function of the program is the calibration of the sensor: The PC-software displays sequentially a set of predefined and optimized (in the sense of calibration) colours and captures the corresponding data of the sensor as XYZ-like data. With these measured and the reference data, the program calculates the correction matrix (a detailed description can be found in the next paragraph). The MAZET software works well and helps minor experienced users to perform and to understand colour (spaces) and their measurement.

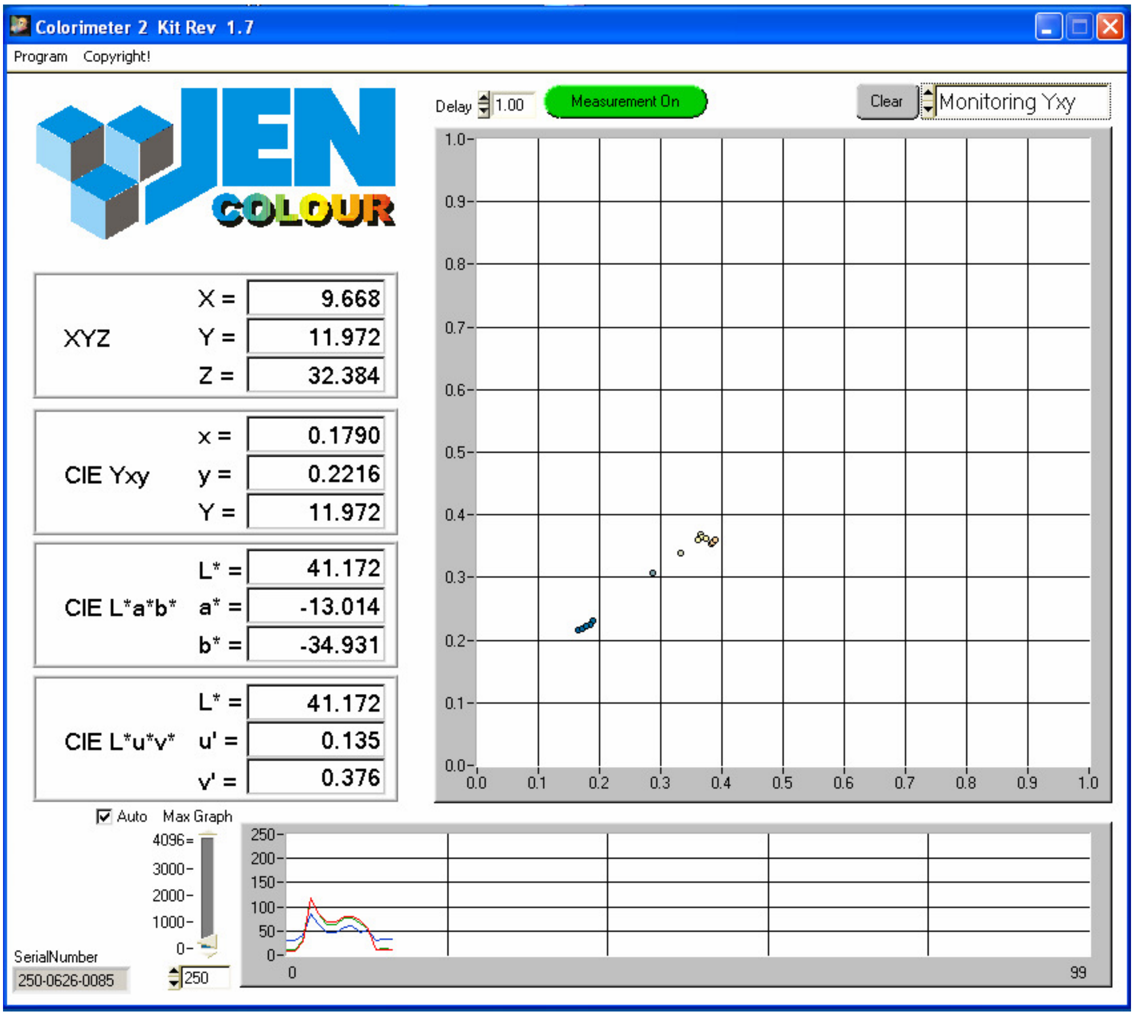

Fig. 4: MAZET colorimeter 2 software

5 Correction Matrix

If there are some differences between Colour Matching Functions and the spectral sensitivities of colorimeters, a correction can be made via reference measurements. Doing this, the accuracy of colorimeters can be enhanced – but unfortunately only for the calibrated display (or light source). The algorithm of calibration is as follows: For calculation of a correction matrix two 3xN matrices have to be determined, whereas N is the number of different colour images that are used for these measurements and '3' stands for the Tristimulus values. Several (optimized) colours have to be displayed and measured with both a reference instrument that outputs real XYZ values and the sensor in XYZ-like values. The 'real' XYZ Tristimulus values set the 3xN matrix **XYZ** and the measured sensor data are stored in the 3xN matrix $\mathbf{X_{SD}Y_{SD}Z_{SD}}$.

With these matrices the 3x3 correction matrix 'cm' can be calculated via Formula 3 (see e.g. [2], [5]). The linear approach is suitable because the spectral sensitivity of the MAZET sensor is close to the original CMFs (see [5], appendix G).

This correction matrix has to be used for the conversion from XYZ-like data measured by the colour sensor to calibrated XYZ Tristimulus values that can be transformed to any CIE colour space. This conversion is performed by a matrix operation given in Formula 4.

$$\begin{pmatrix} cm_{11} & cm_{12} & cm_{13} \\ cm_{21} & cm_{22} & cm_{23} \\ cm_{31} & cm_{32} & cm_{33} \end{pmatrix} = \left(\begin{pmatrix} X_1 & .. & X_N \\ Y_1 & .. & Y_N \\ Z_1 & .. & Z_N \end{pmatrix} x \begin{pmatrix} X_{SD1} & .. & X_{SDN} \\ Y_{SD2} & .. & Y_{SDN} \\ Z_{SD3} & .. & Z_{SDN} \end{pmatrix}^T \right) x \left(\begin{pmatrix} X_{SD1} & .. & X_{SDN} \\ Y_{SD2} & .. & Y_{SDN} \\ Z_{SD3} & .. & Z_{SDN} \end{pmatrix} x \begin{pmatrix} X_{SD1} & .. & X_{SDN} \\ Y_{SD2} & .. & Y_{SDN} \\ Z_{SD3} & .. & Z_{SDN} \end{pmatrix}^T \right)^{-1}$$

cm:	Elements of the correction matrix
XYZ:	Tristimulus values of N colours, measured with a calibrated colour device
$X_{SD}Y_{SD}Z_{SD}$:	Measured XYZ-like values of N shown colours by the sensor
SD:	Sensor data
^{T}:	Transpose of matrix
$^{-1}$:	Inverse of matrix

Formula 3: Calculation of the correction matrix

$$\begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} = \begin{pmatrix} cm_{11} & cm_{12} & cm_{13} \\ cm_{21} & cm_{22} & cm_{23} \\ cm_{31} & cm_{32} & cm_{33} \end{pmatrix} x \begin{pmatrix} X_{SD} \\ Y_{SD} \\ Z_{SD} \end{pmatrix}$$

Formula 4: Transformation of XYZ-like <u>s</u>ensor <u>d</u>ata to <u>c</u>alibrated $X_CY_CZ_C$ Tristimulus values via <u>c</u>orrection <u>m</u>atrix

6 Comparison of the Low Cost Sensor with a Colorimeter

For evaluating the accuracy of the MAZET low cost solution compared to the mid-range priced YOKOGAWA 52002 colorimeter, several tests were undertaken using standard calibration (values from MAZET) and display specific (via correction matrix) calibrations. Different colours are displayed on PC monitors and measured with the two devices. The YOKOGAWA was set to Tristimulus output, the measured values of the sensor board are transformed by software to XYZ via a correction matrix. All data were then transformed to CIELUV colour space for calculating the colour difference (see [3], [5] for more details) between reference and MAZET sensor.

12 series of measurements were performed for 6 different monitor configurations, first with the standard calibration and then with the specific calibration for each display. We evaluated a CRT and an AM LCD monitor, each were set to three different colour temperatures (user defined, 6500 K and 9300 K). During every series of measurement 24 monochrome grey shades and colours (related to the GRETAGMACBETH COLORCHECKER colours) were displayed and measured (see Table 1 as an example, 'YOKAGAWA'-white was used as reference for $\triangle E^*$ calculations). Fig. 5 as an extract of Table 1 clearly shows, that absolute calibration to 'targets' under tests are necessary for the MAZET MTCS 2: The deviations from the reference differ in both direction and distance. Simple linear approaches like X' = aX etc. therefore don't work properly. On the other hand, the accuracy of the sensor calibrated to the device under test is high as also the numerical calculations of Table 1 point out.

The results of all 12 series of measurements (24 colours per series) are shown in Table 2.

Table 1: Exmple data of a CRT monitor (8-bit GS ; 6,500 K)

Displayed Colour			YOKOGAWA Colorimeter			MAZET Colour Sensor MTCS 2							
						Standard Calibration				Calibration to DUT			
R	G	B	X	Y	Z	X	Y	Z	△E*	X	Y	Z	△E*
94	28	13	11.4	6.7	2.2	10.1	6.8	-0.3	**14.9**	11.5	7.1	2.5	**4.2**
241	149	108	100.6	78.6	43.9	87.5	74.0	44.9	**22.7**	100.1	78.1	44.0	**0.6**
97	119	171	39.7	35.3	91.2	38.5	35.8	97.4	**8.7**	40.1	35.9	91.2	**1.2**
90	103	39	19.3	22.1	8.6	17.5	21.5	6.6	**7.9**	19.4	22.3	9.0	**0.7**
164	131	196	69.8	54.3	122.1	65.3	53.9	131.3	**15.7**	70.3	55.0	122.3	**0.9**
140	253	153	96.8	132.3	89.9	88.7	127.5	94.3	**11.3**	96.7	131.6	89.7	**0.9**
255	116	21	96.8	65.7	11.0	81.6	60.7	8.4	**27.2**	96.3	65.5	10.9	**0.9**
7	47	122	10.3	7.0	43.3	11.2	7.9	45.1	**3.0**	10.4	7.3	43.5	**0.8**
222	29	42	65.4	35.3	9.8	54.8	32.0	7.6	**23.5**	64.9	35.0	10.0	**0.9**
69	0	68	8.4	4.3	13.9	8.0	4.5	12.8	**4.5**	8.4	4.4	14.1	**0.8**
187	255	19	105.0	139.6	25.8	92.3	132.1	23.4	**14.1**	104.5	138.1	25.8	**1.5**
255	142	0	102.6	77.3	11.5	86.8	71.6	8.8	**25.9**	101.9	76.9	11.5	**0.7**
0	0	142	11.7	5.2	58.8	12.8	6.3	62.0	**4.3**	11.7	5.4	58.7	**0.8**
64	173	38	32.9	54.3	14.4	30.2	52.2	12.3	**4.8**	32.6	53.7	14.4	**0.9**
203	0	0	52.5	27.8	3.8	44.0	25.1	0.9	**20.2**	52.3	27.5	3.7	**1.1**
255	217	0	127.8	126.0	20.4	109.6	117.9	17.8	**22.8**	126.8	124.9	20.3	**0.7**
207	3	124	63.1	32.5	47.2	54.7	30.3	49.0	**23.5**	62.7	32.4	47.2	**1.1**
0	148	189	40.1	45.0	113.0	40.1	45.6	121.3	**6.6**	40.0	45.1	112.0	**1.0**
255	255	255	179.7	172.1	218.8	160.7	163.2	232.1	**23.2**	176.8	168.9	214.9	**1.0**
249	249	249	170.9	163.7	207.7	153.1	155.3	220.7	**22.7**	168.3	160.7	204.7	**1.1**
180	180	180	87.2	83.4	106.7	79.2	80.4	113.4	**16.6**	86.7	82.7	106.0	**0.5**
117	117	117	35.4	33.6	44.1	32.4	32.5	45.1	**8.9**	35.4	33.6	44.1	**0.0**
53	53	53	7.4	6.8	9.6	7.2	6.9	7.8	**6.2**	7.4	6.9	9.6	**1.0**
0	0	0	0.4	0.4	0.7	0.7	0.7	-1.9	**11.7**	0.4	0.4	0.7	**0.1**
			Reference			**∅ ΔE* : 14.6**				**∅ △E* : 1.0**			

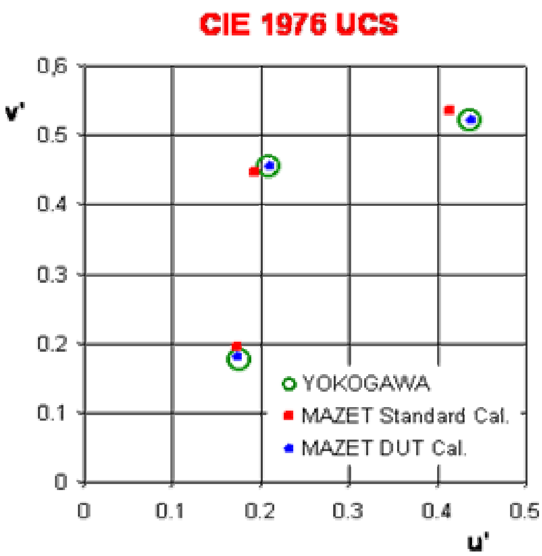

Fig. 5: Extract and visualisation of selected data from Table 1 (W, R, B)

Table 2: Average $\triangle E^*_{LUV}$ for different monitor Correlated Colour Temperatures

	CRT		AM LCD	
	Standard Calibration	Display under Test Calibration	Standard Calibration	Display under Test Calibration
White point	$\triangle E^*_{avg}$	$\triangle E^*_{avg}$	$\triangle E^*_{avg}$	$\triangle E^*_{avg}$
User defined	**13.1**	**1.4.**	**7.4**	**3.1**
6500 K	**14.6**	**0.9**	**6.7**	**2.8**
9300 K	**13.8**	**1.0**	**7.8**	**2.7**

Our results show clearly, that the quality of measurement increases significantly by calibrating the MAZET sensor to the display (light source, device, …) under test. With standard calibration, colour differences $\triangle E^*$ in the range of 10 can be achieved. These values are however too large for absolute colour measurements. By performing an absolute calibration of the MAZET MCTS 2 to the display, $\triangle E^*$ lowers to about 1 for CRTs and 3 for AM LCDs. Especially for CRTs, the MAZET colorimeter evaluation board has an accuracy of the human eye (vision). Shifts in colour temperature have only a slight influence on the measurements results, so this effect can normally neglected.

7 Software for Automatic Calibration of the MAZET Colour Sensor System

We developed a software for PCs with MICROSOFT VISUALSTUDIO C++ for two reasons:

- Test of implementing the MAZET DLL to individual software
- All-in-one 'automatic' solution for calibrating the MAZET sensor by YOKAGAWA

The correction matrix (see §5) is derived from YOKAGAWA XYZ values and the sensor evaluation board XYZ-like data (XYZ_{SD}) of a dedicated set of colours. A screenshot of the software is shown in Fig. 6, its flowchart in Fig. 7.

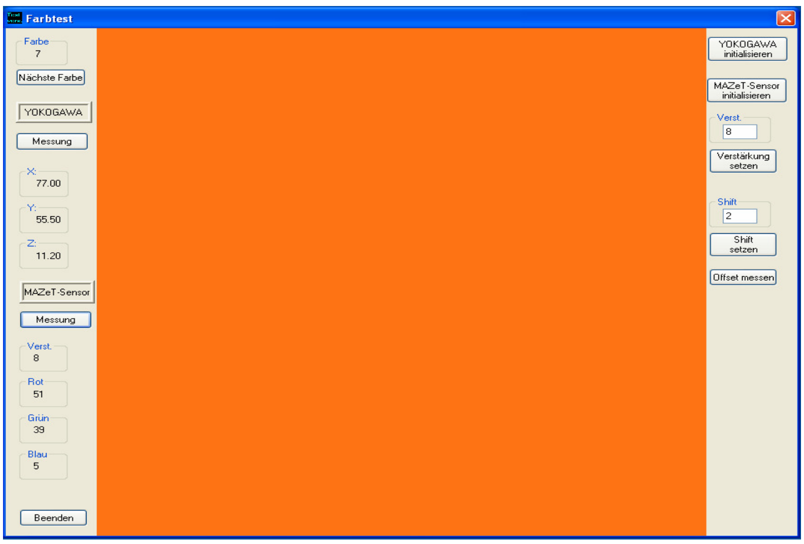

Fig. 6: Software for automatic measurement and calculation of correction matrix

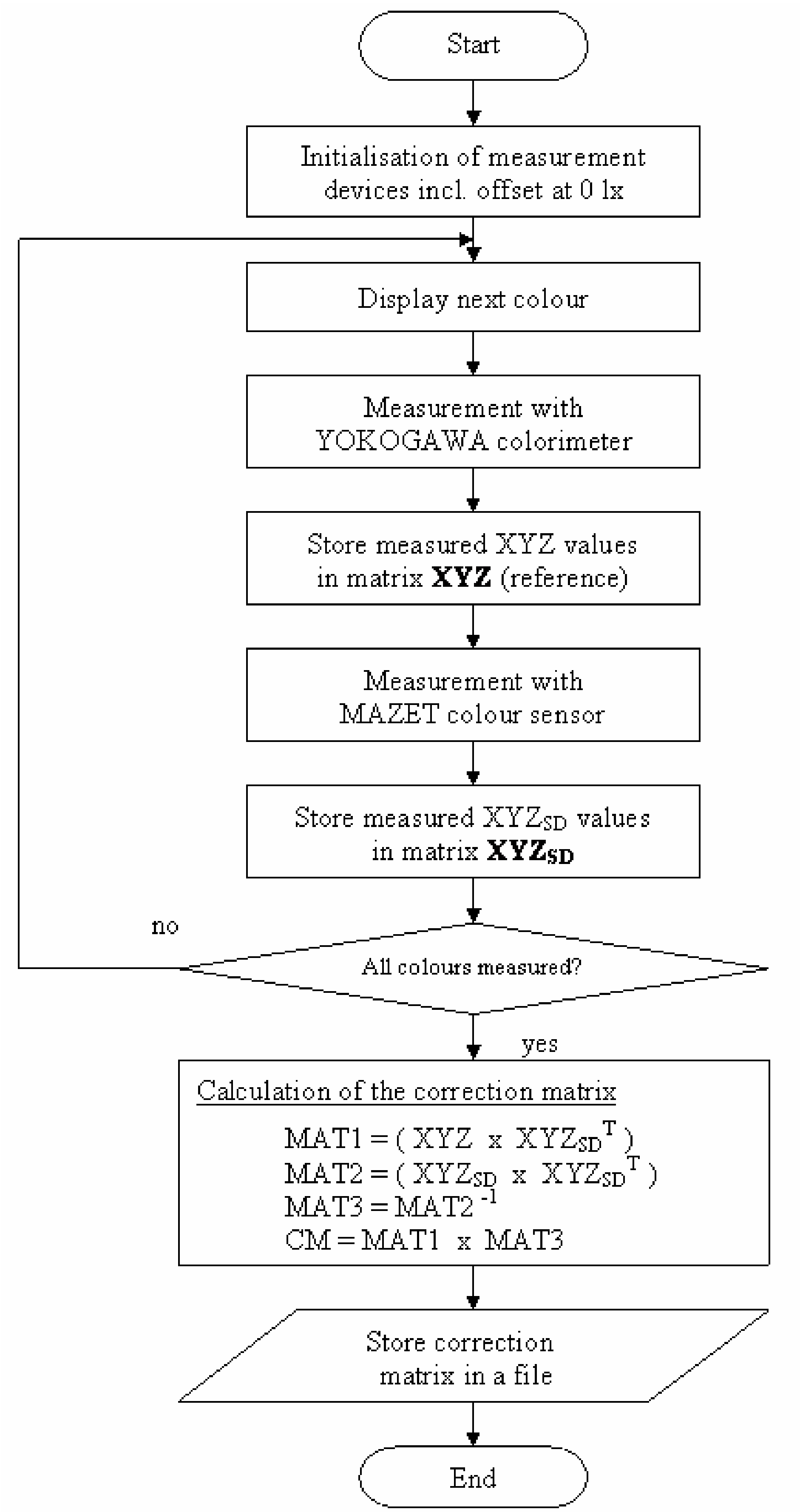

Fig. 7: Flow chart of main functions of the program

The main function of the program is displaying coloured boxes and to acquire their data from the sensor board and the colorimeter. As mentioned above, the sensor board is controlled via a software interface (DLL) that is integrated in this software. The measured data from the MAZET board are XYZ-like values, the YOKOGAWA returns XYZ Tristimulus values which are taken as reference. The software displays sub sequentially a set of colours and measures every colour with both devices. These data are saved and displayed during measurement. The YOKAGAWA reference values are stored in a 3xN matrix called "XYZ" and the sensor data are written to a 3xN matrix named as "XYZ_{SD}". N is the number of colours that are displayed by the program. The 3x3 correction matrix is then calculated via Formula 3 and saved to a file.

8 Software for Automated PC-Display Measurements with MAZET Colour Sensor

The second developed program (see Fig. 8) is dedicated to perform PC-monitor relevant measurements automatically by just pressing one button. This is, e.g., suitable for quality control and series production because the sensor has to be calibrated before for achieving a sufficient accuracy (see §6). Alternatively, single colour measurements can be performed. The software is at the moment more for evaluation but can be easily adapted e.g. to visualize measurements graphically or to print out and store the data.

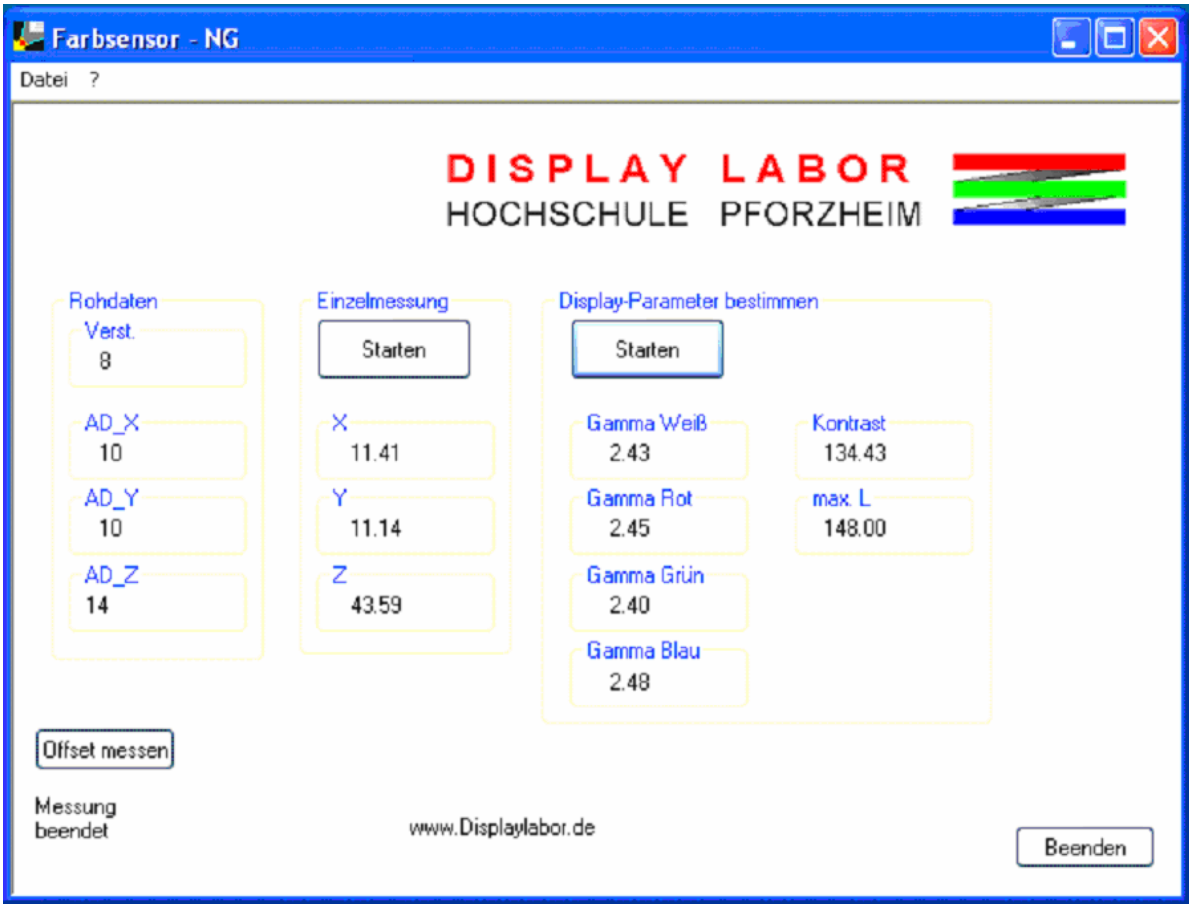

Fig. 8: Software for visualisation of display parameters

The flowchart of this program is visualized in Fig. 9: After initialisation of the sensor (calibration matrix loaded, dark offset measurement) the program displays a monochrome and coloured (primaries) grey shades. The measured data are stored in variables and when all measurements are done, these data are processed: At first, the display calibrated Tristimulus values are calculated from the sensor data via the correction matrix. Based on these values many display parameters can be derived by just pressing a button once:

- Maximum luminance (Y) of white display
- Contrast as ratio of white to black luminance
- Gamma values
  The calculation is done via linear regression from the luminance values. The quality of the approach is enhanced by subtracting the luminance for black from the other luminance values.
- Colour co-ordinates for the primaries and white point by transforming the measured and corrected Tristimulus values to the desired CIE colour space
  (additionally the correlated colour temperature and gamut can be calculated)

9 Discussion

The low cost USB MAZET Colour Sensor System MTCS 2 was evaluated. The original software is good for testing and calibration. However for serious applications, dedicated software should be written. With the MAZET DLL as basis for initialisation and data transfer, it is relative easy for experienced WINDOWS programmers to implement the colour sensor into their own software. This was done by us for two purposes as example applications: automated calibration and display performance evaluation. Furthermore, the mathematical theory of calibration is presented in brief and is implemented in our software.

When discussing accuracy of the MAZET colour sensor, one have to distinguish between absolute measurements of any specimen (display, light source etc.) and relative measurements after a dedicated and absolute calibration with a reference colour measurement device was done. For several PC monitors (both CRTs and LCDs) the CIELUV colour difference $\triangle E^*$ is in the range of 10 for standard calibration which is relative high for doing absolute measurements. After several test and comparison with other measuring systems it is obvious that the evaluation board can only achieve the quality for colour measurements with resolution of human eye ($\triangle E^* < 3$ for adjacent displays) when the sensor is calibrated to the display or light source under test. With the need for calibration and the low costs in mind, the sensor has many advantages in applications like colour detection, control of LED based LCD backlights, etc.

10 References

[1] Webpages of manufacturer: www.mazet.de

[2] MAZET: “Farbmessung mit JenColour Farbsensoren mittels Kalibrierung und Korrekturmatrix”, Application Note

[3] K. Blankenbach: Script “Multimediatechnik”, University Pforzheim

[4] Wikipedia: http://en.wikipedia.org/wiki/CIE_1931_color_space

[5] Billmeyer and Saltzman: Principles of color technology, 3rd Edition, John Wiley & Sons, Inc.

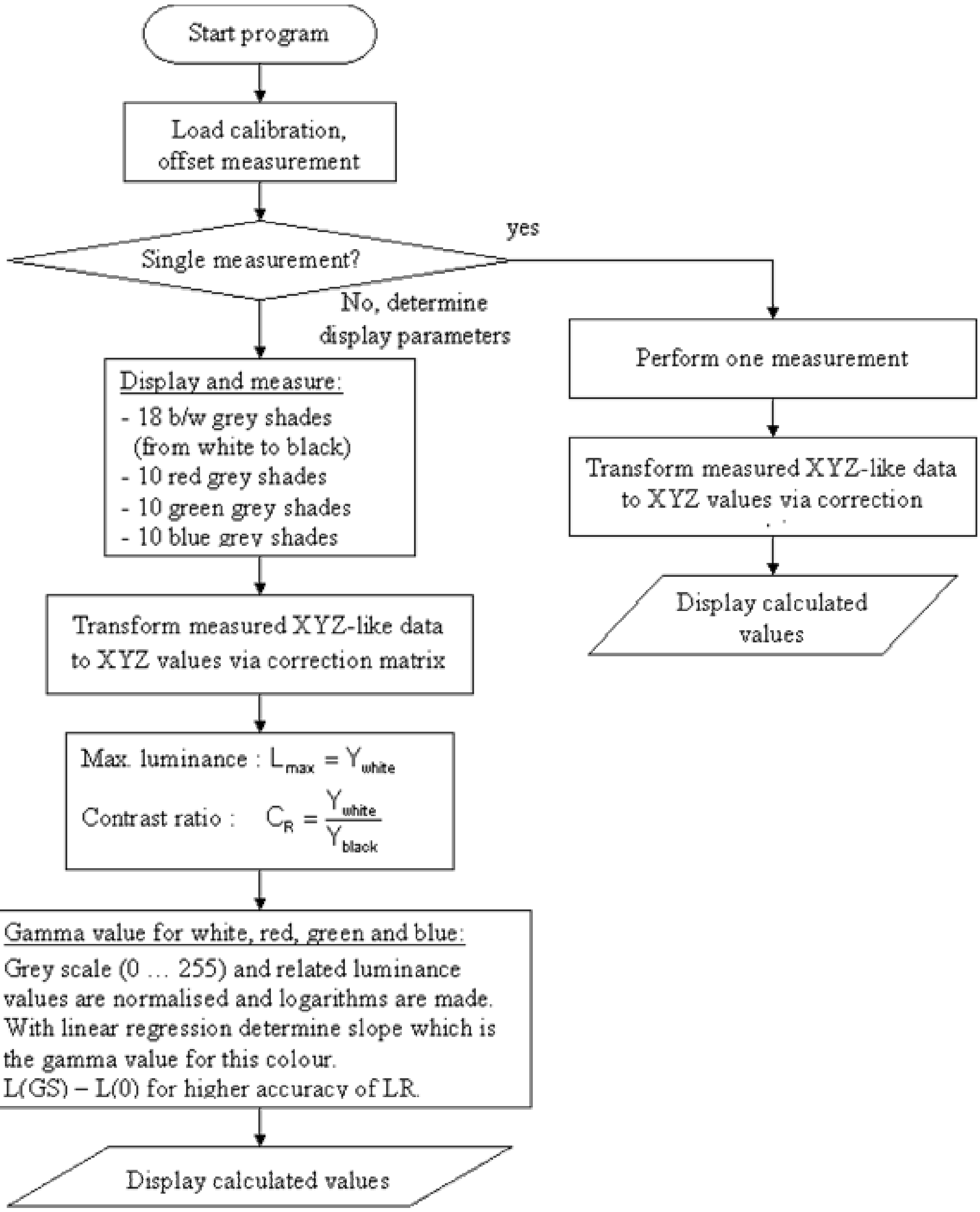

Fig. 9: Flow chart of main functions of the display parameters acquisition software